CLIMATE RESILIENT INFRASTRUCTURE

A Guide to Resilient Infrastructure Investment in Latin America and the Caribbean



UKSIP UK Sustainable Infrastructure Program

IDB | Invest

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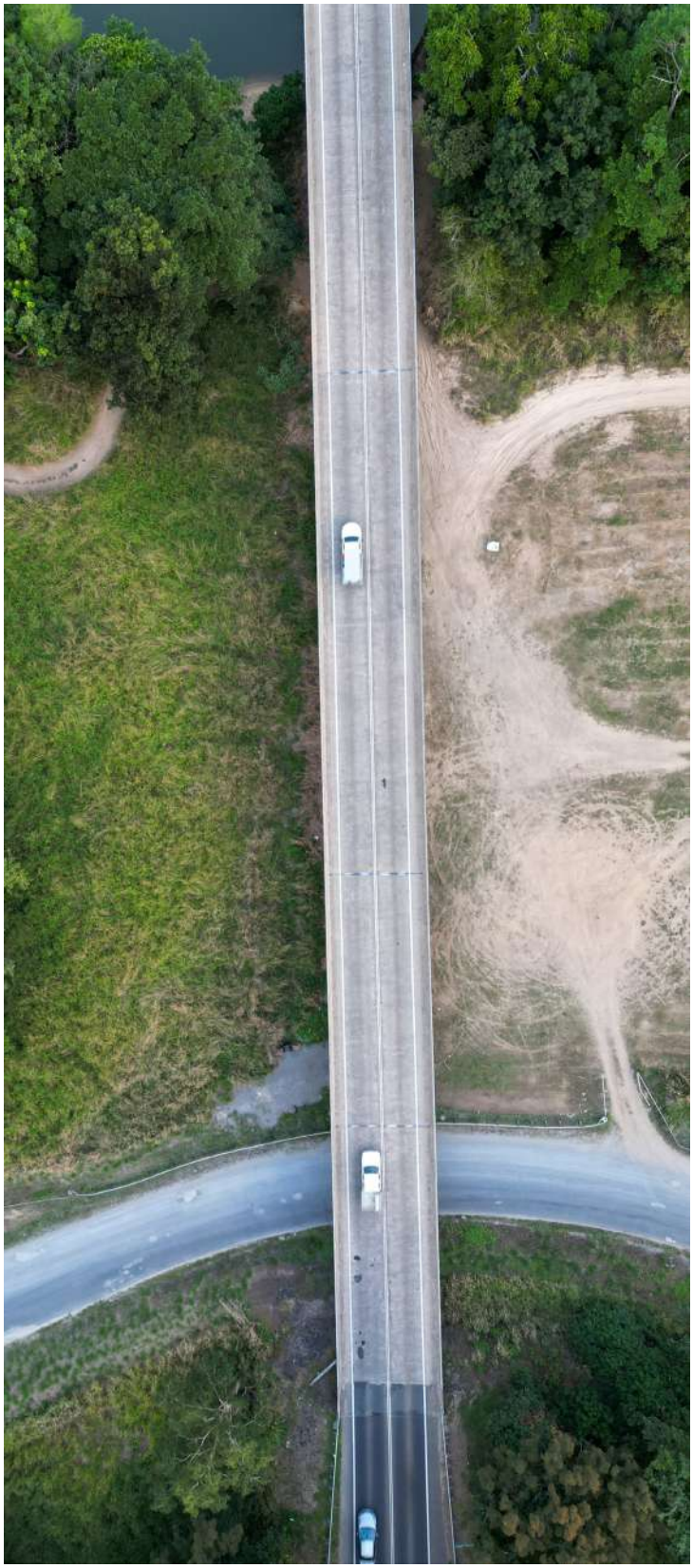
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Executive *Summary*

The purpose of this guide is to equip private infrastructure sponsors in Latin America and the Caribbean (LAC) with a practical, financially grounded framework for understanding, assessing, and managing physical climate risk, demonstrating that climate resilience is a core driver of long-term asset value rather than a peripheral sustainability concern.

By translating physical climate hazards into investment-relevant financial metrics *(such as cash-flow stability, return profiles, and financing conditions)*, **the guide shows how targeted adaptation measures, supported by appropriate financial and technological tools, can reduce losses, improve bankability, and strengthen infrastructure performance under future climate conditions, ultimately enabling sponsors to make more resilient, informed, and profitable investment decisions.**

Key Messages



1. **Climate resilience is good business.** Resilient investments yield, on average, four dollars in benefits for every dollar invested.
2. **Climate hazards are increasing in severity and frequency.** Climate risk in LAC is deeply location-specific and requires asset-level analysis.
3. **Sponsors have many adaptation options.** Understanding asset-level vulnerabilities is key to selecting a cost-effective solution.
4. **Climate risk reaches projects through four financial channels.** Revenue disruption, cost escalation, credit deterioration, and refinancing risk.
5. **A toolkit of financial instruments and a three-step framework address residual risk.** Six families of instruments; Classify, Assess, Match.
6. **Insurance and capital-market instruments transfer residual risk to third parties.** Indemnity and parametric insurance, cat bonds, and risk pools.
7. **New technologies support proactive resilience, reducing downtime and climate losses.** Digital tools help sponsors anticipate disruptions and respond before failures escalate.
8. **Real-world case studies show how sponsors are moving from theory to practice.** Seven cases across transport, water, and energy in LAC.

Climate Resilience Is Good Business

Climate change is no longer a distant environmental concern. It is a material financial risk and a defining variable in infrastructure investment performance. Across LAC, infrastructure assets already face escalating exposure to extreme heat, drought, wildfires, flooding, sea level rise, and increasingly intense storms. These hazards affect asset integrity, operational continuity, revenue stability, creditworthiness, insurability, and long-term valuation.

For infrastructure sponsors, the implication is clear: considering climate risk and investing in adaptation is not a concession to sustainability goals. It is simply good business. Climate hazards translate directly into financial consequences through asset damage, service interruptions, higher operating and maintenance costs, reduced revenues, strained balance sheets, and rising insurance costs. At a macro scale, climate-related losses in LAC are already equivalent to approximately 1% of regional gross domestic product (GDP), and in several countries they exceed expected annual economic growth, with direct implications for asset-level performance and investor returns.[1] For portfolios concentrated in long-lived, location-specific assets, unmanaged climate risk can materially erode value and, over time, eliminate returns altogether.

By contrast, investments in climate-resilient infrastructure consistently deliver strong financial performance. Evidence across sectors demonstrates that resilient investments yield, on average, four dollars in benefits for every dollar invested, with benefit-cost ratios (BCRs) exceeding one in the vast majority of cases—and often far exceeding this threshold. However, these economic returns do not automatically translate into financial returns for sponsors, as benefits may accrue across users, governments, and the broader economy. Flood protection, drainage upgrades, drought preparedness, nature-based solutions, and operational resilience measures repeatedly prove cost-effective when targeted to assets with real climate exposure and vulnerability.

Climate resilience therefore protects against downside risk while preserving—and in many cases enhancing—long-term asset value. It stabilizes cash flows, supports credit ratings, improves access to insurance, and increases investor confidence. Where reductions in risk outweigh additional capital costs, resilience can also improve financial returns. Rather than being an additional burden, resilience is increasingly central to fiduciary responsibility and long-term portfolio performance, particularly in emerging markets where climate hazards can amplify existing development and infrastructure gaps.



Climate Hazards Are Increasing in Severity and Frequency

The climate hazards placing infrastructure assets under increasing stress in LAC are not evenly distributed: coastal zones are highly exposed to sea level rise and storm surge, mountainous areas face landslides and erosion, and arid and semi-arid regions confront growing water scarcity. As a result, climate risk in LAC is deeply location-specific, requiring asset-level analysis rather than reliance on national or regional averages.

Climate-related disasters disrupt transportation networks, energy systems, water services, telecommunications, and social infrastructure, generating cascading impacts across economies and supply chains. Beyond direct physical damage, climate-related disasters also have indirect effects such as asset productivity losses from heat stress, reduced hydropower generation during droughts, increased health burdens, and prolonged service outages following extreme events. These impacts translate directly into financial risk for infrastructure sponsors, affecting revenues, operating expenditures (OPEX), asset lifespans, and credit performance. Recent research estimates that risks associated with potential business interruptions can be 14 times greater than risks of damage to assets.[2]

Future climate conditions will differ substantially from historical norms, making backward-looking risk assessments insufficient for investment planning. Climate projections indicate that extremes, not averages, will increasingly shape asset performance, reinforcing the need for forward-looking climate data in infrastructure design, financing, and operations. This guide frames climate change not as an external shock, but as a structural factor that must be integrated into core investment decision-making, setting the foundation for translating these risks into adaptation strategies, financial analysis, and resilience solutions.

Sponsors Have Many Adaptation Options, and Understanding Asset-Level Vulnerabilities is Key to Selecting a Cost-Effective Solution.

Sponsors are not constrained by a lack of adaptation options. Across transportation, energy, water and sanitation, telecommunications, and social infrastructure, there is a long menu of proven, implementable measures that reduce climate risk. These options range from relatively low-cost design and operational adjustments to more capital-intensive structural interventions. Benefit-cost analysis (BCA) compares the present value of adaptation costs with the present value of avoided damages, reduced repair costs, and sustained revenues. BCA can be measured using a BCR, which is a calculation that quantifies the benefits and costs of a project. Simply put, measures with a BCR above 1.0 indicate that a project is likely to have more benefits than costs under the assumed risk conditions.
For sponsors, however, financial viability depends not only on BCRs but also on how these measures affect cash flows, financing conditions, and return metrics.

The cost-effectiveness of selected adaptation options can differentiate successful climate-resilient investments from ineffective ones. Many of the highest-return adaptation measures are modest, targeted interventions—such as increasing drainage capacity, installing early-warning sensors, modestly elevating assets during construction, or restoring natural buffers that attenuate flood and

storm impacts. These measures often reduce risk from frequent, disruptive events rather than rare catastrophes, which helps explain their very high BCRs. Sponsors can evaluate climate adaptation using established economic and financial tools, even when asset-specific data are incomplete.

Developing a robust understanding of site-specific climate vulnerabilities tends to be more valuable than a big-picture view of regional climate hazards. Sponsors may consider: ***(1)*** *using forward-looking climate projections appropriate to the asset's location, geography, and lifetime;* ***(2)*** *identifying dominant hazards (e.g., flooding, heat, drought) and understanding how they translate into physical damage and operational disruption; and* ***(3)*** *focusing on adaptation measures that directly interrupt these risk pathways.* Once vulnerabilities are defined, sponsors can screen options using BCA. This guide shows that a wide array of measures such as detention and retention ponds, drainage upgrades, dry floodproofing, asset elevation during new construction, and nature-based solutions (NBS) frequently deliver BCRs well above one, sometimes several orders of magnitude higher. Numerous cost-beneficial measures exist for each major sector.

Importantly, BCRs should be interpreted as decision-support tools, not absolutes. High BCRs often reflect targeted measures applied where risk is concentrated; lower BCRs may still be appropriate for socially critical or systemically important assets.

More capital-intensive measures (such as flood walls, slope stabilization, or fully elevating assets to prevent flooding) can also be financially attractive when applied to critical assets with high exposure or cascading system importance, including ports, substations, hospitals, water treatment plants, and major transport corridors. Conversely, not every asset requires maximum protection. Sponsors with some tolerance for short-term disruptions may rationally select lower-cost, medium-effectiveness measures while preserving overall investment viability.

To support consistent decision-making, adaptation options can be assessed using three complementary indicators that help sponsors construct a diversified portfolio of climate risk mitigation measures. Rather than seeking a single "silver bullet," effective resilience strategies typically rely on multiple, layered interventions that address different risks, time horizons, and failure modes across an asset or project. These indicators reflect that the appropriate mix of measures will vary by asset type, site conditions, climate hazards, and investor risk appetite. The objective is not universal hardening of infrastructure, but right-sized resilience achieved through a balanced set of investments aligned with financial, operational, and development priorities.

- Incremental cost, often expressed as a percentage of total project cost;
- Effectiveness, which can initially be identified as low, medium, or high reduction in exposure or impact; and
- BCRs, reflecting avoided damages, reduced downtime, and preserved service delivery over time.

Climate Risk Reaches Projects Through Four Financial Channels.

Physical climate hazards translate into financial stress on infrastructure projects through four pathways.

01. ***Revenue disruption***
Climate events can disrupt revenues when projects cannot operate: a flooded toll road collects no tolls, a drought-affected hydropower plant generates less electricity, and a hurricane-damaged port moves less cargo.

02. ***Cost escalation***
Hazards can escalate costs, both through emergency repairs after events and through higher ongoing maintenance as assets degrade more quickly under climate stress.

03. ***Credit deterioration***
They can weaken the project's credit quality: as cash flows become less stable and predictable, lenders perceive more risk, which translates into stricter covenants, shorter loan tenors, wider interest rate spreads, and additional collateral requirements.

04. ***Refinancing risk***
They can make refinancing more difficult and expensive: when a project needs to roll over its debt in 10 or 15 years, a more climate-exposed asset will face tougher terms, or may struggle to find willing lenders at all.

These four pathways flow through the project's cash-flow structure, which determines how revenues are used. Revenues first cover operating costs and taxes. What remains, the cash available to service debt, goes to lenders to pay interest and principal. Only after all debt service is paid do equity sponsors receive distributions. Because debt service is fixed and contractual while revenues are variable, any climate-driven reduction in cash flow compresses the margin between cash available and debt owed. This margin, the debt service coverage ratio, is one of the most important metrics lenders track. Lenders typically require it to stay above a defined threshold (often 1.20 to 1.40); breaches restrict cash distributions to equity and, if sustained, can trigger default.

Infrastructure projects are particularly sensitive to these effects because they have high fixed costs and committed debt obligations. Even moderate disruptions can have disproportionate financial consequences. Two hypothetical case studies, a toll road concession and a utility-scale solar project, show that a 13% revenue loss from flooding can push coverage ratios below lender thresholds, trigger multiple years of covenant breaches, and turn the value of equity investments negative. A long-term power purchase agreement does not insulate a solar project from physical risk: it shifts the exposure from demand risk to the risk of not being able to generate or deliver electricity, which has the same effect on cash flow.

Adaptation materially improves these outcomes. In both case studies, resilience measures, including drainage upgrades, slope stabilization, and elevating critical equipment, restore projects to bankable coverage levels and recover most of the investor return that climate disruption would otherwise erode. However, adaptation does not eliminate climate risk.

Extreme events can still exceed design thresholds, and this residual exposure continues to affect financial performance, particularly under downside scenarios. This residual risk is what the financial instruments in Chapter 6 are designed to address.

A Toolkit of Financial Instruments and a Three-Step Framework Address Residual Risk.

Six families of financial instruments are available to sponsors and lenders to finance climate-resilient infrastructure and manage the residual risk that remains after adaptation.

Commercial financing

(Senior loans, bonds, sustainability-linked loans) provides the base of the capital stack at market terms and funds the bulk of project costs. Sustainability- and resilience-linked instruments link the borrower's interest rate or coupon to measurable resilience or sustainability targets, aligning financing costs with verified performance.

Concessional and blended finance

Comprises capital provided on better-than-market terms, typically by development banks or climate funds. This includes below-market-rate loans, longer repayment periods, and tranches of capital that agree to absorb losses before commercial lenders do. These instruments make affordable projects that could not otherwise sustain commercial financing terms.

Credit enhancement and risk-sharing tools

Principally guarantees, work by having a creditworthy third party, usually a development bank, promise to step in and pay lenders if specific types of default occur. No cash changes hands unless the triggering event happens, but the backstop allows lenders to extend financing at better rates, offer longer tenors, or reach a broader set of sponsors than they otherwise would.

Liquidity and contingency instruments

Act as cash buffers. A debt service reserve is a ring-fenced account holding enough cash to cover several months of debt payments if revenues dip. A maintenance reserve sets aside cash during normal years to fund large periodic expenditures (replacing inverters, repaving a road, overhauling turbines) without creating sudden shocks to cash flow. Standby credit facilities are pre-arranged loans the project can draw on under stress.

Risk-transfer instruments

Move specific loss exposures to third parties in exchange for a premium and are discussed in detail in the next section.

Equity and mezzanine capital

Sit at the bottom of the capital structure and absorb whatever variability in returns remains after all other obligations are met.

These instruments sit on top of a base of senior commercial debt and sponsor equity. The organizing principle for selecting among them is a matching logic: the choice of instrument should directly address the channel through which climate risk most affects the project's cash flows. A project exposed primarily to revenue disruption calls for revenue stabilization and liquidity tools. A project exposed to government payment risk calls for guarantees. A project facing uncertainty in future

refinancing calls for longer tenors and contingent debt features. Most projects are exposed to more than one channel and combine several instruments.

A three-step decision framework (Classify, Assess, Match) ties the toolkit to project-specific analysis.

01. ***Classify*** the project along five dimensions: sector, revenue model, climate hazards, adaptation measures already planned, and financing mode (project finance, corporate balance sheet, or public balance sheet).

02. ***Assess*** the residual climate risk that remains after adaptation, categorizing it as low, moderate, or high, and identify the specific financial channels through which that risk reaches the project.

03. ***Match*** the financing package accordingly: low-risk projects can rely largely on standard commercial financing; moderate-risk projects typically combine commercial debt with guarantees, development bank loans, liquidity reserves, and insurance; high-risk projects require layered structures that combine concessional loans, first-loss capital, and public guarantees with channel-specific instruments.

Three case studies illustrate the framework in practice. A toll road facing revenue volatility is restored to bankability through a minimum revenue guarantee, a public-sector commitment to top up revenues when traffic falls below a defined threshold, combined with an enhanced debt service reserve. A utility-scale solar project facing high financing costs is restored by replacing part of its commercial debt with a lower-cost loan from a development bank, plus a maintenance reserve and parametric insurance against extreme weather. A high-risk highway project requires a full blended structure: concessional debt, first-loss capital from a climate fund, a minimum revenue guarantee, and a partial credit guarantee on the senior debt, each provided by a different type of investor with a different risk appetite. Together, these layers redistribute risk across stakeholders in a way that makes the project financeable where no single instrument could.

Insurance and Capital-Market Instruments Transfer Residual Risk to Third Parties.

Traditional indemnity insurance remains central for covering direct asset damage and business interruption, and effective physical adaptation can lower modeled losses and, in some cases, reduce premiums or expand coverage availability. Parametric insurance products play a complementary role by providing rapid, rules-based payouts triggered by predefined hazard thresholds, such as a defined wind speed or rainfall level. This improves post-disaster liquidity, even though payouts may not exactly match actual losses (basis risk). For low-frequency, high-severity risks, cat bonds and other insurance-linked securities allow sponsors to transfer tail risk to capital markets, while public or regional risk pools can help spread losses across portfolios or jurisdictions.

New Technologies Support Proactive Resilience, Reducing Downtime and Climate Losses.

Technological innovation is increasingly central to building, operating, and financing climate-resilient infrastructure, particularly in regions exposed to growing climate volatility. Digital tools—such as sensors, remote monitoring, geospatial analytics, and predictive systems—enable asset owners and sponsors to anticipate disruptions, detect early signs of failure, and respond before minor stresses escalate into costly outages or structural damage. Compared with large retrofits, many of these technologies offer high benefit-cost ratios, as they reduce downtime, improve maintenance efficiency, and protect revenue streams with relatively modest capital outlays.

Incorporating resilience considerations early in the investment and project development process is critical to maximizing value and avoiding costly lock-in effects. Decisions made during project conception, site selection, and preliminary design largely determine an asset's long-term exposure to climate hazards and its flexibility to adapt as risks evolve. Early integration allows resilience measures—both physical and digital—to be embedded at lower cost, rather than added later through disruptive and capital-intensive retrofits. It also enables sponsors and developers to evaluate trade-offs across design options, operating strategies, and financing structures using consistent, forward-looking risk information. By treating resilience as a core design and investment parameter from the outset, rather than a late-stage safeguard, projects are better positioned to protect asset value, maintain service continuity, and meet investor risk-return expectations under increasingly volatile climate conditions.

The role of data-driven decision-making is key across the infrastructure lifecycle. During design and construction, tools such as building information modeling, digital twins, drones, and climate-informed scheduling platforms allow developers to stress-test assets against future hazards and integrate resilience features more cost-effectively. During operations, real-time sensing, artificial intelligence, and predictive maintenance systems improve asset reliability and workforce safety by enabling proactive interventions—such as rescheduling work during extreme heat or isolating vulnerable equipment ahead of storms. Together, these applications shift resilience from a static design feature to a dynamic, continuously managed capability.

Technological innovation is crucial for sponsors and lenders to consider. Improved monitoring and data transparency help quantify climate risks and adaptation performance, strengthening engagement with insurers, credit committees, and capital markets. Technologies such as early-warning systems, automated failover, and digital risk analytics can function as credit enhancers, lowering perceived risk and supporting better financing terms. As climate impacts intensify, the chapter concludes that integrating technology with physical adaptation and financial risk transfer will be essential for maintaining asset value, operational continuity, and investor confidence.

Real-World Case Studies Show How Investors Are Moving From Theory to Practice



The **Brazil Pro-Roads Program** demonstrates how systematic integration of climate resilience into road rehabilitation and maintenance can generate substantial economic returns. Using performance-based CREMA (Contrato de Rehabilitación y Mantenimiento) contracts, the program incorporated improved drainage, slope stabilization, and climate-responsive asset management across highway corridors exposed to flooding and landslides. These measures increased upfront costs modestly but significantly reduced maintenance expenditures and service disruptions, yielding a net present value (NPV) of approximately $295 million and an internal rate of return (IRR) near 39%.

Embedding resilience into long-term road management improves cost efficiency, reliability, and investor confidence in transport assets.



The **São Paulo Metro Line 4 project** highlights the financial importance of protecting high-utilization urban transit systems from climate-related disruption. Targeted resilient investments—representing just over 4% of total project cost—were introduced to address flooding and extreme rainfall risks affecting tunnels and stations. These measures significantly reduced expected service interruptions, which otherwise could cause daily economic losses of hundreds of thousands of dollars.

For dense urban systems with high revenue exposure, even relatively small adaptation investments can protect cash flows, maintain service continuity, and preserve long-term asset value.



In **Guatemala's Xochi (Flower) Road project**, climate resilience was integrated into a multi-hazard rural transport corridor exposed to landslides, flooding, wind, and wildfire risks. Adaptation measures included slope stabilization, enhanced drainage, reinforced structures, and improved maintenance practices designed to minimize climate-related closures. Financial analysis showed that these measures substantially improved project viability, with IRRs ranging from roughly 10 to 40% depending on hazard severity and traffic assumptions.

Resilient investments are valuable for secondary road networks that underpin agricultural production and regional connectivity.



The **Corsan water-loss reduction project in Brazil** illustrates how climate resilience can be achieved through operational efficiency and technology rather than large new capital works. By investing in leakage detection, pressure management, and network rehabilitation, the utility reduced non-revenue water from over 40% to approximately 30%. These improvements increased water security during droughts, deferred costly supply expansions, and generated annual financial gains estimated at over $100 million.

Climate adaptation in water systems can deliver strong financial returns while improving service reliability and resilience to scarcity.



The **Ceará Green Hydrogen Hub** case shows how climate resilience considerations can be integrated into emerging clean energy infrastructure. Adaptation measures addressing extreme heat, water scarcity, and coastal exposure were incorporated into project planning at an incremental cost of roughly $9 million. Despite these additions, the project maintained attractive financial performance, with projected IRRs ranging from 19% to more than 40% depending on market conditions.

Embedding resilience early in new low-carbon investments protects performance under future climate extremes.



The **Afobaka Floating Solar-Hydro Hybrid Project** in Suriname demonstrates how hybrid renewable energy systems can strengthen climate resilience and improve the financial performance of hydropower assets under increasing drought risk. The project integrates floating solar photovoltaic (PV) generation onto the existing Afobaka hydropower reservoir, allowing solar output to increase during dry, high-insolation periods when hydropower generation is constrained, while preserving hydropower flexibility during wetter seasons. By leveraging existing transmission infrastructure and avoiding land-use conflicts, the hybrid system reduces capital costs and improves overall system reliability. Additional benefits include reduced reservoir evaporation and improved solar efficiency from water-based cooling.

Supported by IDB Invest through a feasibility study, this is a scalable model for diversifying generation portfolios, stabilizing revenues, and enhancing climate resilience in hydro-dependent energy systems across LAC.



The **Honduras Rural Electrification Project** demonstrates how climate-resilient renewable energy systems can enhance both financial viability and development outcomes in vulnerable communities. Solar photovoltaic (PV) microgrids replaced diesel generation in remote areas highly exposed to extreme weather and fuel supply disruptions. Climate-resilient design features increased construction costs slightly but improved reliability, reduced operating expenses, and supported IRRs exceeding 14%.

Resilient investments in distributed energy systems can simultaneously improve investor returns, energy security, and socioeconomic resilience.

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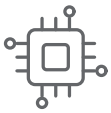
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Abbreviations

AAL	Average annual loss
ALOP	Advance loss of profit
ATS	Automatic transfer switch
BCA	Benefit-cost analysis
BCR	Benefit-cost ratio
BI	Business interruption
BREEAM	Building Research Establishment Environmental Assessment Method
CAPEX	Capital expenditures
CAR	Construction all risks
Cat bond	Catastrophe bond
CCF	Contingent credit facility
CCRIF	Caribbean Catastrophe Risk Insurance Facility
CFADS	Cash flow available for debt service
CIPP	Complexo Industrial Portuario de Pecém
CMAC	Continuous monitoring and adaptive control
CREMA	Contrato de Rehabilitación y Mantenimiento
DDO	Deferred drawdown option
DFI	Development finance institution
DPL	Development policy loan
DSCR	Debt service coverage ratio
DSRA	Debt service reserve account
DSU	Delay in start-up
EAR	Erection all risks
EBITDA	Earnings before interest, taxes, depreciation, and amortization
EDGE	Excellence in design for greater efficiencies
EIB	Environmental impact bond
ESG	Environmental, social, and governance
FEMA	Federal Emergency Management Agency
GDP	Gross domestic product
GHG	Greenhouse gas
GNSS	Global Navigation Satellite System
HTLS	High temperature low-sag
HVAC	Heating, ventilation, and air conditioning
IBRD	International Bank for Reconstruction and Development
ICMA	International Capital Market Association
IDB	Inter-American Development Bank
IEC	International Electrotechnical Commission
IFC	International Finance Corporation
IFM	Industrial facilities model
ILS	Insurance-linked securities
IoT	Internet of things

IPCC	Intergovernmental Panel on Climate Change
IPF	Investment project financing
IRR	Internal rate of return
KPI	Key performance indicators
LAC	Latin America and the Caribbean
LCCA	Life cycle cost analysis
LiDAR	Light detection and ranging
LPP	Livelihood protection policy
MAR	Managed aquifer recharge
MDB	Multilateral Development Bank
MGD	Million gallons per day
MHEWS	Multi-hazard early warning system
MIGA	Multilateral Investment Guarantee Agency
MMRA	Major maintenance reserve accounts
MRG	Minimum revenue guarantee
MW	Megawatts
NAP	National Adaptation Plan
NBS	Nature-based solutions
NDC	Nationally determined contributions
NPV	Net present value
NREL	National Renewable Energy Laboratory
NRW	Non-revenue water
OPEX	Operating expenditures
O&M	Operations and maintenance
PBC	Performance-based contracts
PCG	Partial credit guarantee
PCRA	Physical Climate and Natural Risk Assessment
PG&E	Pacific Gas and Electric
PPA	Power Purchase Agreement
PPP	Public-private partnerships
PRG	Partial risk guarantee
PRI	Political risk insurance
PV	Photovoltaic
RBF	Results-based financing
RO	Reverse osmosis
ROI	Return on investment
SLB	Sustainability-linked bonds
SLL	Sustainability-linked loans
SIDA	Swedish International Development Agency
SPT	Sustainability performance targets
SPV	Special purpose vehicle
T&D	Transmission and distribution
USACE	US Army Corps of Engineers
VGF	Viability gap funding
WACC	Weighted average cost of capital

01 The Case *for Resilience*

This guide is intended to serve as a practical, decision-oriented guide for private sponsors seeking to increase the resilience of their infrastructure investments to climate risks. From hurricanes and flooding to wildfires and heat waves, climate change is already affecting Latin America's businesses. These hazards are projected to increase in severity and frequency over the course of the coming century.[3] Private sector infrastructure sponsors are uniquely exposed due to the **long-term, location-specific, and systemic nature of climate risks**. Climate resilience is no longer a peripheral concern—it is a core determinant of infrastructure performance, valuation, and long-term financial viability. This chapter provides an overview of the business case for investing in resilience and defines key terms used throughout this guide.

1.1 Why Does Investing in Resilience Make Good Business Sense?

Climate-related natural disasters have increased fivefold in the last 50 years, with increasingly adverse effects on morbidity and mortality, ecosystems, and economies.[4] The costs of climate change will continue to mount at both local and regional scales absent aggressive action to reduce risks.

In The **Bahamas** in 2016, Hurricane Matthew led to damages, losses, and additional costs totaling an estimated $28.8 million for privately owned energy infrastructure and an estimated $16.4 million for privately owned telecommunications infrastructure.[5] In the **Panama Canal**, severe drought conditions in 2023 and 2024 reduced water levels, causing shipping routes to be more expensive and, on average, 31% longer.[6]

Droughts have led to temporary shutdowns of major hydropower plants like Santo Antonio in **Brazil** due to low water levels, requiring expensive emergency procedures and backup generation resources to maintain electricity reliability.[7]

In 2024, wildfires in **Chile** damaged over 18,000 hectares of farmland, pastureland, and vineyards and killed over 150 people. Fires destroyed agri-business infrastructure and major tourist destinations in the center-south region; these industries suffered significant losses, with total exposure in the worst-hit municipalities estimated at $120 million. Insurance markets have also seen a rapid increase in claims being filed.[8]

What Does "Climate Resilience" Mean?

The Intergovernmental Panel on Climate Change (IPCC) defines resilience as "a system's ability to anticipate, reduce, accommodate, and recover from disruptions in a timely, efficient, and fair manner." Resilient infrastructure typically has four characteristics that ensure its ability to withstand disruptions and hazards, sometimes known as the four "R's" of resilience.

Robustness: a system's ability to withstand climate hazards without degrading or losing function.

Redundancy: the extent to which a system as a whole can carry out its usual function, even in the event of a disruption to a portion of the wider system.

Rapidity: a system's ability to respond to a climate hazard or disruption quickly and efficiently to minimize losses and resume regular functioning.

Resourcefulness: a system's ability to identify problems and mobilize resources to respond to a climate hazard event.

Figure 1. Illustrative impact pathways with financial consequences for various infrastructure sectors



Across the region, climate change risks to infrastructure assets pose a significant challenge both to private sponsors and to the economy as a whole. The risk of damage due to climate hazards is projected to be roughly equivalent to annual economic growth. Disasters can reduce GDP by up to 0.9% in lower-income countries; in the Caribbean, they can destroy 3.6%. Infrastructure assets at risk due to climate hazards in Latin America represent 1% of GDP.[9] In Colombia, this risk is 1.4% of GDP; in Peru it is 2.1% of GDP, and in El Salvador and Honduras it represents more than 2.7 and 2.8% of GDP, respectively. Regional GDP growth across LAC (excluding the COVID-19 years) has been approximately 1.25% annually over the past decade.[10] The bottom line is that climate change can essentially wipe out much of the region's anticipated annual economic gains without action by the public and private sectors. Furthermore, without climate-resilient infrastructure, these losses will continue to grow as the severity of extreme weather events intensifies over the course of the coming century. Sponsors have strategic, financial, and fiduciary imperatives to integrate climate resilience into their infrastructure investments.

Climate Shocks and Stressors

Infrastructure assets are generally vulnerable to both **climate shocks** (discrete, disruptive events like hurricanes, landslides, or wildfires) and **climate stressors** (chronic, long-lasting challenges that damage infrastructure over time, like sea-level rise, increased average temperatures, or drought). Building resilience means investing in infrastructure systems' ability to withstand both shocks and stressors.

1.2 How Can Investing in Resilience Pay Off?

Investing in resilience improves the financial performance of infrastructure over time, with average returns of approximately 4:1.[11] Investing in more resilient infrastructure is also cost-effective. The World Bank evaluated resilient investments and found the BCRs higher than 1.0 in 96% of scenarios, greater than 2.0 in 77% of them, and higher than 6.0 in 25% of them.[12] Avoiding losses is only one of several reasons to invest in climate-resilient infrastructure; doing so is good for sponsors by (1) protecting assets over the long term, (2) preserving returns on investment, (3) creating complementary opportunities to gain competitive advantages in the market, (4) building portfolio stability, and (5) promoting macroeconomic growth, which can further increase the attractiveness of private-sector investments.

Protecting Assets Over the Long Term

Protecting assets from climate hazards is foundational to their financial performance because physical damage and disruptions from climate events can impair operations, reduce asset value, and increase maintenance costs. Adaptation measures extend the useful service life of assets and limit impacts that cause outages and revenue disruptions. Under extreme climate change conditions, infrastructure sponsors risk losing over half of their portfolios by 2050 if they do not take the necessary steps to enhance asset resilience.[13]

A wide array of infrastructure assets is uniquely vulnerable to severe damage and operational losses from climate hazards. These vulnerable assets range from roads, ports, and airports to

electrical substations and generating facilities, telecommunications infrastructure and data centers, tourist attractions, and water treatment and delivery systems.[14] There are three key reasons for these vulnerabilities:

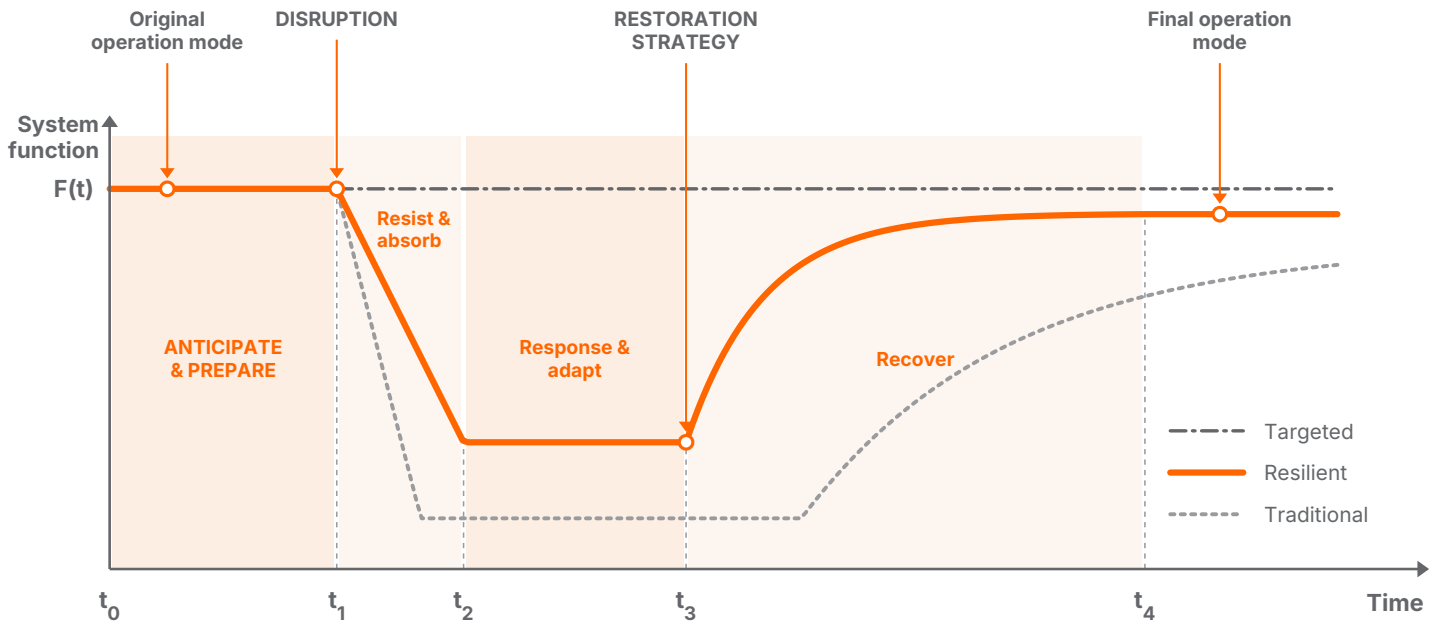
Infrastructure is **geographically fixed**. For example, a port and associated road and supply chain infrastructure cannot be easily moved to avoid coastal flood risk or nearby coastal erosion.

Infrastructure is **designed to last for decades**. A long design life means infrastructure assets need to withstand climate stresses and hazards well into the future; these hazards are likely to change over time and often be more extreme than they are today. A hydropower system may operate effectively under current precipitation patterns but could become oversized and inefficient in drier future conditions, or undersized in wetter scenarios—potentially leading to excess water release and downstream flooding.

Infrastructure is **capital-intensive** to build, meaning disruptions and physical damage can be costly to address. For long-lasting projects, effective capital expenditures can achieve more efficient operational expenditures throughout a project's service life. Building adaptive management protocols upfront allows infrastructure managers to plan for and implement more aggressive adaptation measures as needed over time. These protocols should be incorporated early in the project development cycle to reduce the identified risks associated with climate change throughout the project service life. By embedding resilience early on in an asset's lifecycle through strategic siting and design, sponsors can reduce vulnerability from the start and avoid repair and retrofitting costs down the line. Once facilities are constructed, implementing operations-based resilience measures (such as routine performance monitoring and adequate budgets for inspections and repairs) can allow asset managers to prepare for climate challenges and minimize damage during severe events. For assets with long service lives, adaptive management enables companies to respond flexibly and efficiently to changing conditions, uncertainties, and new information. Conversely, if adaptation is incorporated too late in the project lifecycle, it may be more costly to mitigate future impacts from climate-related natural disasters. Considering adaptation early avoids costly missteps, optimizes resource allocation over time, and reduces exposure to evolving risks. *Figure 2* shows the importance of implementing adaptation measures early in the project lifecycle.



Figure 2. Schematic performance of a resilient power system during a disruption[15]



These measures should complement mandatory and common risk assessment and mitigation practices, such as insurance. For example, new port facilities can be designed and constructed with sufficient foundations that are appropriate for current sea levels and that can accommodate the construction of higher piers as sea levels rise, ensuring the assets' resilience over the long term. By monitoring changing performance conditions and tracking updated climate projections, managers can match investments to near-term conditions while ensuring the capacity to address more extreme conditions in the future.

Physical asset protection and financial performance are linked, and while financial instruments like insurance can offset short-term losses, they may obscure underlying vulnerabilities. Balance sheets can manage physical losses with insurance payouts covering lost revenue, but as climate events become more frequent, insurance premiums may rise, and insurers may exit high-risk markets, reducing coverage options and increasing costs. Additionally, capital for climate-exposed investments is becoming increasingly expensive, and availability is also becoming scarcer. These shifts can disrupt cash flow and erode asset value, making proactive resilience measures a critical part of investment strategy.

Preserving Financial Performance and Investment Returns

Investing in resilience protects capital-intensive infrastructure assets over the long term and can extend the useful life of individual assets. This translates to lower volatility, more stable cash flows, and higher investor and consumer confidence, especially for assets with long service lives.

According to World Bank estimates, every $1 invested in resilient infrastructure yields $4 in benefits and avoided losses.[16]

Physical climate risks are financial risks for sponsors. More than 10% of the banking sector credit portfolio is exposed to flood risk in Brazil, Mexico, Colombia, Argentina, Bolivia, and the Dominican Republic.[17] Climate-related natural disasters also bring less visible, systemic consequences, including business interruptions, legal liabilities, and reputational damage that ripple across financial systems. Recognizing these links is essential to understanding why building resilience is not a marginal issue, but a core financial concern.[17]

Resilient infrastructure can preserve sponsors' returns on investment in several major ways:

Maintaining asset performance.

Without adequate resilience measures, climate hazards can undermine asset performance by causing service interruptions, physical damage, and prolonged downtime. These disruptions directly affect revenue stability and operational reliability, particularly for assets exposed to extreme weather or chronic climate stress. Incorporating climate risk projections into project design, construction, and operations allows developers and operators to anticipate stresses and address vulnerabilities before they affect performance. Proactive resilience planning helps ensure assets continue to operate efficiently and deliver expected revenues across a range of future climate conditions.

Avoiding unnecessary costs.

Unmitigated climate hazards can drive up operations and maintenance costs by increasing energy costs or repair needs and trigger high-cost emergency capital expenditures to repair or replace assets and resume service following climate-related disruptions. Investing in resilience and planning to anticipate and manage hazards help avoid these unplanned costs.

Preserving insurability and managing insurance costs.

Assets that are highly exposed to climate hazards or lack credible risk-mitigation measures are increasingly difficult and expensive to insure. Repeated losses can lead to higher premiums, restrictive coverage terms, or withdrawal of coverage altogether, creating material risks for project viability. By reducing physical vulnerability and demonstrating active risk management, resilient investments can lower expected losses, support continued insurance availability, and help stabilize insurance costs over time. This is particularly important where insurance is a contractual or regulatory requirement for continued operations or financing. Additionally, combining different types of insurance policies, such as traditional indemnity insurance, parametric insurance, and catastrophe bonds, can help sponsors tailor insurance coverage to their specific needs.

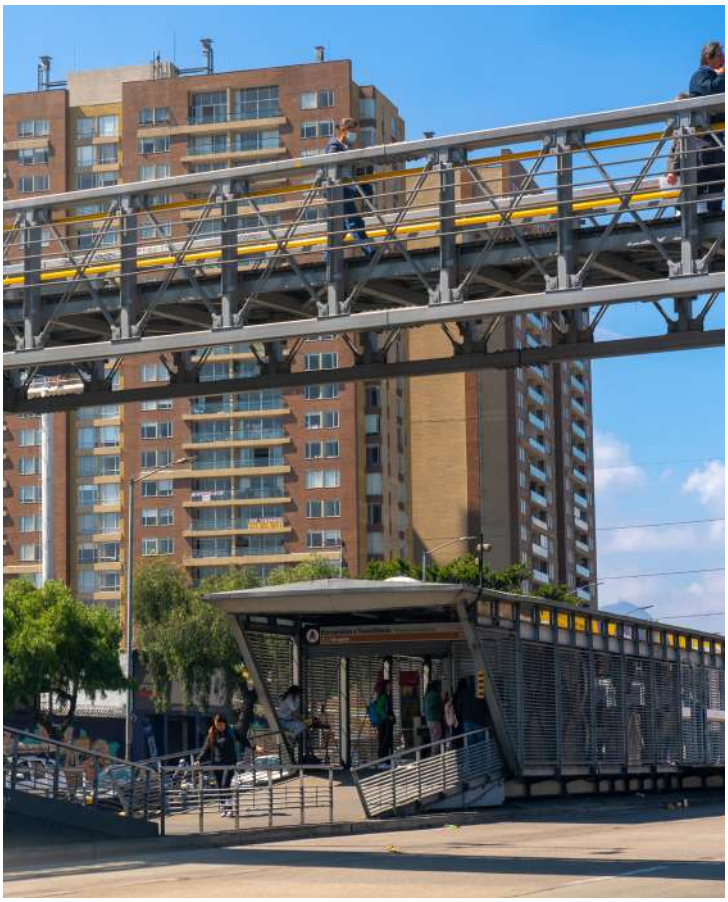


Strengthening credit quality and lowering the cost of capital.

Stable and predictable cash flows are central to an asset's credit profile and its ability to meet debt service obligations. Climate-related disruptions that affect revenue increase financial volatility and can weaken creditworthiness. Integrating resilience into project development and operations lowers the financial materiality of climate risks, supporting more consistent performance under stress. In doing so, resilience measures can help protect—or in some cases improve—credit ratings and financing terms, ultimately contributing to a lower cost of capital, as increasingly recognized by major credit rating agencies.

Example Adaptation Benefits: *Jamaican Mangroves*

In Jamaica, mangroves provide benefits to the fishing industry and coastal protection against climate hazards. The World Bank estimates that an investment of up to $500,000 to strategically conserve, restore, and replant mangroves in Jamaica can provide flood protection valued at $2,500 per hectare per year, in addition to $2.7 million in nearshore mixed species fisheries.[18]



Safeguarding consumer and public confidence.

Beyond financial impacts, climate-related failures can affect communities and ecosystems, leading to reputational damage, regulatory scrutiny, legal challenges, and public opposition. Loss of consumer trust following major disruptions can take significant time and resources to repair. Investing in resilience reduces the likelihood and severity of these external impacts, helping protect public confidence, social license to operate, and long-term asset value.

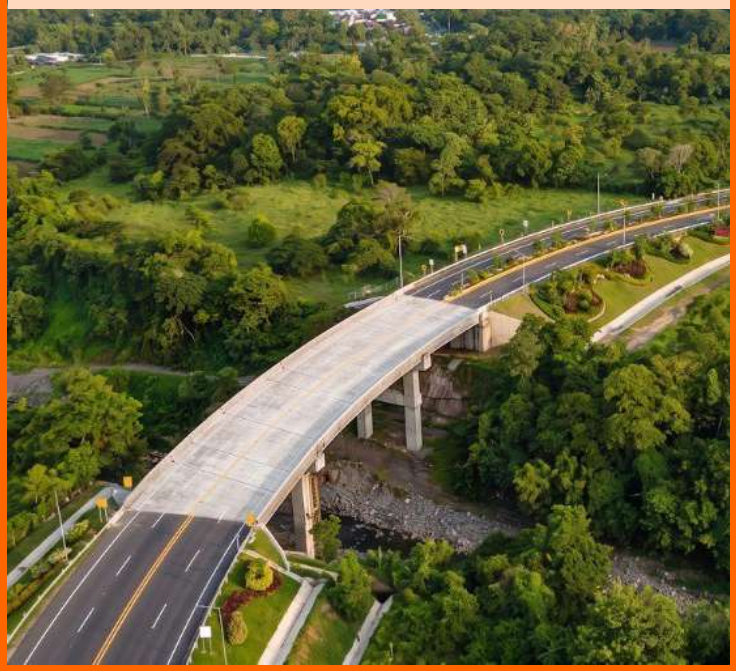
Resilience measures can take place at every stage of infrastructure planning, development, and operation, and they are not always capital-intensive. Incorporating resilience considerations into infrastructure increases overall costs by 3–10% on average across the region.[19]



Climate Adaptation Case Study: *Xochi, Flower* Road

The Xochi (Flower Corridor) project is a privately financed road project designed to ease traffic congestion and improve connectivity in the Suchitepéquez region of Guatemala. The project uses a blended-finance structure in which concessional tranches partially subsidize the incremental cost of adaptation and resilience measures, offering incentives for performance-based resilient investments without burdening the core financing. This is the first infrastructure project in the region to integrate forward-looking climate exposure and vulnerability analysis into planning, design, and capital investment strategy, earning the Envision certification for sustainable and resilient infrastructure.

See Appendix A for more information on this case study.



Creating Opportunities and Gaining Competitive Advantage

Investing in resilient infrastructure offers a strategic edge to sponsors by enhancing projects' bankability, insurability, and attractiveness to co-sponsors. In addition, it can open broader opportunities for sponsors through new financing schemes. Projects that proactively address resilience are more likely to receive permits, funding, and public support, securing owners' and operators' "social license to operate." Climate-resilient infrastructure can also unlock new markets for additional services, expanding growth opportunities for sponsors. In some cases, climate change may improve conditions for certain infrastructure, with favorable projections for certain investment types, such as agricultural infrastructure in an arid area expected to see more rainfall in the future.

- **Gain a competitive advantage***:* Sponsors who consider climate risk when prospecting for new investment targets may see long-term projections that improve the prospects for certain investments. For example, investments in infrastructure that rely on resource availability, such as water, can result in stranded assets if climate change projections for reduced water flows are not considered. However, projections of increasing precipitation may make investments in hydropower systems more viable and increasingly profitable. Sponsors who assume the future will mirror the past risk making costly investment errors and missing new opportunities, while those who actively seek them out can gain a competitive advantage.

- **Mobilizing long-term capital, co-investments, and emerging financing opportunities**. Resilient assets that can withstand changing climate hazards are more attractive to long-term sponsors. Embedding resilience into investments aligns with the growing demand for resilience-linked financing—such as green bonds with adaptation components, impact investing, and resilience-focused public-private partnerships (PPPs)—offering diversified funding opportunities. Investments that reduce physical risks and improve long-term financial performance are better positioned to mobilize co-investments and lower overall capital costs, especially when aligned with investor risk preferences. Additionally, there is a growing number of dedicated funds and facilities focused on climate resilience, which can play a key role in de-risking projects and mobilizing private capital.

- **Social license to operate**: Demonstrating a commitment to sustainability and community well-being builds trust and reduces reputational risk. This can translate into improved community relations and political support, enhanced brand value, and the ability to attract talent and partners in the region. Securing a social license to operate is important across all sectors. Resilient investments often help businesses gain community buy-in, stimulate local supply chains, and create jobs, which can enhance the reliability and lifespan of returns on those investments.

- **New markets and opportunities for innovation:** Sponsors can unlock new markets for climate adaptation services, smart infrastructure, NBS, and resilient urban development. Growing awareness of the importance of resilient investment is creating opportunities for industry growth in new areas, such as innovations in materials, construction techniques, information technologies, asset management, and decision-support tools. This opens up additional growth in sectors, markets, and businesses with potential opportunities for new verticals for sponsors. Piloting these technologies can help sponsors scale up markets that were previously niche or underdeveloped.

New Opportunities May Emerge for Sponsors

Passive cooling and stormwater infrastructure
(green roofs, reflective surfaces)

Water efficiency and drought resilience
(smart irrigation, desalination, metering)

Climate-resilient materials
(heat-resistant concrete, permeable pavement)

Insurance products
(parametric or "revolving door" insurance schemes)

"Climate-as-a-Service"
(subscription-based heat or flood monitoring/alerting)

Monetized co-benefits
(carbon credits or biodiversity offsets)

Building Portfolio Stability and Addressing Systemic Risks

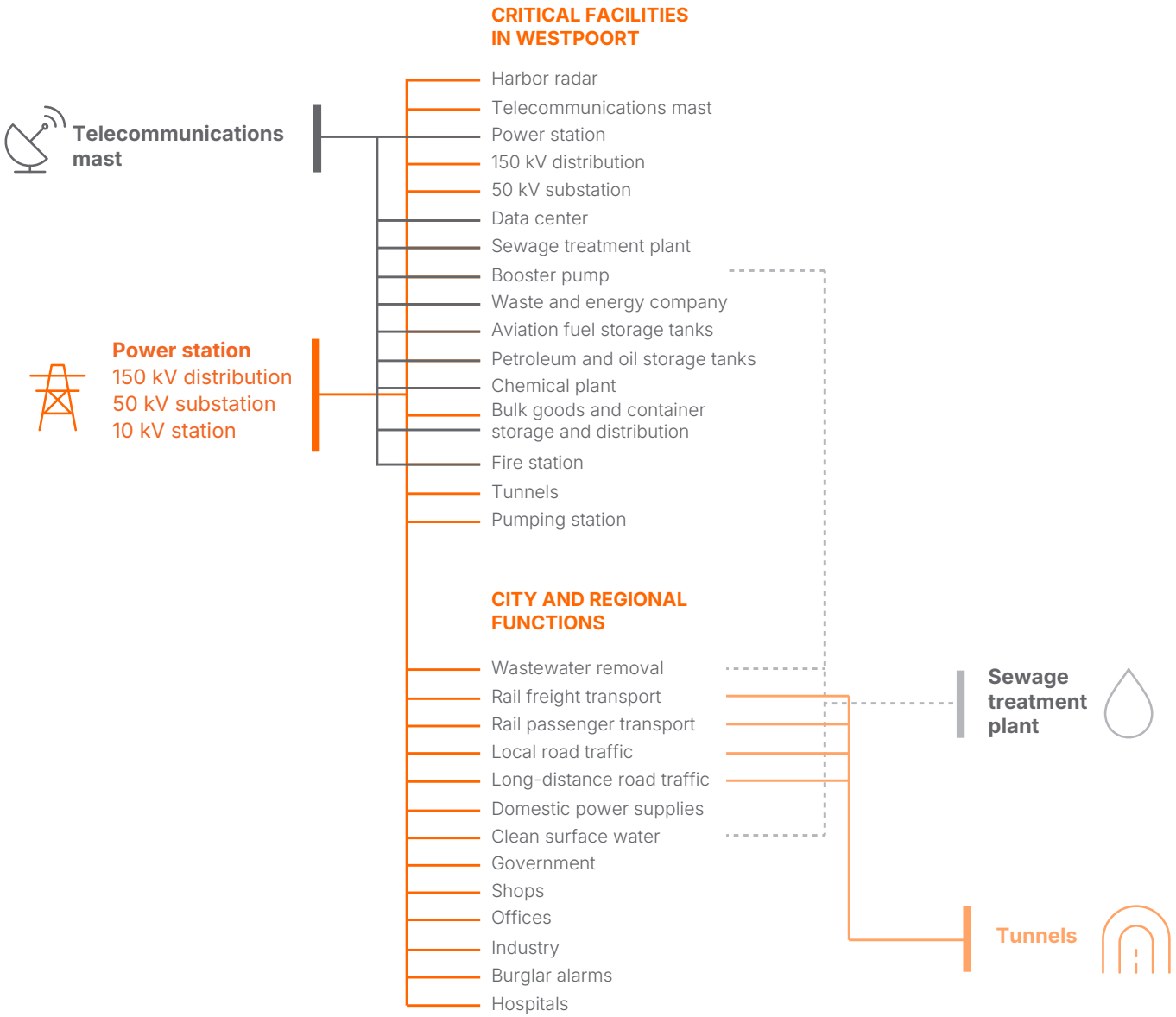
Infrastructure is deeply interconnected. Failures in one system can cascade into others. For example, damage to the electrical grid can disrupt telecommunications systems essential to business operations, and highway closures can impact supply chains critical to agriculture and industry. Disruption in one sector can quickly spread across broad swaths of the economy, shutting down goods movement, production, and trade, as well as critical public services such as water and sanitation, emergency response and recovery, health care, and education. *Figure 3* shows some examples of infrastructure interdependence between systems at a port facility.

Systemic risks in infrastructure often emerge across the entire project lifecycle—from planning and design to operations and external dependencies. Because individual assets are embedded within broader systems, increasing the resilience of a single asset can generate positive ripple effects across the entire value chain for sponsors, strengthening the resilience of the network. An example of this complex system is shown in *Figure 3*. However, this positive cascading effect does not apply to all projects. For example, a building constructed with fire-resistant materials could still be damaged by wildfire if the surrounding infrastructure remains highly flammable.

Nevertheless, early resilience planning helps avoid cascading failures over time, strengthening system-wide performance. This approach—adaptation by strengthening key individual projects—is especially valuable for complex or diversified portfolios, where proactive measures can reduce systemic risk and enhance long-term financial and operational stability.

System-wide impacts can create both immediate and long-lasting problems for local and regional economies, often taking years to recover and degrading the investment environment (see text box). Recognizing and preparing for the cascading risks that may affect an investor's infrastructure assets because of disruptions in other sectors can help sponsors maintain cross-portfolio stability, withstand periods of broader economic fallout, and minimize reputational harm.[20]

Figure 3. Connected infrastructure systems and assets at Westpoort, an international port in the Netherlands. Note that the image below reflects a limited selection of interdependencies. Source: C40 Cities Climate Leadership Group.



Climate Hazards Can Have Long-Lasting Impacts on Economies

In 2023, a drought reduced water levels and hydropower production at the run-of-the-river 2,568 megawatt (MW) Santo Antonio plant in Brazil, interrupting supply to nearby states and disrupting food and energy supply chains. The shutdown also forced the grid operator to activate expensive alternative sources of electricity, raising rates for consumers.[21, 22] The economic impact on the electric company was not limited to lost sales but also included reputational damage, increased emergency generation costs, and impacted long-term market stability.[23] Investing in resilience— leveraging tools such as parametric insurance or building redundancy through more diverse energy generation sources—can mitigate these risks and protect the company´s revenue streams.

Promoting Macroeconomic Sustainability and Growth

A stable economic environment is necessary for investment opportunities and growth. By investing in resilient infrastructure systems, developers and financiers can advance their financial goals while promoting broader economic stability, vitality, and growth, opening up further appealing investment opportunities throughout the value chain.

Resilient infrastructure catalyzes economic development, creating reliable local and regional infrastructure networks that foster an enabling atmosphere for growth and a vibrant business environment ripe for subsequent investments. Strong infrastructure networks are necessary for powering business, lowering transaction costs, improving market access, and improving the



efficiency of other productive factors. They are a prerequisite for connecting workers to their jobs and supporting overall macroeconomic development. Examples of this interconnectedness are ports' dependence on reliable connection roads, or electricity generation plants' dependence on resilient transmission and distribution lines to reach users. Adapting individual assets can strengthen the resilience and functionality of entire infrastructure value chains if they are part of a systems-level planning process. Resilience measures can enhance economic sustainability by creating attractive conditions for sponsors, developers, and financiers to engage and expand their activities across all stages of the value chain.

Infrastructure systems that depend on a small number of large or centralized assets can be especially fragile when climate-related disruptions occur. Damage to a single critical facility can quickly spread across the broader system, interrupting services, slowing economic activity, and discouraging future investment. Strengthening infrastructure to better manage climate risks can reduce these knock-on effects, limit broader economic losses, and make the overall sector more reliable. In doing so, climate-resilient infrastructure supports sustained economic growth and greater investor confidence.

1.3 Conclusions

Climate change has fundamentally altered the risk landscape for infrastructure investment in LAC. Climate hazards such as floods, storms, heat, wildfires, and sea level rise are no longer rare or peripheral events. They are recurring and financially material stressors that directly affect asset performance, revenue stability, operating costs, credit quality, and long-term valuation. **For infrastructure sponsors with long-lived, capital-intensive, geographically fixed assets, unmanaged climate risk is no longer compatible with fiduciary responsibility or sustainable returns.**

Across sectors, targeted adaptation measures consistently deliver strong economic returns and often at relatively modest incremental cost. When appropriately designed and applied to vulnerable assets, resilience investments reduce expected losses, stabilize cash flows, support credit quality, and preserve long-term asset performance. Resilience is therefore best understood not as an add-on or sustainability premium, but as an integral component of a sound investment strategy. The most successful approaches emphasize **right-sized, asset-specific resilience improvements** rather than uniform hardening—deploying layered measures that interrupt key risk pathways, account for future climate conditions, and align with an investor's risk appetite and financial objectives.

Sponsors who proactively embed climate resilience into planning, design, financing, and operations are better positioned to manage downside risk, maintain access to capital and insurance, and protect portfolio performance under increasingly volatile climate conditions.

This guide ultimately provides practical, decision-oriented tools to help sponsors translate climate risks into informed financial decisions by linking climate hazards to cash flows, financing constraints, and returns. It demonstrates that **climate resilience is no longer optional for infrastructure sponsors; it is a core financial strategy.**



02

A Framework for Resilient *Infrastructure Investments*

This chapter outlines the guiding framework for this guide and provides an overview of the remaining chapters. **This guide is intended to serve as a practical, decision-oriented guide for private sponsors seeking to understand, assess, and act on climate-related risks and opportunities across infrastructure investments in the transportation, energy, water and sanitation, telecommunications, and social infrastructure sectors.**

It is designed to help sponsors move from recognizing climate risk as a material financial issue to identifying, evaluating, and managing climate adaptation and resilience measures in investment decisions.

Figure 4. Overview of each chapter in the guide



There are multiple internationally accepted frameworks that lay out pathways to sustainable and resilient investments. However, many frameworks focus on investments by the public sector, are limited to the most common private investments, such as real estate, or contain little information about how private sponsors can practically implement the framework in the context of infrastructure. **This guide provides detailed adaptation information specific to the five focus sectors, allowing sponsors to turn theory into practice.**

At the highest level, this guide supports sponsors in the translation of physical risks into financial scenarios that bolster decisions about climate adaptation. The rest of the guide is organized as follows:

Chapter 3: Climate Change in Latin America and the Caribbean: This chapter provides an overview of how climate hazards such as flooding, heat, and hurricanes are changing across the LAC region. Every decision about climate adaptation needs to be based on the best available climate science, and carefully quantifying climate risks is critical to right-sizing climate adaptation measures. While this chapter cannot replace a full project-specific climate vulnerability assessment, it provides a baseline understanding of key climate trends, allowing sponsors to identify which hazards are of greatest concern in their region of interest.

Chapter 4: Climate Vulnerabilities, Adaptation Measures, and Benefit-Cost Analyses: This chapter serves as a decision-support tool to help sponsors understand unique infrastructure vulnerabilities and develop appropriate adaptation measures using benefit-cost analyses (BCAs). The chapter is aligned with IDB Invest's Physical Climate and Natural Disaster Risk Assessment (PCRA) process. It includes an overview of how the climate hazards in Chapter 3 can cause both physical and financial impacts to infrastructure assets across the five key sectors to support risk **screening**. The chapter also explains how sponsors can begin identifying and prioritizing cost-effective adaptation measures to address identified risks, supporting risk **analysis** and helping sponsors start to **build resilience**. It introduces key concepts related to quantifying adaptation costs and benefits and provides extensive examples from the literature of adaptation measures for different asset types across all five sectors. Each adaptation measure is accompanied by the best available information about the incremental cost increase associated with the measure, the effectiveness of the measure, and an estimated benefit-cost ratio (BCR). These economic indicators can help sponsors identify the adaptation measures that best fit their specific needs. See Chapter 4 for more information on IDB Invest's PCRA process, and how this chapter can be used to support climate-resilient decision-making.

Chapter 5: Assessing the Financial Impacts of Climate Adaptation Measures at the Project Level: Once an investor has characterized the most important risks and identified a small number of potential remedies, it is important to translate the general economic indicators for each adaptation measure into the impacts on a project's financial analysis. Chapter 5 uses two fictional investments (a road and a solar power plant) to demonstrate how climate risks, revenue models, and adaptation measures can be represented in key financial measures such as the cash waterfall. The goal of this chapter is to provide the reader with the tools to adjust their own financial models to accurately estimate the cost-effectiveness of climate adaptation measures. Chapters 5–7 are intended to support the **building resilience** phase of IDB Invest's PCRA process by helping sponsors transition from risk identification to project-level financial decision-making.

Chapter 6: Framework for Financing Climate Adaptation Measures: Following the financial analysis of climate adaptation options, sponsors need to finance the additional resilience investments. Chapter 6 lays out how to match adaptation projects to different financial instruments based on key financial metrics and revenue models across the five sectors. It introduces a toolkit of financial instruments that can be used to finance a project's capital expenditure and manage residual climate risks.

Chapter 7: Insurance Landscape for Sponsors: Climate adaptation measures reduce but never eliminate climate risks completely. This chapter discusses how sponsors can insure their projects against any residual risks and potentially leverage investments in climate adaptation to reduce insurance premiums or obtain otherwise unavailable insurance products. This chapter is tightly linked to Chapter 6, as new insurance and financial tools blur the line between financing and insuring investments.

Chapter 8: Technological Innovations in Resilient Infrastructure: This chapter discusses new developments and technologies in climate adaptation. Readers learn how new digital technologies can impact all phases of the project development process, from preliminary design through maintenance and monitoring. Technical innovations discussed in this chapter can help make climate adaptation easier and more efficient to implement.

Appendix A: Adaptation Case Studies: This appendix provides seven unique case studies of successful climate adaptation projects in the LAC region across the five key sectors. The case studies are highlighted throughout the guide, and this appendix provides a deep dive into the adaptation strategies used in each case study project, as well as the costs and financial returns associated with each project. This appendix also highlights key findings that sponsors can leverage when developing climate adaptation projects.

Appendix B: Overview of Benefit-Cost Analysis Methodologies: This appendix expands the discussion of BCAs and BCRs in Chapter 4 to cover other types of BCA methodologies, including life cycle cost analysis, cost-effectiveness analysis, economic impact analysis, and internal rate of return (IRR) analysis. Each type of analysis has different outputs and use cases, and this appendix is intended to provide sponsors with an overview of the applicability, strengths, and weaknesses of each methodology.

Iterating on Adaptation Measures

As shown in the framework graphic above, there are multiple points in this process where sponsors may need to reassess climate vulnerabilities and adaptation measures. For example, if plugging adaptation measures into a project-level financial model in *Chapter 5* does not prove to be cost-effective, an investor may return to *Chapter 4* to consider alternative adaptation measures. Similarly, if certain financing options in *Chapter 6* are not feasible, sponsors may need to reassess vulnerabilities and adaptation options in *Chapter 4.* In general, climate adaptation is an iterative process, especially when determining the appropriate adaptation measure or combination of measures to protect a specific infrastructure asset.

Appendix C: Hypothetical Adaptation Project Methodology: As part of Chapter 4, hypothetical adaptation projects were developed for a subset of the infrastructure asset types in order to demonstrate how adaptation costs and benefits vary depending on the project scale. This appendix provides an overview of the methodology used for this process, as well as the key tools, inputs, and assumptions used for each hypothetical project.

Appendix D: Financing Instruments for Climate-Resilient Infrastructure: Chapter 6 introduces six families of financial instruments used in climate-resilient infrastructure transactions. This appendix provides more detailed descriptions of each family of financial instruments. For each instrument, the appendix describes what the instrument is, how it works, and when it is most appropriate to use it. This appendix also provides illustrative examples for each family of instruments.

Taken together, this document presents a systematic guide to climate adaptation for infrastructure projects in the LAC region.

Each chapter represents a key step toward an informed investment decision. Building on advances in climate science, engineering, and finance, this methodology provides a structured, repeatable framework for assessing how physical climate impacts affect asset performance, valuation, insurability, and long-term returns, while also evaluating the cost-effectiveness of adaptation measures. Importantly, this guide shifts the conversation from climate risk as a purely defensive exercise toward one that also identifies opportunities for value protection and enhancement, including resilient investments and nature-based solutions that can strengthen cash flows over an asset's lifespan. This methodology is especially important in today's market context, where regulators, insurers, and beneficiaries increasingly expect credible, useful assessments of physical climate risk, and where unmanaged climate impacts pose a growing threat to asset values, portfolio stability, and fiduciary outcomes.

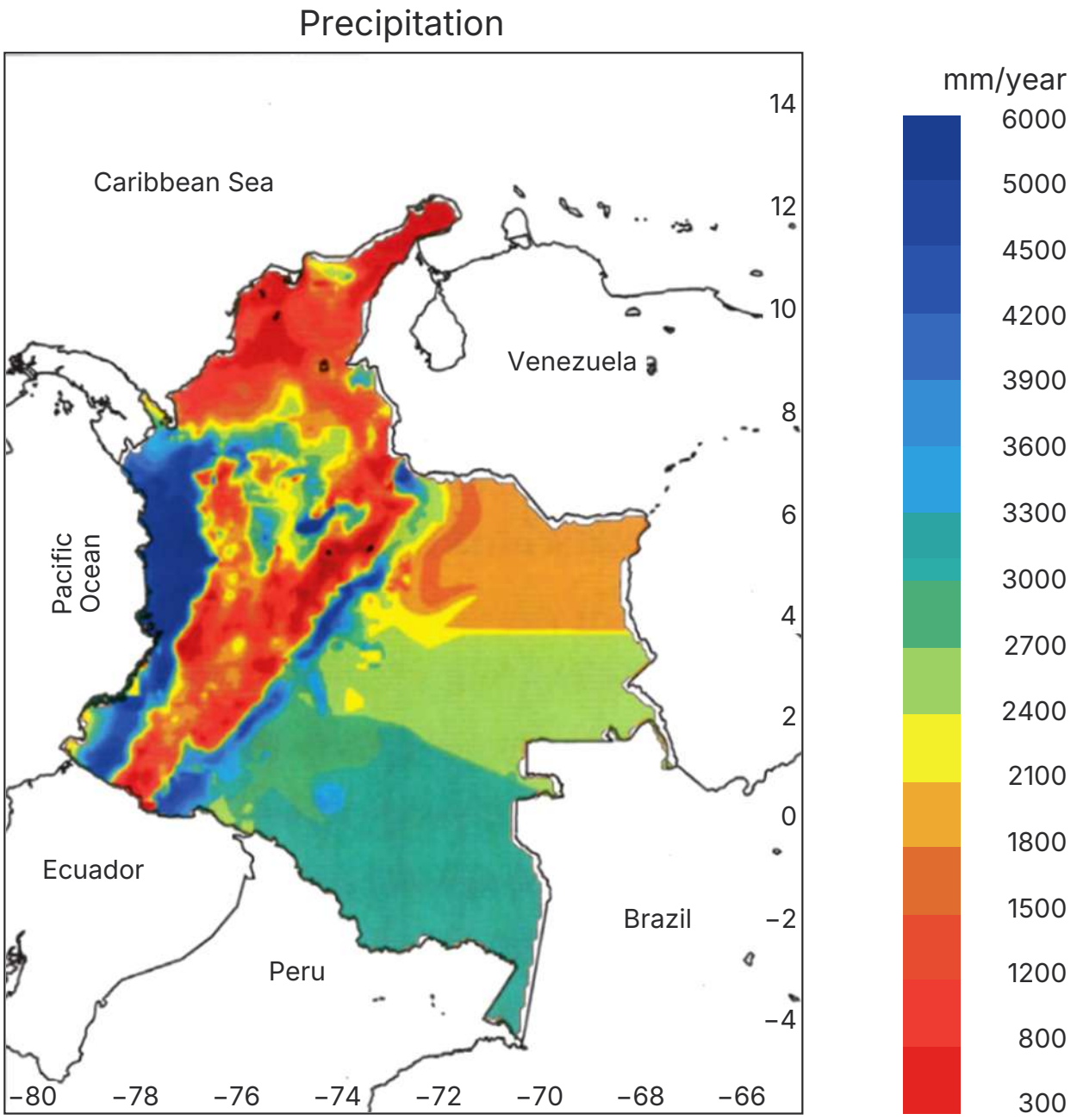


03

Climate Change *in Latin America and the Caribbean*

This chapter provides an overview of how the climate is changing in LAC, helping sponsors better understand potential risks to their assets. Almost every location in LAC experiences some level of exposure to one or multiple climate hazards, from hurricanes and flooding to wildfires and heat waves. Many of these hazards are projected to intensify in future decades due to the accelerating impacts of climate change.

Figure 5. Average annual precipitation in Colombia



The effects of climate change across LAC are diverse given the size of the region and its significant geographic variability across the region. Similarly, because economic contexts vary so widely in the region, the consequences of climate change impacts on infrastructure also vary widely.

Take, for example, precipitation in Colombia (Figure 5).[24] A single country contains a wide range of precipitation patterns, from very dry to very wet. **For this reason, readers are encouraged to consider the "geo-type" of their asset's location rather than the specific country or region** *(see Table 1).*

Table 1. Hazards by geo-type. Based on the physical and climate conditions of the site where the asset of interest is located, consider which geo-type or geo-types the location falls into, and see which hazards are most relevant. One location may contain multiple geo-types, if it is, for example, forested and mountainous.

	Hazards						
Geo-type	**Extreme Heat**	**Heavy Rain & Flooding**	**Landslides**	**Drought**	**Wildfire**	**Sea Level Rise**	**Hurricanes & Storms**
Coastal	✓					✓	✓
Desert/arid	✓			✓	✓		
Grasslands/shrublands	✓	✓		✓	✓		
Humid or tropical/semi-tropical	✓	✓					✓
Temperate	✓	✓		✓			
Mountainous			✓				
Inland low-lying		✓					
Riverine		✓					
Forested					✓		

This exercise should not be used as a replacement for a formal vulnerability assessment, which will deliver more robust and quantitative risk information and will offer a comprehensive look at the relevant hazards for a specific site. IDB Invest has information on its vulnerability assessment process available online.

The following section describes the historical characteristics and projected trends of climate hazards in LAC. Countries in the region have been grouped into the following four groups based on their location and geo-types:

- **Central America**: Mexico, Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua, Panama
- **Caribbean:** Barbados, The Bahamas, Guyana, Haiti, Jamaica, Suriname, Trinidad and Tobago, the Dominican Republic
- **Andean Group:** Bolivia, Colombia, Ecuador, Peru, Venezuela
- **Southern Cone**: Brazil, Chile, Uruguay, Paraguay, Argentina

Based on *Table 1*, readers should navigate to the relevant sections to understand how climate hazards are impacting the region where the asset of interest is located



Climate Vulnerability Assessments and Climate Projections

Conducting a climate vulnerability assessment to determine a given asset's vulnerability to climate change hazards is a crucial step in successfully building resilience. The results of this assessment will determine which adaptation measures asset designers and planners should implement to best protect investments from disruptions and damages caused by climate hazards and extreme weather events. Additionally, adaptation measures are context- and location-specific, and it is critical to understand the unique project site and its vulnerabilities before developing adaptation measures.

It is important that these vulnerability assessments are conducted using **climate change projections**. Projections are generated using climate models and indicate how key variables like temperature, precipitation, sea level, and floodplains will change in the future due to changes in the concentration of atmospheric greenhouse gases. **Using only historical data is insufficient to capture the full extent of climate risks in the future**, given that climate change is likely to affect the severity and frequency of these hazards over the next several decades. **See Section 3.8 for more details on climate projection sources.**

3.1 Compound Climate Pathways

Compound climate pathways are the occurrence of multiple, simultaneous, or sequential climate hazards that generate impacts often greater in magnitude and impact than a singular climate hazard. Compound climate hazards such as droughts leading to increased flooding due to decreased soil water retention are significant risks and may occur more frequently in the future due to climate change. In particular, compound climate pathways are a large risk to infrastructure with an adaptation measure built to withstand a singular climate hazard (e.g., a flood wall only built to withstand sea level rise, but not extreme storm surges caused by wind and high rainfall, may fail under a wind, storm surge, and rainfall compound pathway). To address compound climate pathways, sponsors can evaluate potential pathways shown in Table 2 and consider how a package of multiple adaptation measures may be best suited to address the compound pathways. Monitoring (for example, closely tracking the combined effects of rain, sea level, and wind events at ports) is especially important when designing adaptation measures to withstand compound pathways because the impacts of these events are specific to each site's geography, existing infrastructure and adaptation measures, and climate risks. Finally, natural compound hazards can interact in complicated ways with infrastructure assets. For example, climate change can lead to increased glacier melt in the mountains, which can lead to floods that can overwhelm human-made reservoirs for hydropower production, leading to secondary flooding and landslides.

Table 2. Dominant compound climate pathways in LAC

Region	Dominant Compound Climate Pathways				
	Heat & Drought	Drought-Flood Transition	Wind-Surge-Rainfall	Wildfire-Landslide	ENSO-Driven Multi-Hazard Clustering
Central America	✓	✓	✓	✓	✓
Caribbean	✓	·	✓	·	✓
Andean Group	✓	✓	·	✓	✓
Southern Cone	✓	✓	·	·	✓

- **Heat and drought**: Heat-drought pathways are periods of prolonged high temperatures and low rainfall that together increase evaporation, reduce water availability, and stress energy and agricultural systems, often leading to higher water-use competition and more frequent service interruptions across infrastructure.

- **Drought-flood transition**: Dry periods degrade soil structure and reduce vegetation cover, so that when heavy rainfall returns, the land cannot absorb water, leading to rapid runoff, flash floods, and landslides in watersheds and urban basins. Such transitions are particularly risky for infrastructure built to withstand either drought or flood, but not both, and can overwhelm drainage and slope-stability measures.

- **Wind-surge-rainfall (tropical cyclones & coastal storms):** High winds, coastal storm surge, and intense precipitation from tropical cyclones can simultaneously damage ports, power lines, and low-lying settlements, often exceeding the design thresholds of single-hazard protection measures.

- **Wildfire-landslide:** After drought and heat raise wildfire risk, burned slopes become highly vulnerable to erosion and landslides when heavy rain arrives, threatening roads, pipelines, and water infrastructure that may have been prepared for fire but not post-fire hydrological failure. This compound sequence is especially important in mountainous terrain, where infrastructure corridors are often confined to narrow valleys and steep slopes.

- **ENSO-driven multi-hazard clustering:** ENSO-linked multi-hazard clustering refers to periods when El Niño or La Niña phases synchronize drought, flooding, heatwaves, and tropical storms across large parts of LAC, creating stresses on water, transport, energy, and health systems.

3.2 Extreme Heat

Rising average temperatures, as well as more frequent and severe instances of extreme heat, are impacting LAC, and these hazards are projected to continue through the end of the 21st century.

Caribbean: Between 1961 and 2010, there was an observed increase in the intensity, duration, and frequency of warm and hot days and nights in the region.[25] In 2024, Cuba experienced three heatwaves in April, May, and July, with May 2024 being the warmest May on record in the country since 1951.[26] Under RCP4.5, the region is projected to experience an average of 124 heat waves per year by mid-century (2026–2045) and 1,848 heat waves per year by late-century (2081–2100).[27] Under RCP8.5, the region is projected to experience an average of 356 heat waves per year by mid-century (2026–2045) and 4,463 heat waves per year by late-century (2081–2100).[28]

Central America: In early 2024, 60% of the land area in Mexico experienced a heatwave with temperature abnormalities of +3°C or higher compared with normal conditions.[29] under both RCP 2.6 and 4.5, Central america, Central America is projected to experience increases of 1–2°C in the most extreme temperature on the hottest day of a heat wave by mid-century (2045–2054).[30] This pattern is projected to be especially significant along the coastal areas of the region.[31]

Andean Group: In mountainous regions of South America, rising average temperatures are leading to glacial melt. In Colombia, the Conejeras Glacier was declared extinct in 2024, and data from 5,500 glaciers across the Andes showed a 25%

decrease in ice coverage since the end of the nineteenth century.[32] In particular, tropical glaciers are experiencing this decline at a more rapid rate, melting ten times faster than the cumulative global average.[33] Under RCP8.5, two of the most glacierized areas of the Peruvian Andes (Rio Santa and Vilcanota-Urubamba) are projected to experience increases in maximum daily temperature of between 3.6°C and 4.1°C by late-century (2062–2100).[34]

Southern Cone: In August and September 2024, western central Brazil experienced a heatwave that brought temperatures 7°C higher than usual.[35] Buenos Aires, Argentina, recorded its highest-ever temperature (38.9°C) on March 11, 2024.[36] A 2024 study found that the Amazon region is projected to experience the greatest increase in the frequency and duration of heatwaves under RCP8.5, with the frequency of heatwaves increasing 12-fold and the duration increasing 9.3-fold from historic conditions to mid-century (2045–2054).[37] In Central South America (encompassing northern Chile and Argentina, as well as Uruguay and Paraguay), the most extreme temperature during the hottest day of a heat wave is projected to increase by 1–2°C under both RCP2.6 and RCP8.5 by mid-century (2045–2054).[38] In southern South America (encompassing southern Chile and Argentina), the average number of heat waves per year is projected to at least double under RCP8.5 by mid-century (2045–2054).[39]

3.3 Drought

Even as instances of extreme precipitation become more frequent and severe, intervening periods of drought are also projected to become more commonplace and more intense across Latin America. As discussed in the previous section, the Caribbean and Central America in particular are projected to experience general drying trends over the course of the coming century. In many countries, droughts are intensifying and will continue to exacerbate human-driven water stress conditions. Across LAC, El Niño cycles tend to influence intra-annual trends in drought and precipitation.

There are five main types of drought:

- **Meteorological drought:** periods of below-normal precipitation, driven by local variations in climate.
- **Agricultural drought:** periods of below-normal precipitation that have negative impacts on agricultural systems.



- **Hydrological drought:** periods of below-normal precipitation that have negative impacts on watershed or basin water levels.

- **Socioeconomic drought:** periods of below-normal precipitation that have economic consequences associated with drought impacts on hydrological and agricultural systems, often tied to population and consumption patterns.

- **Ecological drought:** periods of below-normal precipitation that have negative impacts on ecosystems.[40]

Caribbean: Periods of drought in the Caribbean tend to be correlated with El Niño cycles.[41] The entire region experienced a period of severe drought from 2013 to 2016, the driest period on record for the Caribbean since 1950, overlapping with the 2015–2016 El Niño cycle.[42] Even in years without El Niño conditions, the Caribbean experiences seasonal drought variability, with the dry season peaking in February and March.[43] The Caribbean struggles with water stress, a measure of water availability in relation to water demand, driven by poor water management practices and high freshwater demand, especially in the tourism industry.[44] Drought can exacerbate water stress by reducing water availability. Seven of the world's 36 most water-stressed countries are in the Caribbean, including Antigua and Barbuda, Barbados, and St. Kitts and Nevis, with less than 1,000 m^3 of freshwater resources per capita.[45] The Intergovernmental Panel on Climate Change (IPCC) projects that average annual precipitation and average summer precipitation are likely to decrease throughout the Caribbean as a result of climate change over the coming century.[46]

Central America: Central America is prone to drought and is home to the "dry corridor," a strip of land stretching across El Salvador, Guatemala, Honduras, and Nicaragua that experiences chronic dry conditions.[47] Between 1998 and 2017, all four of these countries were among the 20 countries most affected by extreme weather events globally.[48] In 2020, 7.5% of the land area within the dry corridor suffered from severe drought, and 50.5% of the region is faced high drought conditions.[49] Other portions of Central America outside of the dry corridor also deal with drought. In 2023, the Panama Canal faced historic drought conditions as water levels in Gatún Lake, the primary water source for the canal, dropped to the lowest levels ever recorded, approximately two meters lower than recorded a year prior.[50] Baja California and central and northwestern Mexico also experienced 20% to 50% less rainfall in 2024, as compared to the 1991–2020 average.[51] The IPCC projects that average annual precipitation and average summer precipitation are likely to decrease throughout Central America due to climate change over the course of the 21st century.[52]

Andean Group: Countries in the Andean Group have experienced drought historically. For example, in October 2024, northern Peru, eastern Colombia, and southern Venezuela experienced a record-breaking drought, with the affected region receiving 160 millimeters less rainfall than usual and with stream flows dropping fourfold.[53] Even as extreme precipitation events are projected to occur more frequently and with more intensity, droughts in the Andes are projected to persist for longer and to be more severe in the interval between instances of heavy rainfall.[54] Similarly, even as melting glaciers may increase riverine flooding risks at a short-term scale, this trend is likely to contribute to regional megadroughts on a long-term scale. Glacial retreat will decrease the amount of freshwater supplied to rivers throughout the region, exacerbating reductions in precipitation over the course of the coming century.[55]

Southern Cone: Regions throughout the Southern Cone have historically experienced severe drought. In 2024, rivers in the Amazon basin fell to record-low water levels, affecting regions across Brazil.[56] For example, water levels in the Solimões River fell 254 centimeters below the gauge's zero mark on October 4, 2024, and record-low water levels were recorded near Porto Velho, Jirau-Justante, Fonte Boa, Itapéua, Manacapuru, Rio Acre, and Beruri.[57] In 2023, the worst drought on record in Uruguay since 1947 affected more than 80% of the country's land area.[58] Since 2010, central Chile and western Argentina have been experiencing a megadrought. This drought ranks among the top 20 longest and most severe droughts to occur globally between 1987 and 2016.[59] As in glaciated regions of Peru, Ecuador, Colombia, and Venezuela, shrinking glaciers in the Southern Cone are projected to contribute to regional megadroughts, especially in Chile and Argentina, as decreasing glacial melt lowers water levels in rivers that supply freshwater throughout the region.[60]



3.4 Heavy Precipitation, Inland Flooding, and Landslides

In many regions of South America, heavy precipitation events are projected to become more severe and occur more frequently over the course of the 21st century due to climate change, even as intervening periods of drought between extreme precipitation events also become more intense and more commonplace. The Caribbean and Central America are projected to experience overall drying trends over the coming century, despite historical observations of increases in extreme precipitation.

More extreme precipitation events, especially when paired with long-term drought conditions, can increase the risk of riverine flooding and landslides, as drier soils are less stable. In glaciated mountainous areas, such as the Andes and Patagonia, melting glaciers are projected to increase the risk of riverine flooding, as well as glacial lake outburst floods, which occur when water from a lake, previously contained by a glacier, is released and causes significant flooding downstream.

Caribbean: Researchers have observed increases in instances of extreme precipitation in the Caribbean. Between 1995 and 2004, the Greater Antilles experienced an increase in the average intensity of precipitation and an increase in the contribution of heavy precipitation to overall rainfall totals.[61] In 2024, Haiti and Jamaica experienced 20% more precipitation than the 1991–2020 average.[62] Extreme precipitation, from hurricanes or other storms, can lead to floods and landslides. For example, in 2017, precipitation from Hurricane Maria triggered 40,000 landslides in Puerto Rico.[63] Despite these observed increases in extreme precipitation events, the IPCC reports that the Caribbean is projected to experience a

likely decrease in average annual precipitation and average summer precipitation under climate change.[64]

Central America: In 2024, eastern Mexico and the Yucatán Peninsula experienced between 20% and 40% more rainfall than during the period between 1991 and 2020.[65] In 2024, Guatemala, El Salvador, Costa Rica, Honduras, and Nicaragua also experienced above-average rainfall (10%–30% higher than the 1991–2020 average).[66] Despite these observed increases in instances of extreme precipitation events, the IPCC reports that Central America is projected to experience a likely decrease in average annual precipitation and average summer precipitation under climate change.[67]

Andean Group: According to the IPCC, parts of Colombia and Venezuela could see increases in the intensity and frequency of extreme precipitation events and rain-driven flooding under climate change.[68] In the Peruvian Andes, annual average precipitation is projected to increase by 12% by late-century and the amount of precipitation falling on very wet days is projected to increase by 75%. At the same time, droughts are projected to persist for longer and to be more severe in the interval between extreme precipitation events.[69] Furthermore, as stated in the section on extreme heat, increasing average and maximum temperatures in the Andean Group are increasing the rate of glacial melt. Faster and more severe glacial melt is likely to increase the risk of riverine flooding, as melting glaciers deposit high volumes of water into streams and rivers.[70] This phenomenon, paired with permafrost thawing, may also increase the likelihood of glacial lake outburst floods, which occur when water from a lake, previously contained by a glacier, is released and causes significant flooding downstream.[71]

Southern Cone: Regions in southeastern South America (including eastern Brazil, Patagonia, and northern Argentina and Chile) also experienced above-average rainfall in 2024 (10%–30% higher than the 1991–2020 average).[72] In the state of Rio Grande do Sul in Brazil, record-breaking flooding in April and May 2024 affected 2,398,255 people and led to 183 fatalities.[73] In much of the Southern Cone region, including the southern half of Brazil, as well as Uruguay, Paraguay, and Argentina, the IPCC reports that rain-driven flooding is projected to increase in frequency and severity over the coming decades, even as droughts persist for longer intervals between flooding events.[74] The IPCC also projects that a reduction in glacial cover in Chile due to warming average and maximum temperatures will increase the risks of riverine flooding and glacial outburst floods.[75]

3.5 Wildfire

As regions in Latin America become hotter and drier, wildfire risk is likely to increase. Rapid development along the wildland-urban interface exposes more communities to wildfire risks, and other human-driven phenomena, like burning trash due to poor sanitation infrastructure or land clearing for agriculture, can further increase the likelihood of wildfires.

Central America: Much of Central America is prone to wildfire, and wildfire risks are increasing with climate change. In 2024, wildfires burned 660,475 acres in Honduras; 43,497 acres in El Salvador; 715,886 acres in Nicaragua; and 208,223 acres in Costa Rica.[76] El Niño cycles influence wildfire risk in Central America, as the climate pattern brings dry weather to the region.[77] The IPCC projects that over the course of the 21st century, Central America will likely experience an increase in the number of fire-weather days per year.[78]

Andean Group: In 2024, regions of Peru and Bolivia in the Amazon rainforest experienced record-breaking wildfires. Bolivia faced approximately 30,000 wildfire alerts in 2024 alone, nearly double the previous national record this century in 2010.[79] The same year, Bolivia lost the most forest area (60% of its primary tropical forests) to wildfires since 2002.[80]

Southern Cone: Much of the Southern Cone is prone to wildfire risk. In 2024, Brazil lost the most forest area to wildfires in a single year since 2002, as extreme heat and drought driven partially by El Niño combined to create prime conditions for fire to spread across hot, dry landscapes.[81] That year, 76% of all wildfires reported in Latin America were in Brazil.[82] In January and February 2025, Argentina experienced severe wildfires, with the Magdalena Valley fire burning 15,000 hectares, the Los Manzanos fire burning 10,000 hectares, and the Confluencia fire burning 3,600 hectares.[83] The IPCC projects that fire-weather days are likely to increase in frequency and severity in Chile and southern Brazil over the course of the 21st century.[84]

3.6 Sea Level Rise and Coastal Hazards

Globally, sea levels are rising due to an increase in the volume of ocean water from melting polar ice and due to thermal expansion, the process by which ocean water expands in volume because of increasing temperatures. Sea level rise is projected to affect coastlines globally, including the coasts of LAC. Rising sea levels are likely to exacerbate other coastal hazards, like storm surges, coastal erosion, and saltwater intrusion—the process by which saltwater contaminates freshwater aquifers.

Caribbean: The Caribbean experienced an average rate of 2.5 mm (+/- 1.3 mm) per year of local sea level rise between 1993 and 2010.[85] Observed sea level rise has not been uniform across the region, with the Lesser Antilles experiencing higher rates of sea level rise than other islands in the region.[86] By 2050 in the Caribbean, sea level is projected to rise 8 inches from 2020 levels.[87]

Central America: Regionally, sea levels are rising at the most rapid rate in the Gulf of Mexico at approximately 4.0 mm per year, whereas Mexico's Pacific coast is experiencing the slowest rate of sea level rise in the region at approximately 2.0 mm per year.

Andean Group: At a local scale, ground subsidence can exacerbate the effects of sea level rise by increasing the rate of erosion. For example, researchers found that in Cartagena, Colombia, local sea levels are rising at a faster rate than the global average due to ground subsidence, which is responsible for 41% of observed increases in local sea level.[88]

Southern Cone: Brazil's coastline has experienced about 8 cm of sea level rise since 1993 and is expected to experience an additional 18 cm by 2050 and about 68 cm by 2100. Taken together, these changes could significantly impact coastal erosion, coastal storms, and ocean circulation, which all impact infrastructure assets on Brazil's coastline.



3.7 Hurricanes and Extreme Storms

Extreme storms in Latin America include hurricanes, severe thunderstorms, and dust storms. Hurricanes are projected to become more severe with climate change, due to rising sea levels, warming oceans, and warming air temperatures.[89]

Caribbean: Hurricanes are a major climate hazard for the Caribbean and are a dominant source of extreme precipitation. The peak of the hurricane season occurs from mid-August to late October. In 2024, there were 18 Atlantic hurricanes, up from the 1991–2020 average of 14 storms per season. Nine of these storms made landfall in LAC.[90] In the Caribbean, El Niño conditions can lead to decreased hurricane activity, while La Niña conditions can lead to heightened hurricane activity.[91]

Central America: Hurricanes are a major climate hazard for Central America, as the region is vulnerable to both Pacific and Atlantic hurricanes. In 2015, Hurricane Patricia made landfall in southwestern Mexico along the country's Pacific coast as the strongest hurricane on record.[92] El Niño years can bring more hurricanes to the Pacific Ocean while bringing fewer hurricanes to the Caribbean.[93]

Andean Group: The countries that make up the Andean Group regularly experience extreme storm events. Lake Maracaibo, Venezuela, is home to the highest concentration of lightning on Earth, averaging 150 flashes per square km per year, typically occurring 300 days annually.[94] The phenomenon, known as Catatumbo Lightning, is caused by the unique topography and climate of the area, with warm water from the Caribbean Sea and hot tropical air mixing with cold air from the surrounding mountains.[95] Peru sees annual cycles of extreme winds, known as Paracas winds, causing severe dust storms and usually occurring in the afternoon in August, the end of the austral winter.[96]

Southern Cone: The region of central Argentina east of the Andes is a global hotspot for extreme thunderstorms due to the collision of warm, moist air and cool, drier air that characterizes this region.[97] Among the most severe storms on Earth, these phenomena are associated with extreme precipitation, severe winds, and occasionally hail and tornadoes.[98] The arid regions of Argentina and Chile are susceptible to dust storms that peak in the summer (December through March), usually seeing between 15 and 30 moderate to severe dust events per year.[99] Drought conditions can exacerbate the severity of these storms.

3.8 Other Sources of Climate Information

It is crucial that planners and designers use the best available climate information when conducting climate vulnerability assessments for proposed assets. This includes designing assets to withstand both historical, observed conditions and future, projected conditions. For example, an asset that is not within the historical 100-year floodplain may be in the projected future 100-year floodplain, as flood risks increase in severity and extent with climate change. Readers may consult the following sources in Table 3 to access the necessary climate information. However, this table may be incomplete as new tools are constantly being developed. Sponsors are encouraged to explore whether their country or region has developed local resources for more climate information.

Table 3. Sources of regional climate information

Title and Source	Region	Year	Climate Information
State of the Climate in LAC: World Meteorological Organization (WMO)	LAC	2024	Annually published climate report written by national and regional meteorological and climate organizations. Includes projections about extreme climate events identified in this report and other climate-related social impacts.
Climate Change Knowledge Portal: World Bank	Global	2026	Interactive portal providing country-level historical and future climate data until 2100 with multiple emissions scenarios.
IPCC AR6—Chapter 12: Central and South America: IPCC	Central and South America	2022	Regional chapter covering observed and projected climate risks from 2030–2050 and impacts.
IPCC Interactive Atlas: IPCC	Global	2021	A tool accompanying the IPCC AR6 report. Shows regional climate changes by season, variable (temperature, precipitation, etc.), and future emissions scenario.
NDC LAC Digital Platform	LAC	2026	A regional digital platform tracking Nationally Determined Contributions (NDCs) implementation for all LAC countries. Includes links to National Adaptation Plans (NAPs).
Climate Change Projections in LAC: IDB	LAC	2016	Technical publication that reviews regional climate model outputs in 2040 and 2070 for 26 LAC countries using multiple emissions scenarios.
Explore Nationally Determined Contributions (NDCs): Climate-Watch	Global	2026	A platform aggregating NDC data, historical emissions, and climate targets by country. Users can compare NDC ambition, track progress, and explore sector-level data for LAC countries.
CMIP5 Data: CORDEX	Global	2014	Downloadable regional climate projections with simulations available at 25–50 km resolution under multiple emissions scenarios.
Climate Risk (Risco Climático): Adapta Brasil MCTI	Brazil	2021	Interactive mapping tool showing a climate risk index in Brazil that combines three factors: climate hazard, exposure, and vulnerability.
Climate Risk (Risco Climático): Adapta Brasil MCTI	Chile	2020	Collection of maps that show impact chains from climate hazards across 12 sectors. For each impact chain, maps of climate hazards, exposure, and sensitivity of the affected system are shown.
Panama Climate Risk Atlas (Atlas de Riesgo Climático de Panamá): BID	Panama	2024	Interactive mapping tool that allows users to visualize hazards, exposure, vulnerability, and risk under different future climate scenarios in Panama.

04

Climate Vulnerabilities, Adaptation Measures, *and Benefit-Cost Analyses*

This chapter dives into asset-specific climate vulnerabilities and adaptation measures, including their costs and benefits, across the following key sectors: transportation, energy, water and sanitation, telecommunications, and social infrastructure. The previous chapter provides an overview of how the climate is changing in Latin America and the Caribbean, providing a critical foundation for sponsors to understand which climate hazards present the greatest risk to their region. The next step is to understand how climate hazards translate into physical and financial impacts to infrastructure assets, and how best to adapt those assets to reduce vulnerabilities.

Chapter 4 is organized as follows:

Section 4.1: Introduction to Benefit-Cost Analysis Methodologies and Financial Risk Channels: In order to select appropriate and cost-effective adaptation measures for a specific project, sponsors first need to understand the costs and benefits of those measures. This section introduces key concepts related to benefit-cost analysis (BCA) and financial risk channels, laying the groundwork for the adaptation cost and benefit discussion in Section 4.2, as well as the financial analysis discussion in Chapter 5.

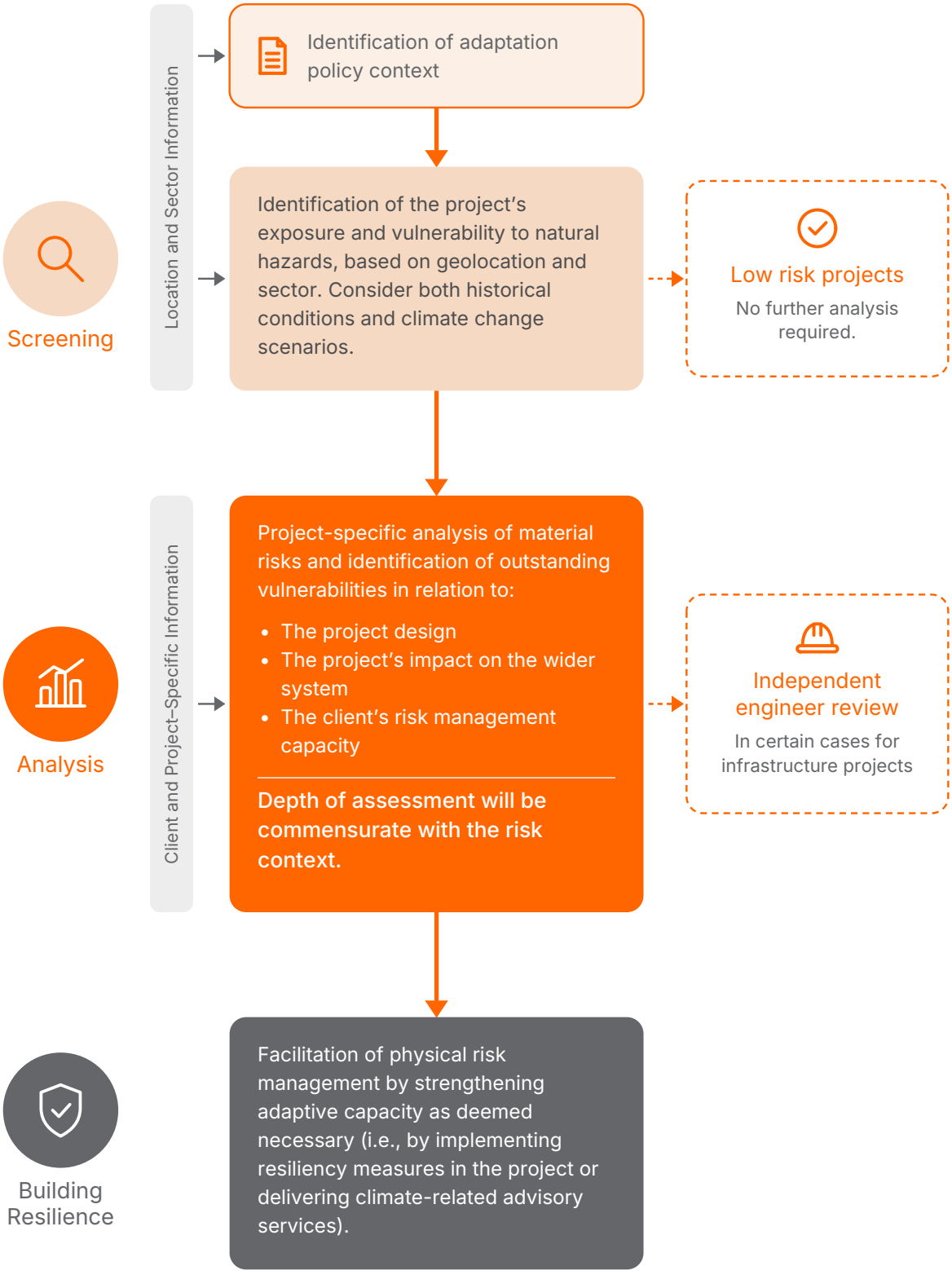
Section 4.2: Infrastructure Vulnerabilities and Adaptation Costs and Benefits Across Key Sectors: This section provides a detailed description of asset-level vulnerabilities and potential adaptation options for each key sector. This section also provides estimates of unit-level costs and benefits for each adaptation option, based on either hypothetical adaptation projects or case studies from established literature. **Sponsors are encouraged to jump to the sector or asset type that is most relevant to them after reviewing Section 4.1:**

- **Transportation:** Roads, ports, rail
- **Energy:** Transmission and distribution assets (e.g., substations, electrical wires and poles), solar farms, wind farms, hydropower assets
- **Water and Sanitation:** Drinking water infrastructure (e.g., pump stations, desalination plants) and wastewater infrastructure (e.g., lift stations, wastewater treatment plants [WWTPs])
- **Telecommunications:** Data centers, communication networks
- **Social Infrastructure:** Hospitals, schools



As mentioned in *Chapter 3*, private sponsors are strongly encouraged to conduct site-level vulnerability assessments before designing projects in order to understand the climate risks to the site and develop appropriate adaptation measures. IDB Invest requires climate vulnerability assessments for most projects it funds, but the level of assessment for each project may vary. *Figure 6* shows IDB Invest's Physical Climate and Natural Risk Assessment (PCRA) process. The PCRA covers the project design, its impact on the wider system, and the capacity of the client to cope with a hazardous event or natural disaster. The assessment process is divided into three stages: screening, analysis, and building resilience.

Figure 6. IDB Invest's climate risk assessment process, adapted from IDB Invest's website[100]



This chapter is aligned with each stage of the PCRA process:

1. **Screening:** For each sector, this chapter explains how climate hazards translate into physical and financial impacts, supporting sponsors in understanding unique infrastructure vulnerabilities.

2. **Analysis:** Hypothetical adaptation projects and real-world case studies are used throughout this chapter to help sponsors understand how climate risks and vulnerabilities change based on the specific project.

3. **Building Resilience:** This chapter provides a suite of adaptation measures and information on their costs and benefits to help sponsors begin identifying appropriate measures to increase the resilience of their project. Chapters 5 through 7 take this a step further by translating high-level incremental costs and benefit-cost ratios (BCRs) into project-level financial metrics and helping sponsors understand different financing and insurance mechanisms.

When identifying and designing adaptation measures, sponsors should also consider the potential for maladaptation. Adaptation interventions can inadvertently increase climate-related risks, shift risks to other people, places, or sectors, or create new vulnerabilities if broader social, environmental, and systemic impacts are not adequately considered. IDB Invest's Building Better Resilience: Note on Avoiding Maladaptation provides a framework and practical guidance to help project teams identify and mitigate these risks and support adaptation investments that deliver effective and equitable resilience outcomes.

This chapter focuses primarily on adaptation measures and understanding adaptation costs and benefits. See IDB Invest's website for more details on the PCRA process.

4.1 Introduction to Benefit-Cost Analysis Methodologies and Financial Risk Channels

Once the vulnerabilities of a project are identified, the next step for sponsors is to develop and implement appropriate adaptation measures to reduce those vulnerabilities. However, simply choosing adaptation measures is just one piece of the puzzle. In most cases, sponsors also need to determine the cost-effectiveness or financial viability of potential adaptation measures. For example, constructing a flood wall or elevating an asset can have high upfront construction costs, but the long-term flood protection benefits could ultimately outweigh those costs. A common approach to determining whether a project is cost-effective is through a **BCA**, which typically considers both the cumulative long-term costs of an infrastructure investment and whether the proposed investment provides sufficient benefits over the project lifecycle to justify the overall cost.[i]

There are several different methodologies available for understanding adaptation costs and benefits beyond a typical BCA, including life cycle cost analysis, cost-effectiveness analysis, economic impact analysis, and internal rate of return (IRR) analysis. **For the purposes of this chapter, the focus is on BCAs for adaptation measures.**

i The BCA methodologies used in this guide are intended to support comparison across adaptation measures for different infrastructure assets, but do not replace project-specific financial analyses.

See Appendix B: Overview of Benefit-Cost Analysis Methodologies for more information on alternative methodologies for understanding adaptation costs and benefits.

It is important to understand different benefit-cost methodologies in order to choose the approach, or combination of approaches, that is best suited to the specific project. Regardless of the methodology used, most benefit-cost methodologies require additional context to capture the full picture of an asset's value. For example, most methodologies factor in the asset's useful life to account for multi-year construction periods and long-term operations and maintenance (O&M) activities.

The following sections summarize key terms and concepts related to BCAs and introduce financial risk channels to help sponsors understand asset-level adaptation costs and benefits in Section 4.2.

Adaptation Benefits

In the context of climate change, the primary benefit of adaptation investments is a **reduction in damage or disruption from climate hazards** (e.g., reduced repair costs due to flooding events). While some adaptation measures may create new revenue, it is likely that most of the value will come from mitigating climate-related risks such as extreme weather, sea level rise, or drought.

Benefit-Cost Analysis

A BCA, also referred to as a cost-benefit analysis, compares the present value of an investment's future costs (initial capital investments and long-term O&M) against the monetized present value of benefits to both users and non-users. In many cases, BCAs consider societal benefits, including but not limited to avoided user costs, reduced damage, safety improvements, emissions reductions, and time savings. Sponsors will need to determine which benefits and costs are most relevant to include in their BCA. Table 4 below outlines the measures quantified in a BCA and the relevant data and information sources used to determine costs and benefits for an infrastructure investment.



Table 4. BCA quantified measures, data, and information sources

Category	Transportation	Energy	Water & Sanitation	Telecommuni-cations	Social Infrastructure
Costs					
Capital Costs Initial investment	Asset elevation, improved drainage, etc.	Heat-resistant materials, floodproofing	Floodproofing, redundant intakes	Elevated equipment, backup power, cooling upgrades	Floodproofing, backup power
O&M Costs Long-term O&M over useful life of investment	Drainage maintenance, frequent inspections, monitors	Vegetation management, monitoring and inspections	Maintenance of sewer and water lines, water quality monitoring	Increased HVAC maintenance, emergency planning, backup power	Increased maintenance, fuel supply for backup power, preparedness planning and costs
Benefits					
Risk Reduction Typically, measured as a reduced frequency or severity of impacts to assets from hazard events	Reduced closures from hazards such as flooding and storms; reduced repairs or less significant impacts from hazards	Reduced power outages from hazards such as heat, storms, floods, and wildfire	Less frequent containment and service failure events	Better coverage, fewer outages, better-performing data centers	Avoided closures, reduced damages from hazards
Revenue Protection Payments from tolls, fees, and purchase agreements; potentially subject to fines.	Maintains traffic volumes (tolls) or port throughput, avoids force majeure revenue loss	Fewer curtailments and penalties, improved availability and capacity factors	Smaller regulatory penalties, stable revenue	Service continuity, access to contracts with valuable clients (e.g., governments)	Continuity of operations (high demand for medical facilities during extreme events), tuition revenue
Financial Performance Ability of the project to meet its financial metrics (e.g., cash flow)	Reduced volatility in cash flows, lower insurance premiums, improved credit performance	Enhanced resilience screens by lenders and insurers, reduced risk of stranded assets	Reduced compliance and liability costs, better insurance conditions	Lower risk of customer churn, fewer penalties, better performance in ESG screenings	Reduced liability risk, higher likelihood of public support

The result of a BCA is often captured using a benefit-cost ratio (BCR):

- A BCR greater than 1.0 indicates the project likely has more benefits than costs (meaning that the project is likely profitable and beneficial).
- A BCR less than 1.0 indicates more costs than benefits (meaning that the project could be less profitable and beneficial).

The above definitions are a simplification of a complex calculation often used for infrastructure projects with multiple external variables. A higher BCR does not directly correlate with higher benefits: for example, a BCR of 10 is not necessarily ten times more beneficial than a BCR of 1 because there are many underlying and external factors to consider, such as project timelines, uncertainty, risk assumptions, opportunity costs, and benefits that are difficult to monetize (e.g., environmental or social impacts). BCRs are a powerful screening tool used to demonstrate whether resilient investments translate into tangible financial value and provide social or environmental gains. However, they should be interpreted alongside other considerations such as a specific asset's criticality, risk tolerance, and the effectiveness of the adaptation measure. On their own, BCRs do not capture all financial, operational, or strategic factors relevant to investment decisions. Table 5. shows a wide range of BCR examples for adaptation measures.

Table 5. BCR examples for adaptation measures

Adaptation Measure	BCR	Costs and Benefits	Impact
Retrofitted pipe	**800**[ii] $1 → $800	For each $1 invested in a large, retrofitted pipe that has an incremental project cost of 60% of the total project cost, it is expected to produce approximately $800 in benefits.	The retrofitted pipe can greatly increase the capacity of drainage structures and pump stations and delivers extremely high benefits relative to its cost.
Flood wall	**67** $1 → $67	For each $1 invested in a 5-foot flood wall that has an incremental project cost of 79% of the total project cost for a substation, it is expected to produce approximately $67 in benefits.	The flood wall can very effectively protect against extreme weather and other climate risks and delivers high benefits relative to its cost.
Asset elevation	**2** $1 → $2	For each $1 invested in elevating a social infrastructure asset that has an incremental cost of 13% of the total project cost, it is expected to produce approximately $2 in benefits.	Elevating a social infrastructure asset such as a school can slightly improve the adaptation capacity of the asset but may not be the most cost-effective solution to reduce flood risk.

[ii] High BCRs (typically over 100) often reflect targeted measures that preserve existing benefits under specific conditions, rather than comprehensive risk reduction. Measures with lower BCRs may be more appropriate for critical assets or higher-risk contexts where effectiveness, reliability, and residual risk matter more than a higher BCR.

See Appendix B: Overview of Benefit-Cost Analysis Methodologies for more information on other benefit-cost methodologies.

Financial Risk Channels

BCAs are a useful tool for understanding big-picture adaptation costs and benefits and are especially helpful for choosing between different adaptation measures. **However, more detailed financial analyses are typically needed at the project level to determine whether a specific adaptation measure or design approach is profitable for that specific project.** Additionally, most adaptation measures do not eliminate all climate risks, and project-level financial analyses can help sponsors understand financial risk channels and identify appropriate financial instruments to address residual climate risks (see Chapter 6 for more information on financial instruments for adaptation).

This section provides a brief introduction to **financial risk channels**, which are mentioned throughout the discussion of adaptation costs and benefits across sectors (see Section 4.2). Financial risk channels and project-level financial decision-making are then discussed in more detail in Chapter 5. Table 6 defines the key channels through which climate hazards can have financial consequences for sponsors, including through revenue disruption, cost escalation, credit deterioration, and refinancing risk.

Table 6. Financial risk channels

Channel	Definition	Example Triggers	Financial Metric Impact
Revenue Disruption	Operations halted or demand reduced, cutting project income	Flooding closes a toll road in Colombia; drought reduces hydropower output in Brazil	Immediate loss of toll revenue; energy sales fall below Power Purchase Agreement (PPA) commitments; DSCR drops below covenant thresholds
Cost Escalation	Higher repair, maintenance, emergency, or insurance costs	Hurricane damage to transmission and distribution (T&D) infrastructure in Puerto Rico; extreme heat degrades solar panel efficiency in Mexico	Unplanned capital expenditures (CAPEX) for repairs; rising O&M budgets; insurance premiums increase or coverage withdrawn
Credit Deterioration	Weakened debt service coverage, credit metric erosion, rating risk	Repeated drought impacts on water utility revenues in Central America's dry corridor	Rating downgrade risk; covenant breaches; restricted access to capital markets; higher spreads
Refinancing Risk	Greater uncertainty makes refinancing harder or costlier	Sponsors re-price climate-exposed port assets in the Caribbean after successive hurricane seasons	Shorter tenors demanded; higher refinancing spreads; reduced exit valuations; potential stranded assets

Climate hazards affect infrastructure finance through four channels that shape project cash flows. However, these four channels do not operate in isolation. A single hurricane can simultaneously disrupt revenue, escalate costs, deteriorate credit, and worsen refinancing prospects. **Effective financial structuring must address the channels most relevant for a given project, which depend on the sector, revenue model, and residual risk level after adaptation.** The four financial risk channels can erode financial margins, trigger credit deterioration, and increase refinancing risk. These channels highlight the need for financial structures that reflect sector-specific exposure and residual climate risk after adaptation. Understanding severity levels of residual risk (Table 7) is the next important step in assessing the future impacts of climate hazards on infrastructure assets. See Chapter 6 for more information on the financial instrument families available for addressing residual risks.

Table 7. Residual risk tiers and characteristics

Risk level	Low	Moderate	High
Post-Adaptation Climate Exposure	Climate hazards well-managed through adaptation; remaining exposure limited to extreme tail events	Material climate exposure remains; periodic disruptions possible but manageable with financial buffers	Significant unmitigated exposure; adaptation reduces but does not eliminate material risk
Cash Flow Stability	Stable and predictable; DSCR comfortably above covenants under stress scenarios	Generally stable but vulnerable to climate stress; DSCR may approach covenants in severe scenarios	Volatile; DSCR likely to breach covenants in climate stress scenarios without support
Typical Instrument Families	Commercial loans, infrastructure/green bonds, sustainability-linked loans	Partial credit guarantees, subordinated climate funds, contingent financing, parametric insurance	Concessional loans, first-loss capital, grant support, public guarantees, catastrophe insurance backstops
Example	A water utility in a flood-prone area builds flood barriers, backup pumps, and backup power at a treatment plant. After upgrades, the remaining risk is from very rare and extreme floods. Revenues are stable, so this is the kind of project that could usually still be financed with a commercial infrastructure loan or green bond.	A port in the Caribbean raises key electrical equipment and improves drainage, but hurricanes can still force it to shut down temporarily. In most years, the project performs well, but a severe storm season could put pressure on cash flow. In this case, financing might need extra support, such as an MDB loan, parametric insurance, contingent financing, or perhaps concessional debt.	A run-of-river hydropower project in a drought-prone basin improves turbine efficiency and manages sediment, but electricity output still depends heavily on rainfall. That means revenues vary widely from year to year, and in bad years the project may struggle to meet debt service requirements. In that situation, the financing often needs stronger support, such as concessional debt, public guarantees, first-loss capital, or catastrophe backstops.

4.2 Infrastructure Vulnerabilities and Adaptation Costs and Benefits Across Key Sectors

The previous section sets the stage for understanding BCAs and how climate hazards translate into financial impacts. **This section takes this a step further by diving into asset-specific climate impacts and adaptation measures across the following key sectors: transportation, energy, water and sanitation, telecommunications, and social infrastructure.** Sponsors can use this section to understand the main hazards of concern for their assets and begin to develop cost-effective adaptation strategies *(see text box)*.

Developing Cost-Effective Adaptation Strategies

Investors can use this section to answer the following key questions across the five sectors:

01

How do climate hazards impact infrastructure assets and revenue?

02

What measures can be taken to adapt infrastructure assets to climate change?

03

What are the costs and benefits of adapting infrastructure to climate change?

Sponsors are encouraged to jump to the sector or asset type that is most relevant to them after reviewing Section 4.1.

Table 8 shows the asset types and hazards covered in this section. The sensitivity of each asset to the different climate hazards is rated on a scale of low to very high based on the level of impact, where low corresponds to minor damage and limited or no impact on functionality, and very high corresponds to significant damage and/or extended service disruptions. This table is not comprehensive and focuses on the hazards that are most relevant to sponsors.[iii] The sensitivity of each asset is based on the current level of climate risk. When considering specific adaptation measures, it is important to consider how climate risks may change in the future by monitoring risks throughout the project and modifying adaptation measures in response to changing risks as needed.

iii IDB Invest has a more detailed sensitivity matrix that covers other sectors, asset types, and hazards.

Table 8. Climate hazard sensitivity matrix, showing which hazards are most likely to have a significant impact on each asset type

Risk level Low Moderate High Very High

	Extreme Heat	Heavy Precipitation & Inland Flooding	Landslides	Drought	Wildfire	Sea Level Rise & Coastal Hazards	Hurricanes & Extreme Storms
Transportation							
Roads	High	Very High	Very High	High	High	High	Very High
Ports	Moderate	Low	High	High	High	Very High	Very High
Rail	High	High	Very High	Low	High	High	High
Energy							
Hydropower	Low	Very High	Very High	Very High	High	Moderate	High
Solar Farms	Moderate	High	High	Low	High	Moderate	High
Wind Farms	Low	High	High	Low	High	Moderate	High
T&D Infrastructure	High	High	High	Low	High	High	High
Water and Sanitation							
Aboveground Assets (e.g., treatment plants)	High	High	High	Very High	High	High	High
Distribution Pipes	Low	High	High	Moderate	Low	Moderate	Low
Telecommunications							
Data Centers	Moderate	High	High	Moderate	High	Low	High
Cell Towers	High	High	Very High	Low	High	Low	High
Social Infrastructure							
Hospitals and schools	Moderate	Very High	Very High	Low	Very High	High	Very High

Selecting Adaptation Measures

There is a wide range of adaptation measures available to sponsors, from built infrastructure solutions (such as upgrading equipment or elevating assets) to green infrastructure solutions (such as restoring wetlands or installing bioretention ponds) to operational solutions (such as changing shift schedules to avoid the hottest hours of the day). Selecting adaptation measures can be overwhelming, and this section can help sponsors narrow down potential options based on the asset type and climate hazard of concern. However, the effectiveness, costs, and benefits of adaptation measures are highly site- and project-specific. **Sponsors are strongly encouraged to use the economic metrics in this chapter as a foundation for diving into project-level financial decision-making in Chapter 5.**

Planning to implement adaptation measures early in the investment process can protect assets from damage and disruptions associated with climate hazards and can help asset managers avoid revenue losses, as well as increased maintenance and material repair costs. It is crucial that planners choose an adaptation strategy that is well suited to the characteristics of the asset and site in question to ensure adaptation measures are appropriate and cost-effective for the specific project. **Adaptation measures require upfront investment, but, when executed effectively, can yield long-term benefits for sponsors that outweigh the initial costs.**

Approach to Estimating Adaptation Costs and Benefits

There are few studies comparing adaptation measures on a level playing field. Even fewer studies focus on private sector investments in adaptation measures, and private sponsors typically do not publish data on adaptation investments, making it difficult to compare adaptation projects, costs, and benefits.

To address this significant data gap, this section leverages two distinct approaches for estimating adaptation costs and benefits:

1. **Developing Hypothetical Adaptation Projects:** Hypothetical adaptation projects, such as elevating a small road segment versus a large one, were developed to demonstrate how incremental costs and BCRs vary depending on the project scale, as well as the asset type. Appendix C provides a detailed explanation of the tools, inputs, and assumptions used for all hypothetical projects included throughout this section. All hypothetical project costs are in US dollars, adjusted for a Brazil purchasing environment in 2025. Additionally, it is assumed that all hypothetical projects are at high risk from climate hazards, and adaptation measures are implemented as part of a new construction project.[iv]

2. **Reviewing Available Literature on Adaptation Costs and Benefits:** A comprehensive literature review was conducted to supplement data gaps with costs and benefits from real-world projects and studies, with a focus on case studies from LAC.

For each adaptation measure included in this section, an effectiveness rating was determined based on the scale shown in Table 9 below. This scale rates effectiveness based on the asset's **exposure** to the climate hazard. It is important to note that some adaptation measures may not change an asset's exposure but can still be effective at increasing broader resilience or redundancy. For example, installing solar panels or backup generators does not affect an asset's exposure to flooding, but can increase resilience to power outages during flooding events.

iv For all adaptation measures included in this section, the BCR is highly dependent on the asset and site characteristics. Additionally, it is assumed that the adaptation measures are implemented as a component of a new construction project. In most cases, it is not cost-effective to implement these measures as retrofits to an existing asset. The BCR results likely represent the upper limits of the project benefits. This is because the research team assumed that the adaptation measures would be implemented for assets that have high exposure, and that the adaptation measures would be very successful in protecting the asset once implemented. Incremental costs and BCR estimates do not reflect factors such as permitting and availability of qualified labor.

Table 9. Adaptation measure effectiveness rating scale

Adaptation Measure Effectiveness Rating Definitions		
Low	**Moderate**	**High**
Asset remains exposed to the hazard, but the severity of the hazard or its impact has been slightly reduced.	Asset remains somewhat exposed to the hazard, but the severity of the hazard or its impact has been significantly reduced.	The asset is no longer exposed to the hazard.

Transportation

Transportation infrastructure is highly exposed to climate hazards in LAC**.** It is estimated that the transportation sector sustains 25%–50% of total losses caused by natural disasters globally.[101] Because supply chains, trade networks, and labor economies rely heavily on transportation infrastructure, disruptions to these systems can have dramatic economic consequences. *Table 10* summarizes the physical impacts and financial consequences of climate hazards for the transportation sector. As discussed in Chapter 3, sponsors are encouraged to **consider the geo-type of their asset's location** to determine what hazards are most relevant before diving into asset-level vulnerabilities and adaptation measures.

This section focuses on **roads, ports, and rail.** There are a wide range of adaptation measures available to increase the resilience of these assets *(see Table 11)*. **Climate adaptation measures in the transportation sector are almost always a good investment if they are targeted at the areas most at risk, appropriate to the risk, and included early in the planning phase of a project.** There are many low-cost options for infrastructure planners to implement that will increase the resilience of transportation assets in the long term. For example, installing flood sensors to monitor conditions along roads and respond accordingly can increase overall project costs by less than 5%. Additionally, NBS like incorporating porous asphalt or building retention or detention ponds to mitigate flooding hazards can increase overall project costs by less than 5%. Detention ponds in particular have very high returns on investment and low upfront costs, with BCRs between 400 and 8,100, depending on the size of the project. This is likely because they tend to be very effective adaptation measures, reducing damage from floods by 83%.[102]

High-cost options can be valuable for assets that are very vulnerable or have high exposure to a given risk. For example, stabilizing slopes with geosynthetic reinforcement to prevent landslides can increase project costs by over 100%, depending on the size of the asset and site characteristics. However, this type of adaptation measure can have BCRs of over 1,000 if installed properly and can effectively mitigate landslide risks. For critical roadways, such high-cost and high-benefit options can be useful ways to increase the resilience of key transportation systems. *Table 11* summarizes some of the key adaptation options available for transportation infrastructure assets.

Table 10. Climate hazard impacts and financial consequences for transportation

Hazard	Physical Impacts	Financial Channels		Illustrative Financial Consequences
		Primary	Secondary	
Flooding and landslides	Road closures, bridge damage, slope failure, corridor disruption	**Revenue disruption**	Cost escalation	Lower traffic volumes and higher repair, stabilization, and reconstruction costs
Storms and coastal flooding	Damage to ports, airports, coastal roads, and related transport assets	**Cost escalation**	Credit deterioration Revenue disruption	Emergency repair and reconstruction costs; prolonged outages weaken operator finances and interrupt throughput
Drought	Reduced water levels in inland waterways and canal systems	**Revenue disruption**	Credit deterioration	Lower throughput and transit volumes, with resulting revenue losses
Extreme heat	Pavement deterioration, rail stress, and accelerated asset wear	**Cost escalation**	Refinancing risk	Higher maintenance costs and rising long-term lifecycle expenditures
Supply chain disruption following hazard events	Delays across logistics networks and longer travel times	**Revenue disruption**	Cost escalation	Higher logistics costs, delayed deliveries, and wider economic disruption across connected supply chains

Table 11. Illustrative adaptation options for different transportation assets

Hazard	Adaptation Measure	Roads	Ports	Rail
Extreme Heat	Heat-resistant materials	✓	✓	✓
	Shade trees	✓	·	·
	Plant vegetation along rail corridors and implement "green tracks"	·	·	✓
	Rail cooling measures	·	·	✓
Heavy precipitation & flooding (both inland and coastal)	Increasing the capacity of drainage structures and pump stations	✓	✓	·
	Early warning technology/flood sensors	✓	·	·
	Retention or detention ponds	✓	✓	·
	Asset elevation	✓	✓	✓
	Landscape restoration for flood storage (wetland, streams, floodplains)	✓	·	·
	Water-resistant materials	✓	·	·
Sea level rise, hurricanes, and other coastal hazards	Permanent flood barriers	✓	✓	·
	Nature-based shoreline protection	✓	✓	·
Landslides	Slope stabilization	✓	·	✓
Drought	Slope stabilization	✓	·	·
Wildfire	Fire-resistant materials	✓	·	·

Roads

Which Climate Hazards Can Impact Roads?

Extreme heat can cause pavements to buckle, increasing maintenance and material repair costs, or necessitating a full replacement of the asset. These disruptions can have cascading impacts on economies, leading to supply chain disruptions or costing businesses more for gas if trucks need to take alternate, less efficient routes.

Heavy precipitation, inland flooding, and landslides make roads impassable, wash out pavements, or erode embankments. The damages will increase maintenance, repair, and replacement costs. Flooding and landslides most commonly activate the **revenue disruption and cost escalation channels**. Road closures or damaged bridges reduce traffic flows and interrupt logistics networks, while repairs, stabilization works, and reconstruction increase CAPEX and maintenance costs. Transport disruptions also propagate through supply chains by increasing travel times, raising logistics costs, and delaying deliveries.[103]

Drought can destabilize slopes, potentially leading to pavement damage or ground subsidence. Such damages can increase maintenance and repair costs. When heavy rain follows periods of drought, dry soils cannot hold excess water, increasing the risk of landslides and erosion and potentially leading to road closures with cascading economic consequences. Drought provides a clear illustration of the revenue disruption channel in water-dependent transport systems. During the 2023–2024 drought affecting the Panama Canal watershed, reduced water levels limited vessel draft and forced authorities to reduce daily transits from typical levels of around 38 ships to about 24 ships per day, constraining throughput and forcing some vessels to take longer alternative routes.[104]

Example:

Precipitation-driven flooding can disrupt road networks and damage pavements, leading to severe financial impacts due to unexpected replacement and repair costs. In 2010 and 2011, El Niño-driven extreme precipitation in Colombia caused an estimated $1.6 billion in damages to 31,635 km of the country's road infrastructure.[107] In 2015 and 2016, extreme rainfall in Paraguay damaged 40 bridges and 11,000 km of local roads, resulting in $220 million in damages.[108] Precipitation-driven flooding can also disrupt public transportation systems that rely on roads. In Rio de Janeiro, Brazil, bus delays due to heavy rainfall can lead to annual estimated costs between $37 million and $54 million.[109]

Wildfires can impact roads that are not built with fire-resistant materials, increasing repair and maintenance costs and potentially leading to road disruptions with cascading economic consequences. In 2023, wildfires in central and southern Chile led to road closures, including the main road to the city of Quillón.[105]

Sea level rise and coastal hazards can impact exposed roads. Coastal roads can be vulnerable to tidal flooding due to sea level rise, as well as increased coastal erosion. These hazards can lead to increased operating, repair, and maintenance costs and can lead to road closures with cascading economic consequences.

Hurricanes and extreme storms can damage roads by causing flooding, and storm surges can wash out entire segments of roads. Such damage to roads can have costly consequences, increasing repair and replacement costs for asset managers. Impassable roads prevent goods and workers from moving easily, disrupting supply chains and economies. Storms and coastal flooding can also trigger credit deterioration when infrastructure damage or prolonged outages weaken the financial position of transport operators or public infrastructure providers. When reconstruction costs are large relative to available revenues or public budgets, the resulting financial stress can affect debt service capacity and investor confidence.[106]

The dominant **compound climate pathway** for roads is **drought-flood transition.** Extended droughts can weaken road embankments and pavements through thermal stress and soil shrinkage, leaving them susceptible to structural failure when intense precipitation occurs, leading to widespread washouts and connectivity loss.

What Are the Costs and Benefits of Adaptation for Roads?

Table 12 shows adaptation options for roads and the incremental costs and BCRs for **two hypothetical roadway projects:**

1. A **small road project**, defined as an 8-km, two-lane, non-interstate road project. The total cost for a new construction project in Brazil is $3,168,000.

2. A **large road project**, defined as a 16-km-long, two-lane, interstate road project. The total cost for a new construction project in Brazil is $9,680,000.



Table 12. Adaptation measures for roads and cost/benefit information

Adaptation Measure	Effectiveness	Small Project		Large Project	
		Cost as % of Total Project Cost	BCR	Cost as % of Total Project Cost	BCR
Increasing the capacity of drainage structures and pump stations	Medium	• New pipe: 10–20% • Retrofitted pipe: up to 80%	40	• New pipe: 10–20% • Retrofitted pipe: up to 60%	800
Early warning technology/flood sensors	Low	• Flood sensors: <5%	1.4	• Flood sensors: <5%	1.4
Retention or detention ponds	Medium	• Detention ponds: <5%	400	• Detention ponds: <5%	8100
Permanent flood barriers	High	• Seawall: 70–240% • Flood wall: 100–240% • Breakwater: 10–20%	8	• Seawall: 50–160% • Flood wall: 70–215% • Breakwater: 10–20%	200
Asset elevation	High	• New road: 10–20% • Retrofitted road: 20–40%	30	• New road: 10–20% • Retrofitted road: 10–30%	820
Landscape restoration for flood storage (wetlands, streams, floodplains)	Medium	• Revetments: 20–60%	2	• Revetments: 10–40%	45
Nature-based shoreline protection	Medium	• Reef: 10–20% • Beach nourishment: 20–40%	7	• Reef: 5–10% • Beach nourishment: 10–30%	150
Slope stabilization	Medium	• Geosynthetic reinforcement: 25–125%	1600	• Geosynthetic reinforcement: 20–100%	3400
Heat, fire, and water-resistant materials	Medium	• Porous asphalt: <5%	8	• Porous asphalt: 5–10%	45
Shade trees	Low	• Street trees: 5–10%	Between 1 and 10	• Street trees: <5%	Between 1 and 10

Ports

Which Climate Hazards Can Impact Ports?

Coastal hazards are the most significant climate-related risk at seaports, given their position along coastlines. Increased tidal flooding from sea level rise can make portions of a port impassable and damage critical equipment, disrupting operations and halting supply chains. In addition to these operational disruptions, the damage to critical equipment can be costly to repair or may necessitate replacements. A 2023 report estimated that 19 seaports across Latin America that carry 12.8 million tons of goods could experience sea level rise-driven flooding by 2100.[110] The seaports of Cartagena and Barranquilla in Colombia, and of Progreso, Tampico, Altamira, and Lázaro Cárdenas in Mexico could experience average increases in sea level of more than a meter by 2100.[111]

Hurricanes and extreme storms threaten port functioning and infrastructure. Because of their

exposure to coastlines, seaports are especially vulnerable to high winds and storm surges associated with hurricanes, both of which are likely to be exacerbated by climate change and rising sea levels. Because of their importance for local, regional, and international trade markets, weather-driven disruptions can have significant economic consequences.

The dominant **compound climate pathway** for ports is **wind-surge-rainfall.** The combination of high winds, storm surges, and heavy rainfall during tropical cyclones can create immense damage: storm surges erode port foundations and inundate cargo areas, while high winds damage cranes and terminal infrastructure, and heavy rain overwhelms storm drainage, causing significant operational downtime.

Example:

Between 2018 and 2023 at the Port of Itajaí in Brazil, extreme winds and high tides caused 76 instances of disruptions to regular port functioning, leading the port operator to lose an estimated $25,000 and $50,000 for every 24 hours of interrupted time.[112] *Climate-driven disruptions at ports can lead ships to be rerouted, often taking longer and less efficient routes. For a container ship that requires 150 tons of fuel per day, each additional day at sea can cost approximately $75,000.*[113]

What Are the Costs and Benefits of Adaptation for Ports?

This section provides example costs and benefits for port adaptation measures **based on available literature**.

Permanent flood barriers

Effectiveness: **High**

Hazards: Sea level rise and coastal hazards; Hurricanes and extreme storms

Description

Permanent flood barriers are designed to prevent coastal and tidal flooding from inundating port facilities. These structures reduce damage to critical assets, including terminals, storage areas, and access roads, helping maintain port operations during extreme weather events. By limiting flood exposure and erosion, permanent barriers can extend asset lifespans and reduce maintenance and repair costs. They are most effective when designed to account for future sea level rise and changing storm intensity.

Example costs

A 2018 global review of floodproofing measures found that complex flood barriers range from $1.4 million/km to $6 million/km. For developing countries, costs vary between **$0.13 and $0.5 million/km**.[114]

Example benefits

A 2017 feasibility study for a proposed flood protection system in Red Hook, Brooklyn, New York (including flood barriers, roadway elevation, bulkhead reconstruction, and storm system upgrades) found the project had a **BCR of 2.03** because it protected a major portion of a densely populated area against a 10-year coastal storm surge and 1 foot freeboard, which was costly: the total project cost was over $74 million, with over $200 million in total project benefits.[115]

Retention or detention ponds

Effectiveness: **Medium**

Hazards: Sea level rise and coastal hazards | Hurricanes and extreme storms

Description

Retention or detention ponds help ports manage stormwater by storing excess runoff and releasing it gradually after heavy rain. This reduces flooding, erosion, and strain on drainage systems, helping protect cargo areas, access roads, and other critical port assets. Retention ponds can also improve water quality by allowing sediments and pollutants to settle before water is discharged.

Example costs

Drainage improvements made in ports were identified from a comprehensive review of floodproofing climate adaptation measures published in 2018. For example, in Peru, a detention area (373 million cubic meters) cost **$1.9/cubic meter** (2016 CPI adjusted).[116]

Example benefits

Creating detention areas within or next to river networks to reduce peak flows during flood events has been found to have a **BCR of 4.2** because these areas reduce the intensity of flooding, especially as flood hazards increase due to climate change, and protect populations and property**.** Additionally, creating detention areas has been found to reduce economic damage from floods by 83%.[117]

Asset elevation

Effectiveness: **High**

Hazards: Sea level rise and coastal hazards | Hurricanes and extreme storms

Description

Asset elevation protects ports by raising critical infrastructure such as cargo yards and access roads above projected flood and storm-surge levels. This reduces the likelihood and severity of inundation, helping maintain operations during extreme rainfall and sea-level-rise events. By keeping key assets above water, elevation can lower repair costs, extend service life, and support more reliable trade flows. This measure is especially valuable for low-lying or coastal port facilities exposed to frequent or intensifying flooding.

Example costs

The Muelles el Bosque terminal in Cartagena, Colombia, is the fifth largest port in Colombia. An adaptation project planned to finish in 2032 will improve flood resilience at the port. The adaptation portion of the project is estimated to cost **$27.1 million**. Resilience improvements include raising roads that connect port terminals to islands to avoid flooding and sea level rise risks, protecting property from seawater flooding by raising retaining walls, and identifying vulnerable areas around the port.[118]

Example benefits

The 2018 study on port adaptation measures in China discussed above found that raising port elevations has **average effectiveness (score of 0.54)** and a moderate cost because it provides strong but incomplete protection against flooding and sea level rise and requires complex engineering. Raising port elevation can allow water to flow more effectively downhill, increasing drainage efficiency. [119]

Nature-based shoreline protection

Effectiveness: **Medium**

Hazards: Sea level rise and coastal hazards | Hurricanes and extreme storms

Description

Nature-based shoreline protection fortifies port shorelines using living systems such as mangroves, salt marshes, and oyster reefs that absorb wave energy and reduce erosion. These measures help stabilize sediments, buffer storm surge, and protect assets without fully replacing the need for additional hard infrastructure.

Example costs

The Beira Coastal Development Protection Strategy in Mozambique is an initiative that seeks to build resilience to climate hazards, including flooding and extreme storms, through investment in NBS, like dune conservation with a sand suppletion buffer. The total cost of this adaptation option was estimated at **$50.7 million in 2025**.[120]

Example benefits

Dune restoration with a sand suppletion buffer in Mozambique as part of the Beira Coastal Development Protection Strategy was calculated to have a **BCR of 2.6**, as the measure used sand that was easy to acquire from nearby areas to build a simple but effective buffer. By integrating natural and engineered defenses, nature-based shoreline protection can lower long-term maintenance costs and enhance ecological co-benefits, though it requires careful site selection and time to mature. This makes it a moderately effective, medium-cost option that complements other port adaptation measures.[121]

Rail

Which Climate Hazards Can Impact Rail?

Extreme heat can cause rails to buckle and expand, preventing trains from running properly and disrupting the flow of goods and workers across distances. These disruptions can have cascading economic consequences.

Heavy precipitation, inland flooding, and landslides can disrupt rail infrastructure by making railways impassable or rendering rail yards unusable, thus disrupting supply chains and the movement of workers. Flooding and landslides can damage critical equipment, necessitating costly repairs and replacements.

The dominant **compound climate pathways** for rail are **wildfire-landslide** and **drought-flood transition**. Wildfire damage to vegetation on rail corridors leads to slope instability, which is then triggered by intense rainfall into landslides that derail trains and block tracks, while rapid drought-to-flood shifts frequently cause ballast washout and track foundation subsidence.

Example:

If flood hazards were to cause individual railway links to fail in Argentina, the resulting economic impacts could reach up to $4.2 million per day for the Roca railway line in Buenos Aires.[122] A transport report estimated that 23% of railway lines in Brazil are in locations at risk of landslides, with a total asset value of $60.72 billion exposed.[123] Landslides caused by extreme precipitation in the city of Antofagasta, Chile, caused total losses to railway infrastructure estimated at $34 million.[124]

Sea level rise can lead to more frequent tidal flooding for rail infrastructure located close to coasts. Flooding and erosion can render railways impassable and rail yards unusable and can damage critical equipment, increasing repair costs. Rail transfer stations near seaports are especially vulnerable to sea level rise and coastal hazards.

Example:
A 2007 study estimated that if 8% of land is lost due to sea level rise in LAC, $2.6 million per km of rail will be lost by 2080.[125]

What Are the Costs and Benefits of Adaptation for Rail?

This section provides example costs and benefits for rail adaptation measures **based on available literature**.

Plant vegetation along rail corridors and implement "green tracks"

Effectiveness: **Low**

Hazards: Extreme heat | Heavy precipitation | Inland flooding

Description

Planting vegetation along rail corridors and implementing "green tracks" helps railways better withstand extreme heat, heavy precipitation, and inland flooding by using vegetation to cool rails, slow runoff, and stabilize soils. Grass, sedum mats, and other low-height ground cover on or around the track reduce surface temperatures, lowering the risk of thermal expansion and track buckling in hot weather. These green surfaces also capture and slow stormwater, reducing localized flooding and runoff-related erosion on embankments and cuttings. When combined with well-designed drainage and periodic maintenance, vegetation-lined corridors can enhance resilience while providing biodiversity and amenity co-benefits, making them a cost-effective but context-dependent adaptation for many railways.

Example costs

Based on a BCA of low-maintenance green tramway tracks, sedum greenery is estimated to cost **$79–395 per m²**, and maintenance costs are $0.18 per m² (2019).[126]

A new 20-km green tramline corridor with three new trams was built in 2024 in Barcelona, Spain. The tramline included 7,753 m² of green space and 266 trees. Adding greenery helped reduce flooding during heavy rainfall. The total project investment cost was **$68 million**.[127, 128]

Example benefits

A 2022 case study in Georgia, US, found that urban green infrastructure designs (such as green railways) have **a BCR of 13 over 50 years**, potentially because long-term benefits such as reduced flood risk and lowered heat-related service disruptions may exceed the initial installation and maintenance costs.[129]

Rail cooling measures

Hazards: Extreme heat

Effectiveness: **Medium**

Description

Rail cooling measures such as painting rails with light-colored coatings help reduce track temperatures by reflecting more solar radiation, thereby lowering the risk of heat-induced rail buckling and service disruptions. Using continuously welded rail and other mechanical improvements further reduces the tendency of rails to kink or deform under high temperatures.

Example costs

5 km of track in the US is estimated to use 1,500 liters of paint, which is around 300 liters per km of single track. Industrial reflective white paint is approximately $8–20 per liter. In bulk, this could cost $2,400 for each km of track.[130, 131]

A 2011 cost estimation for high-speed rail estimates that building 136 or 141 pounds continuous welded rail with plates, fasteners, and longitudinal restraints on existing cross-ties (does not include grading or structures) typically costs **$400,000 per mile**.[132]

Example benefits

Railway lines in southeast England were painted white, which could reduce rail temperatures by up to 10°C and prevent buckling and kinks.[133] Painting rails is a relatively cheap but highly effective method, especially if applied to critical sections of rail. A 2017 UK study found that the costs of repairing damage associated with buckling events in the UK can be $21,000 (2017 USD) and can take 14 hours to repair. Building tracks with continuous welded rail and other heat-resistant techniques could prevent these costs.

Rail elevation

Hazards: Heavy precipitation and inland flooding

Effectiveness: **High**

Description

Rail elevation protects railway lines by raising tracks, embankments, and associated infrastructure above projected flood and stormwater levels. This reduces the likelihood of inundation, washouts, and debris-related damage during heavy rainfall and inland flooding events.

Example costs

A 2011 cost analysis for high-speed rail in the US estimates that adjusting elevation for railways by building land bridges cost **$3,000 per linear foot**.[136]

Example benefits

A 2025 report found a **BCR of 2** for elevating railways to prevent flooding in Iowa and Missouri, US[137] Elevating rail is an effective, but costly and engineering-heavy adaptation measure, resulting in a lower BCR.

Slope stabilization

Hazards: Heavy precipitation and inland flooding; Landslides

Effectiveness: **Medium**

Description

Slope stabilization protects rail corridors by reinforcing embankments against erosion and landslides caused by heavy rainfall and intense storms. Techniques such as retaining walls, soil nailing, vegetation cover, and proper drainage reduce the risk of slope failure, helping maintain track alignment and service continuity.

Example costs

In a 2002 landslide remediation guide published in the United States, it is estimated that a rock shear key (a structure that reinforces slopes) reinforcing an 800-foot-wide, 60-foot slide would cost **$2–3 million**. Construction costs for pile tieback walls (earth retention systems that anchor soil and rock) are estimated to cost $400–500 per foot for a 4-foot-diameter pile.[134]

Example benefits

Implementing proactive adaptation measures in railways, such as slope stabilization to prevent landslides and rockslides during extreme weather events, can result in a **$0.9 average annual increase in costs** compared to the baseline, while implementing no adaptation measures, which can result in a $11.3 average annual increase in costs relative to the baseline.[135] This is because an initial stabilization project can significantly reduce the risk of disasters, effectively protecting long-term operations.

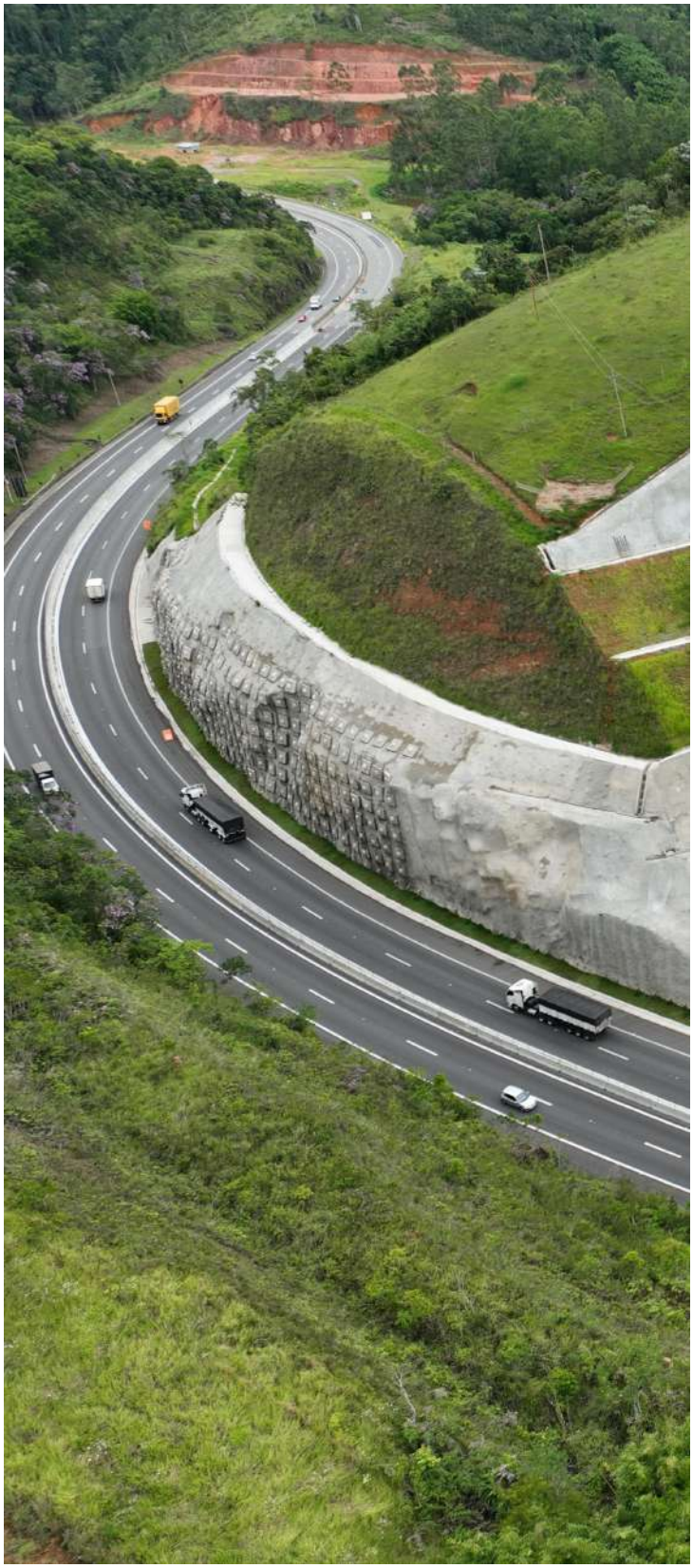


Climate Adaptation Case Study: *Metro São Paulo*

The São Paulo Metro Line 4 Phase III Extension is a $847 million public-private partnership to expand high-capacity urban transit in one of Brazil's most climate-exposed metropolitan regions. The 3.3 km extension was delivered by the State of São Paulo and private company ViQuatro with support from the World Bank. The project incorporates climate risk analysis to develop flood protection, durable materials, thermal management, resilient energy systems, and real-time monitoring technologies for the metro. Adaptation measures represent an estimated incremental cost of $33 million, or around 4% of total infrastructure costs. These investments significantly reduce the likelihood of service disruptions that would otherwise result in revenue losses. Financial risk analysis indicates that avoided climate-related disruptions over the project's planning horizon can offset resilient investments. *See* Appendix A *for more information on this case study.*



Key Takeaways



- Transportation systems across LAC are highly exposed to a wide range of climate hazards, with roads, ports, and rail each facing distinct but interconnected risks that can trigger significant revenue disruption, cost escalation, and broader economic impacts through supply chain interruptions.

- Well-targeted adaptation measures—particularly when integrated early in project planning—can deliver strong economic returns, often at relatively low incremental cost. Highly cost-effective transportation adaptation measures include **asset elevation, slope stabilization, and retention or detention ponds.**

- Prioritizing resilient investments in the **most exposed and economically critical transport assets** is essential for safeguarding long-term mobility, trade, and economic stability in the region.

- Adaptation measures for transportation are almost always more cost-effective when implemented in **new construction projects, rather than as retrofits to existing assets.**

Energy

Across LAC, approximately 60% of the electricity supply comes from renewable resources like hydropower, solar power, and wind power.[138] Some countries in the region are almost entirely dependent on renewables; in Uruguay and Brazil, for example, 91% of electricity is generated using renewable resources, and as of 2023, Paraguay boasts a 100% renewable grid.[139, 140, 141] At a regional scale, LAC has about 97% electricity access, with very large sub-regional variability. Some countries have nearly 100% electricity access, while the Caribbean has a below-average electricity access rate of 83%.[142] Table 13 summarizes the physical impacts and financial consequences of climate hazards for the energy sector. As discussed in Chapter 3, sponsors are encouraged to **consider the geo-type of their asset's location** to determine what hazards are most relevant before diving into asset-level vulnerabilities and adaptation measures.



Table 13. Climate hazard impacts and financial consequences for energy

Hazard	Physical Impacts	Financial Channels		Illustrative Financial Consequences
		Primary	Secondary	
Drought	Reduced reservoir levels and lower hydropower generation	**Revenue disruption**	Credit deterioration Refinancing risk	Lower electricity sales and reduced generation revenues
Hurricanes and storms	Damage to generation plants, substations, transmission lines, and distribution networks	**Cost escalation**	Revenue disruption Credit deterioration	Emergency repair and reconstruction costs; outages interrupt electricity sales
Flooding and landslides	Damage to hydropower facilities, solar farms, substations, and transmission corridors	**Cost escalation**	Revenue disruption	Reconstruction costs and temporary outages
Extreme heat	Lower thermal efficiency, higher cooling needs, equipment stress	**Cost escalation**	Revenue disruption	Higher operating expenditures (OPEX) and reduced generation efficiency
Wildfires and network failures	Transmission disruptions and forced outages	**Cost escalation**	Revenue disruption	Network restoration costs and interrupted power delivery

Energy infrastructure often poses unique challenges in terms of implementing adaptation measures and protecting assets from disruptions for two reasons:

1. Infrastructure networks, like T&D systems, are difficult to protect from site-specific hazards like flooding, due to their distributed nature.

2. The energy sector tends to have strong industry engineering standards, sometimes leaving little room for planners to make changes to designs.

In many cases, energy assets are already designed with climate resilience in mind, given that they are key parts of critical infrastructure systems. **However, it is important that designers and planners take future climate conditions into account, as opposed to looking only at historical climate conditions.** In some instances, designers and planners can leverage local or regional design standards that have been developed specifically with climate change in mind to ensure the resilience of a specific asset.

In addition to hard engineering strategies to strengthen or protect physical assets, there are also a wide range of operational strategies to improve the ability of the energy system and the grid to withstand disruptions. For example, in addition to making poles and distribution lines stronger, operators can install sectionalizing switches. This measure ensures that if a line segment fails during a storm, the disruption does not affect other systems.

Many of the adaptation measures discussed in the following subsections apply to a range of energy assets and are not asset-specific. For example, all energy assets have electrical equipment, which can be vulnerable to overheating under extreme heat conditions. The following sections dive into asset-specific impacts and adaptation measure costs and benefits for transmission and distribution (T&D) infrastructure, solar farms, wind farms, and hydropower. Table 14 summarizes some of the key adaptation options available for energy infrastructure assets.



Table 14. Illustrative adaptation options for different energy assets

Hazard	Adaptation Measure	T&D Infrastructure	Solar Farms	Wind Farms	Hydropower
Extreme heat	Shaded electrical equipment	✓	✓	✓	✓
	Heat-resistant materials and design	✓	✓	✓	✓
	High-temperature low-sag conductor (HTLS)	✓	•	•	•
Heavy precipitation & flooding (both inland and coastal)	Asset elevation	✓	✓	•	•
	Flood walls	✓	✓	•	•
	Dry floodproofing	✓	✓	•	•
	Retention or detention ponds	✓	•	•	•
	Water-resistant materials and design	✓	•	•	✓
	Retention or detention ponds	•	•	•	•
	Flood protection measures	•	•	✓	✓
Sea level rise, hurricanes, and other coastal hazards	Nature-based shoreline protection	✓	✓	✓	•
	Sectionalizing switches[v]	✓	•	•	•
	Undergrounding T&D lines[vi]	✓	•	•	•
	Hurricane safe room	✓	•	•	•
	Hurricane-resilient solar panel design	•	✓	•	•
	Hurricane-resilient wind turbine design	•	•	✓	•
Drought	Operational adjustments to increase frequency of solar panel cleaning	•	✓	•	•
	Reduce water consumption and demand	•	•	•	✓
Wildfire	Fire-resistant materials and design	✓	•	•	•
	Vegetation management	✓	•	•	•
	Defensible space and hazardous fuels reduction	✓	✓	•	•

v This measure can also be used for wildfires.
vi This measure can also be used for wildfires.

All Assets

What Are the Costs and Benefits of Adaptation for Energy Assets?

This section provides example costs and benefits for energy adaptation measures **based on available literature**.

Shaded electrical equipment

Hazards: Extreme heat

Effectiveness: **Medium**

Description

Install electrical equipment in shaded areas (such as below or in the shadow of solar panels) to reduce extreme heat impacts, which can lower operating temperatures and slow insulation and component degradation.

Example costs

Industry sources estimate that moving an electrical panel typically costs around **$1,500–$3,500.** Fuse box relocation costs between **$1,000–$1,500**, moving a breaker box costs up to **$3,500**, and moving a subpanel costs between **$1,000–$3,000**.[143]

Example benefits

Moving electrical equipment and other energy assets into safer, shaded areas can prevent blackouts and power failures, which reduce offline costs. Shading electrical equipment typically has low-to-moderate upfront costs but delivers strong benefits by reducing overheating failures, extending asset life, and avoiding costly downtime.[149]

Flood protection

Hazards: Extreme precipitation and inland flooding; Sea level rise

Effectiveness: **High**

Description

Elevate water-sensitive equipment to withstand flooding, or install flood barriers and implement floodproofing measures, which can keep critical infrastructure above projected flood levels and reduce outage risks.

Example costs

- In New York City, it costs **$41,800** to build a concrete platform to raise a generator.[144]
- In 2009 in Texas, it cost **$825,000** to elevate a substation by 8 feet.[145]
- A 2020 study found that it can cost **$415,000–$2,490,000** to elevate a 50–300 MW solar.[146]
- Flood protection costs vary with the size of the asset and the specific solution. The Menlo Park, Ravenswood Substation total project cost was **$67.6 million**. The cost of the substation is not available but is estimated at between **$35 and $50 million**, making the % of total cost in this case between 1.35 and 1.9 times the total cost.[147]

Example benefits

BCR: 9.1. Flood protection measures typically deliver strong returns because the upfront investment in platforms, barriers, and localized protection is outweighed by avoided outage costs and asset loss, as well as longer asset lives. Protecting energy assets also extends to customer service and revenue protection for utilities, which adds to the potential benefits.[148]

Fire-, water-, and heat-resistant materials and design

Hazards: Wildfire | Extreme precipitation and inland flooding | Extreme heat | Effectiveness: **Medium**

Description

Use materials that can withstand water, fire, and heat conditions to protect critical assets from hazards. Implement design practices to safeguard assets from these hazards.

Example costs

- Southern California Edison's wildfire hardening program installed 4,500 miles of covered conductors, with an estimated cost of $2 billion and $440,000 per mile.[150]
- The UK Environment Agency estimated costs for mobile flood barriers such as geodesigns, which cost $916–$1,037 depending on their size (2006). A mobile dam of 100 m height costs $1,600 (2006). These flood barriers can be used for energy infrastructure.[151]

Example benefits

Using fire-, water-, and heat-resistant materials can help operators avoid costs associated with extreme weather-related disruptions. A US report estimated that weather-related power blackouts cost the US economy **$18–$33 billion** annually. In Canada, outages cost **$8.76 billion** per year. Implementing fire, water, and heat-resistant materials can prevent these outage costs.[152]

Nature-based shoreline management

Hazards: Extreme precipitation and inland flooding | Effectiveness: **High**

Description

Implement nature-based shoreline management practices to protect assets from coastal hazards.

Example costs

In 2008, a coral restoration project in Jamaica (with a coral survival rate over 95%) cost $142 for materials and $350 for permitting, with around 34 hours of labor. This equals $5.96 per coral fragment and **$321,840** per hectare restored.[153]

Between 2011 and 2013, a mangrove restoration project planted 420,000 mangrove seedlings to reduce erosion and buffer coasts. 35 hectares were restored, and the project cost **$20,000** per hectare.

A project in a harbor in Jamaica built seawalls for **$60.7 million** and dikes for **$294.75 million**. Per km, it cost **$5.2 million** for seawalls and $91.6 million for dikes.

Example benefits

A 2021 study found that living shorelines can have a **BCR of 1.82–8.72.** A living shoreline can be highly cost-effective because they require lower long-term maintenance costs than a bulkhead or other barrier, while also providing ecological co-benefits such as improved water quality. Living shorelines also generally have a longer design life than other non-nature-based adaptation measures.[154]



Climate Adaptation Case Study: *Ceará Green Hydrogen Hub*

The Ceará Green Hydrogen Hub is a $175 million climate-resilient energy infrastructure project designed to enable large-scale clean hydrogen production at the Port of Pecém, an export hub in northeastern Brazil. Financed by the World Bank, the Climate Investment Fund, and the port authority, the project contains infrastructure such as climate-resilient utility corridors, port terminal expansion, and pier upgrades. The project addresses key climate risks such as drought and sea level rise that threaten hydrogen production and port operations in the region. Adaptation measures include the use of recycled wastewater for electrolysis and climate-resilient port and coastal engineering to protect infrastructure from climate hazards. Approximately $9 million of project financing is allocated to climate adaptation. BCA demonstrates strong economic viability under a range of climate and market scenarios, with IRRs remaining above the cost of capital even during climate-related disruptions. The project illustrates how incorporating adaptation measures into energy infrastructure can protect long-term returns and benefit private investment in resilient energy systems. See Appendix A for more information on this case study.



Transmission & Distribution

Which Climate Hazards Can Impact T&D Infrastructure?

Extreme heat can impact T&D infrastructure by reducing the efficiency of infrastructure. Some energy is always lost in T&D, but extreme heat combined with inefficient infrastructure and environmental conditions can exacerbate these losses. Every one-degree increase in ambient air temperature above 20°C reduces transmission rates by 0.4%.[155] Extreme heat can exacerbate these losses by further contributing to pre-existing system inefficiencies.

Example:

Some energy is always lost in T&D, but extreme heat combined with inefficient infrastructure and environmental conditions can exacerbate these losses. In 2019, Mexico had one of the highest electricity loss rates in Latin America due to inefficiencies in its built infrastructure, losing 14% of its electricity in T&D.[161] The economic consequences of these losses are stark; in 2019, electricity losses in Mexico cost the country between $656 million and $2.346 billion, representing between 0.05% and 0.18% of GDP.[162] The same year, electricity losses in Latin America cost the region cumulatively between $9.614 billion and $16.564 billion, representing between 0.19% and 0.33% of regional GDP.[163] Extreme heat can exacerbate these losses by further contributing to pre-existing system inefficiencies. In early 2024, 60% of the land area in Mexico experienced a heatwave with temperature anomalies of +3°C or higher compared with normal conditions.[164]

Example:

In 2019, a wildfire overheated one of the main transmission lines that carries power from the Guri Dam in Venezuela, causing a blackout that affected all 23 Venezuelan states and lasted more than five days in most regions.[165] In addition to causing costly damage to critical transmission infrastructure, the blackout had cascading impacts across sectors; at least 26 people died in hospitals where dialysis machines and ventilators failed, public transportation and telecommunications systems collapsed, and most schools and businesses closed.[166] Experts estimated that economic losses associated with the blackout exceeded $875 million.[167]

Wildfires can threaten T&D infrastructure, and T&D infrastructure can be a wildfire risk. For example, wildfires can raise ambient temperatures, leading to transformer explosions that damage power lines and substations and cause widespread power outages.[156] Additionally, power lines can spark wildfires when they come into contact with dry vegetation, or when lines are otherwise damaged.[157] Extreme heat can exacerbate this risk, as power lines sag when exposed to high temperatures. This sagging may cause power lines to come into contact with tree branches and other vegetation, which may be drier under heatwave or **drought** conditions and thus more susceptible to burning.[158]

Hurricanes and extreme storms can also impact T&D infrastructure by damaging power lines and substations due to high winds and flooding.[159] High winds can damage overhead lines and poles, and flooding can damage substations and other critical electrical infrastructure. Hurricane Maria in 2017

knocked down approximately 80% of Puerto Rico's utility poles and all transmission lines, leaving almost the entire island without electricity while contributing to total damages estimated at around $90 billion.[160]

Example:

In 2017, Hurricanes Maria and Irma significantly damaged T&D infrastructure in Puerto Rico, leaving some parts of the island without power for almost a year. The hurricanes impacted 2,478 miles of transmission and subtransmission lines, 48 transmission centers, 31,446 miles of overhead lines, 1,723 miles of underground lines, and 293 substations. The damage to T&D infrastructure alone was estimated at $100 billion.[168]

The dominant compound pathway for T&D infrastructure is **wildfire-landslide events,** which can obstruct corridor access with debris.

What Are the Costs and Benefits of Adaptation for T&D Infrastructure?

Hypothetical Projects: Substations

Table 15 summarizes estimates of incremental costs and BCRs for a range of climate adaptation measures for **two hypothetical substation projects**:

1. A **small substation project**, defined as a 400 sq. ft. compact kiosk or indoor distribution substation that serves 40,000 customers. The estimated total cost for a new construction project in Brazil is approximately $186,000.

2. A **large substation project**, defined as a 30,000 sq. ft. full urban primary distribution substation that serves 300,000 customers. The estimated total cost for a new construction project in Brazil is approximately $18 million.



Table 15. Adaptation measures for substations and cost/benefit information[vii]

Adaptation Measure	Measure Effectiveness	Small Substation Project		Large Substation Project	
		Cost as % of Total Project Cost	BCR	Cost as % of Total Project Cost	BCR
Asset elevation	High	13%	**412**	20%	**63**
Dry floodproofing	Medium	2%	**1925**	1%	**596**
Detention ponds for floodwater diversion and storage	Medium	2%	**3293**	1%	**2530**
Flood wall (5 feet tall)	High	79%	**67**	8%	**160**
Hurricane safe room	Low	6%	**110**	1%	**113**
Defensible space and hazardous fuels reduction for wildfires	Medium	8%	**3**	1%	**6**

vii See Appendix C for more details on the hypothetical project methodology and inputs.

Other T&D Infrastructure Adaptation Measures From the Literature

Other T&D infrastructure includes electrical wires and poles that support electrical networks. Adaptation measures, costs, and benefits for these assets are described below **based on available literature.**

High temperature low sag (HTLS) conductor

Hazards: Extreme heat

Effectiveness: **Medium**

Description Composite-core HTLS conductors sag significantly less than conventional steel-core conductors and can safely transfer up to twice as much power for the same conductor diameter. During extreme heat events, composite-core HTLS conductors can enhance infrastructure resilience and grid reliability by maintaining high power transmission capacity even at elevated operating temperatures.[169]

Example costs

A 2025 grid expansion proposal for India proposed that using HTLS conductors in all planned line expansions would cost **$22 billion**, out of the total grid expansion cost of **$100 billion**.[170]

In India in 2025, adding 64,000 circuit km of HTLS conductors would cost **$14.9 billion**. Adding 55,000 circuit km of 400 kV HTLS conductors would cost **$1.1 billion/year**. Adding 57,000 circuit km of 220/230 kV HTLS conductors would cost **$0.5 billion/year**.[171]

The cost to upgrade one mile of 230 kV transmission lines with new HTLS conductors is approximately **$2,003,125**.[172] 230 kV ACSR conductors cost $1/mile; HTLS conductors cost **$3.60/mile**.[173]

Example benefits

A 2025 study reported that HTLS conductors can have a **BCR of 7.4**. HTLS conductors are recognized for their value in rapid and cost-effective capacity increases that support a wide range of energy uses, including load growth, renewable integration, and addressing congestion.[174]

Higher class poles

Hazards: Extreme heat, Wildfires, Wind

Effectiveness: **Medium**

Description Choosing stronger poles (class 1 versus class 3) when building new transmission or upgrading existing transmission reduces the number of pole failures.

Example costs

A utility report lists a 70-foot class 1 pole costs **$1,845**, and a 70-foot class 3 pole costs **$2,100**.[175]

Example benefits

A 2001 study from the Caribbean Disaster Mitigation Project reported a **0.9–1.25 BCR** for installing higher class poles. The costs can slightly outweigh the benefits of installing higher-class poles because the stronger, more durable materials and heavier construction increase costs, while the avoided damage and outage savings do not always rise proportionally unless the line is highly exposed.[176]

Sectionalizing switches

Hazards: Wildfires | Hurricanes | Other storms

Effectiveness: **Medium**

Description

Installing sectionalizing switches on transmission or distribution feeders can reduce the number of customers interrupted per event, improving resilience to extreme weather.

Example costs

An Alaskan utility implemented automatic feeder switching capabilities in 2014 that allow for sectionalizing, which cost **$333,000**, of which **$308,000** was for hardware and software.[177]

A Kentucky utility spent **$107,000** total to install sectionalizing switches in 2014. The same utility spent $1.32 million total to install sectionalizing switches on a different project around the same time, and **$817,000** of the total cost was for hardware and software.[178]

Example benefits

A 2024 Florida utility estimates that sectionalizing switches are expected to provide a decrease of 40% or more in customer minutes interrupted, accounting for a large portion of the expected total **$1.6 billion in total savings** associated with reduced customer interruption minutes.[179]

Undergrounding T&D lines

Hazards: Extreme heat | Hurricanes | Wildfire

Effectiveness: **High**

Description

Bury T&D lines to reduce vulnerability to hurricanes, winds, and wildfires.

Example costs

Medium-voltage underground distribution costs **$0.3–1.1 million** per mile and up to **$1.8–4.5 million** per mile for more complex settings. Converting overhead transmission lines to underground lines would cost around **$5 million per mile**. Within this, it would cost **$180,000 per mile** to replace single, wood pile transmission lines and **$459,000 per mile** to replace overhead transmission lines that meet current National Electric Safety Code standards as of 2009.[180]

A Pacific Gas and Electric (PG&E) study estimated that undergrounding transmission/distribution lines costs around **$3.75 million per mile**.[181]

Estimates for burying high-voltage transmission lines in different eastern North American locations range from **$1.2 billion to $2.2 billion** in total project costs.[182]

Example benefits

A 2020 study found that undergrounding transmission lines can have a **BCR of 0.3**.[183] Undergrounding T&D lines does not prevent outages and can be more expensive to maintain or repair. Also, the upfront construction costs are extremely high.

Vegetation management

Hazards: Wildfire

Effectiveness: **Medium**

Description Implement vegetation management plans to reduce the risk of wildfire near T&D infrastructure. Work with private landowners who own land adjacent to T&D infrastructure to implement vegetation management plans.[184]

Example costs

The cost of a vegetation management plan ranges depending on environments and utilities from **$1,000 per mile to $42,000 per mile**. For example, groups of utilities in Texas estimate the average cost of vegetation management for distribution costs **$3,000 to $12,000 per mile,** and transmission costs **$300 to $12,000 per mile** (1998–2008). A Florida utility estimates that vegetation management for distribution costs **$11,000 per mile** and transmission costs **$42,000 per mile**.[185]

The average cost of mowing for utility vegetation management is around **$1,379 per acre,** and herbicides cost **$945 per acre**. These costs are expected to decrease over time as vegetation decreases.[186]

Based on a PG&E study, the average per-mile cost for utility vegetation management is **$250,000.** PG&E spent **$400 million per year** on routine vegetation management and tree mortality from 2016–2017, estimated at **$16,000 per mile**.[187]

Example benefits

Mechanical vegetation treatments have been found to have a **BCR of 0.13**, and chemical vegetation treatments have been found to have a **BCR of 0.91**.[188] Although vegetation management is moderately effective at preventing outages, reducing vegetation cannot completely prevent outages from other hazards such as wind, flooding, etc., and operations are typically recurring and labor-intensive, which raises costs.



Solar Farms



Which Climate Hazards Can Impact Solar Farms?

Extreme heat decreases the efficiency of solar panels, posing a risk for solar farms. Every one-degree increase in ambient air temperature above 25°C reduces photovoltaic (PV) energy generation by 0.66%.

Drought can increase the amount of dust in the air and heighten the likelihood of dust storms in arid regions.[189] Guatemala, El Salvador, Belize, Nicaragua, Paraguay, and Uruguay are countries in Latin America that have high intensities of atmospheric dust.[190] A combination of extreme heat and drought can have compounding effects, jointly decreasing the efficiency and output of solar farms.

Example:

Dust coverage on solar panels can reduce power output by more than 1% per day, depending on the characteristics of the dust and the extent of the coverage. In Mexico, studies have found that dust accumulation can lead to $11.60 in losses per month per photovoltaic module.[191]

Hurricanes and other storms can decrease PV generation by 18 to 60% when compared to clear days by obstructing the sun with cloud cover.[192] Solar panels are also vulnerable to damage from high wind speeds and hail during extreme storms.

The dominant **compound climate pathway** for solar farms is combined **heat and drought conditions** that PV efficiency and increase maintenance requirements for cooling and dust management.

What Are the Costs and Benefits of Adaptation for Solar Farms?

Hypothetical Projects: Solar Farms

Table 16 summarizes estimates of BCRs for a range of climate adaptation measures for **two hypothetical solar farm projects**:

1. A **small solar farm project**, defined as a 50 MW PV plant spanning 1 million sq. ft. and serving 175,000 customers. The estimated total cost for a new construction project in Brazil is approximately $37,400,000.

2. A **large solar farm project**, defined as a 300 MW PV plant spanning 6 million sq. ft. and serving 1,050,000 customers. The estimated total cost for a new construction project in Brazil is approximately $197,600,000.

Table 16. Adaptation measures for solar farms and cost/benefit information[viii]

Small Project			
Adaptation Measure	**Measure Effectiveness**	**Cost as % of Total Project Cost**	**BCR**
Asset elevation	High	1%	242
Dry floodproofing	Medium	5%	22
Detention ponds for floodwater diversion and storage	Medium	6%	36
Defensible space and hazardous fuels reduction for wildfires	Medium	2%	5

Large Project			
Adaptation Measure	**Measure Effectiveness**	**Cost as % of Total Project Cost**	**BCR**
Asset elevation	High	1%	581
Dry floodproofing	Medium	6%	67
Detention ponds for floodwater diversion and storage	Medium	5%	100
Defensible space and hazardous fuels reduction for wildfires	Medium	1%	12

Other Solar Farm Adaptation Measures From the Literature

An additional adaptation measure that is solar-specific is **hurricane-resilient solar panel design.** Example costs and benefits for this adaptation measure are included below **based on available literature**.

viii See Appendix C for more details on the hypothetical project methodology and inputs.

Hurricane-resilient solar panel design

Hazards: Hurricanes

Effectiveness: Medium

Description

Implementing hurricane-resilient design features (e.g., modular solar panels, stronger racking, better module fasteners, and adequate anchoring) can reduce damage to solar panels during hurricanes. For microgrids, this could include using reinforced solar frames, placing batteries in secure enclosures, and elevating infrastructure.

Example costs

The average cost to build a 1 MW ground-mounted solar plant with hurricane-resistant materials is **$1,060,000** and **$106,000** for a 100 kW roof-mounted solar plant.

A US study found that hurricane-resilient solar panel designs cost **$1.06/W** for a 1 MW ground mount and **$1.83/W** for a 100 kW roof mount.[193]

Example benefits

A 2020 report found that hurricane-resilient solar panel design can have a **BCR of 2.0–2.6**. Hurricane-resilient solar panel design improves the strength and durability of solar panels and prevents damage from other natural disasters. However, engineering and hardware upgrades can increase capital cost, and hurricane events with catastrophic winds are relatively rare. [194]



Climate Adaptation Case Study: *Remote Area Rural Electrification*

The Remote Area Rural Electrification Program is a $6.7 million investment designed to expand reliable electricity access in rural areas of Honduras through decentralized renewable energy and microgrid systems. The project is financed by IDB Invest and delivers solar PV and renewable microgrids in climate-exposed coastal and rural communities and uses durable materials, drainage, and contingency planning to withstand flooding and extreme storms. Benefit-cost analysis comparing renewable microgrids with diesel alternatives shows strong financial performance, with IRRs exceeding 14% and positive net present values (NPVs) under conservative assumptions. Sensitivity analysis indicates that the projects remain economically viable even with higher construction costs and can support long-term reliability in vulnerable and remote settings. See Appendix A for more information on this case study.



Wind Farms

Which Climate Hazards Can Impact Wind Farms?

Extreme heat can shorten the lifetime of battery cells by disrupting chemical reactions inside the battery, leading to reduced capacity and faster degradation. Heat can also lengthen downtimes for turbines, since some turbines are designed to shut down when temperatures exceed 45°C.[195]

Sea level rise and coastal hazards can impact offshore wind farms and coastal wind farms. Offshore wind farms and coastal wind farms are also vulnerable to damage from storm surges and erosion, both of which are exacerbated by sea level rise.[196]

Hurricanes and extreme storms can impact wind farms. By nature, wind farms are highly sensitive to extreme changes in wind speeds, either from hurricanes and other storms or extended periods of wind drought. Although most wind turbines are engineered to withstand 112-mile-per-hour winds (equivalent to a Category 3 hurricane), high wind speeds and rapid changes in wind direction can damage turbine blades, power systems, and other critical structures.[197, 198] While turbines need winds of at least a certain speed to generate any energy (known as the cut-in speed), winds that are too strong can cause turbines to cease production (known as the cut-out speed). The energy that turbines generate also plateaus at a given wind speed (known as the rated speed, somewhere between the cut-in and cut-out speeds).[199]
All wind farms are vulnerable to lightning strikes during storms.[200]

Example:

Hurricanes can severely damage wind generation infrastructure, leading to costly repairs. For example, Hurricane Maria in 2017 took down all 13 turbines at the Punta Lima wind farm in Puerto Rico, with a total replacement cost of $50 million.[201, 202]

What Are the Costs and Benefits of Adaptation for Wind Farms?

Most wind farms are appropriately sited and designed to ensure wind turbines can withstand extreme weather conditions, and there are strong industry standards in place that sponsors need to adhere to when designing wind turbines.

Therefore, most climate risks are already addressed at the design stage. However, the adaptation measures that apply to all energy assets can still be considered for wind farms, especially for supporting infrastructure or equipment that may be exposed to climate hazards.

An additional adaptation measure that is wind-specific is **hurricane-resilient wind turbine design.** Example costs and benefits for this adaptation measure are included below **based on available literature**.



Hurricane-resilient wind turbine design

Hazards: Hurricanes

Effectiveness: **Medium**

Description

Increasing the design reference wind loading for wind turbines to higher International Electrotechnical Commission (IEC) standards and ensuring that the nacelle can reliably rotate to track changing wind direction can reduce the risk of damage during hurricanes.

Example costs

A National Renewable Energy Laboratory (NREL) concept study for a hurricane-resilient wind plant estimated annual maintenance costs of **$71 million** per year for a hurricane-resilient wind power plant, versus **$62 million** per year for a baseline wind power plant. The overall cost of the hurricane-resilient design (0.04 $/kWh/year) is less than the baseline (0.05 $/kWh/year). The hurricane-resilient plant also produces more net annual energy (2,235,000 MWh/year) than the baseline (1,822,000 MWh/year). Blades for the hurricane-resilient turbine cost **$350/kW** and the tower costs **$353/kW**.[203]

Example benefits

The NREL concept study described above found that hurricane-resilient design innovations, such as downwind configuration and tailored controls, **reduced the levelized cost of energy relative to a conventional IEC-class wind turbine designed for the same site by 21.5%.** This corresponds to a higher NPV of energy for similar or lower capital expenditure for hurricane-resilient wind turbine design. Hurricane-resilient wind turbine design reduces energy costs because turbines can stay online for longer and avoid storm-related failures, which lowers repair costs and keeps energy costs lower over the turbine's lifetime. Flexible, lighter blades and optimized controllers can further reduce energy costs and increase the benefits of resilient wind turbines.[204, 205]

Hydropower

Which Climate Hazards Can Impact Hydropower?

Landslides, driven by **extreme precipitation events,** can damage hydropower infrastructure, threaten operations, and lead to flooding if dams collapse, as was the case in the Rio Grande do Sul floods in Brazil in 2024.[206] At the Ituango hydropower project in Colombia, heavy rainfall and landslides in 2018 forced emergency engineering interventions and resulted in large infrastructure recovery and insurance claims, including billions of dollars in infrastructure losses and profit interruption claims.[207]

Example:

Hydroelectric infrastructure in mountainous regions can be vulnerable to severe damage from landslides. In 2017, a landslide in Peru shut down the Callahuanca hydropower plant.[211] In 2018, the Ituango Dam in Colombia sustained severe damage while it was still under construction following a series of landslides that prevented lake water from draining properly, causing the dam to overtop.[212] The dam, the construction of which was never completed, was valued at $2.8 billion and would have been responsible for generating 17% of Colombia's power.[213]

Drought is the natural hazard with the most significant impact on hydroelectric generation, lowering water levels in the rivers and reservoirs that sustain hydropower plants and thus reducing the rate of electricity production. In LAC, **drought** is particularly important because hydropower accounts for roughly 45% of regional electricity generation, making electricity supply highly sensitive to hydrological conditions.[208] Generally speaking, a 1% decrease in flow results in a 1% decline in energy production.[209] Run-of-river facilities that exploit natural declines in riverbeds are more susceptible to droughts because they are more sensitive to river water levels. In contrast, facilities that store river water in a reservoir can better withstand drought conditions because they are less reliant on river water levels. Rising temperatures may also change patterns of glacial melt, leading to water shortages and disrupting hydroelectric systems.[210] **Extreme heat** can exacerbate drought conditions by increasing evaporation rates.

Example:

45% of LAC's electricity is generated by hydropower.[214] Because of this heavy reliance on hydropower, droughts can have significant consequences for the region's energy systems. In 2001, when about 90% of Brazil's energy came from hydropower, a severe drought forced the government to implement electricity rationing for three-quarters of the population.[215] The economic losses associated with this disruption were estimated at $26 billion, and Brazil's GDP growth rate declined from 4.39% to 1.39% during this time.[216] Brazil is still Latin America's leader in hydroelectric generation, responsible for 55% of the region's installed hydropower capacity, with 80% of its electricity coming from hydropower plants.[217, 218] This story of drought interrupting hydropower infrastructure is not unique to Brazil; other Latin American countries like Ecuador and Venezuela have been forced to ration energy due to pressures on their hydroelectric systems in periods of extreme drought.[219]

The dominant **compound climate pathway** for hydropower is **heat and drought,** as multi-year moisture deficits reduce generation head, while **drought-flood transition** cycles introduce accelerated reservoir sedimentation and operational challenges regarding spillway management and water availability.

What Are the Costs and Benefits of Adaptation for Hydropower?

A unique concern for hydropower is ensuring sufficient water supply for energy production. There are a wide range of water resource management strategies that can be used to optimize water usage, including maximizing power production while preparing for the next drought or flood and reducing water consumption and demand. Although these strategies do not directly protect or strengthen infrastructure against climate hazards, they can help ensure operational continuity during extreme weather events. The table below provides example costs and benefits for reducing water consumption and demand **based on available literature.**

Reduce water consumption and demand

Hazards: Drought

Effectiveness: **Medium**

Description

Implementing demand-side measures to reduce water consumption can increase water availability for power generation. This could include improving irrigation systems, increasing efficiency, or protecting ecosystems.

Example costs

Water demand management programs in California found that it was cost-effective to conserve water when the price of extracting another unit of water is higher than the cost of saving another unit of water. The cost savings of implementing water demand management programs in three major cities in California range from **$1,192–$4,908 per acre-foot**.[220]

The variable production costs of implementing water demand management programs in three major cities in California range from **$67–$1,139 per acre-foot**.[221]

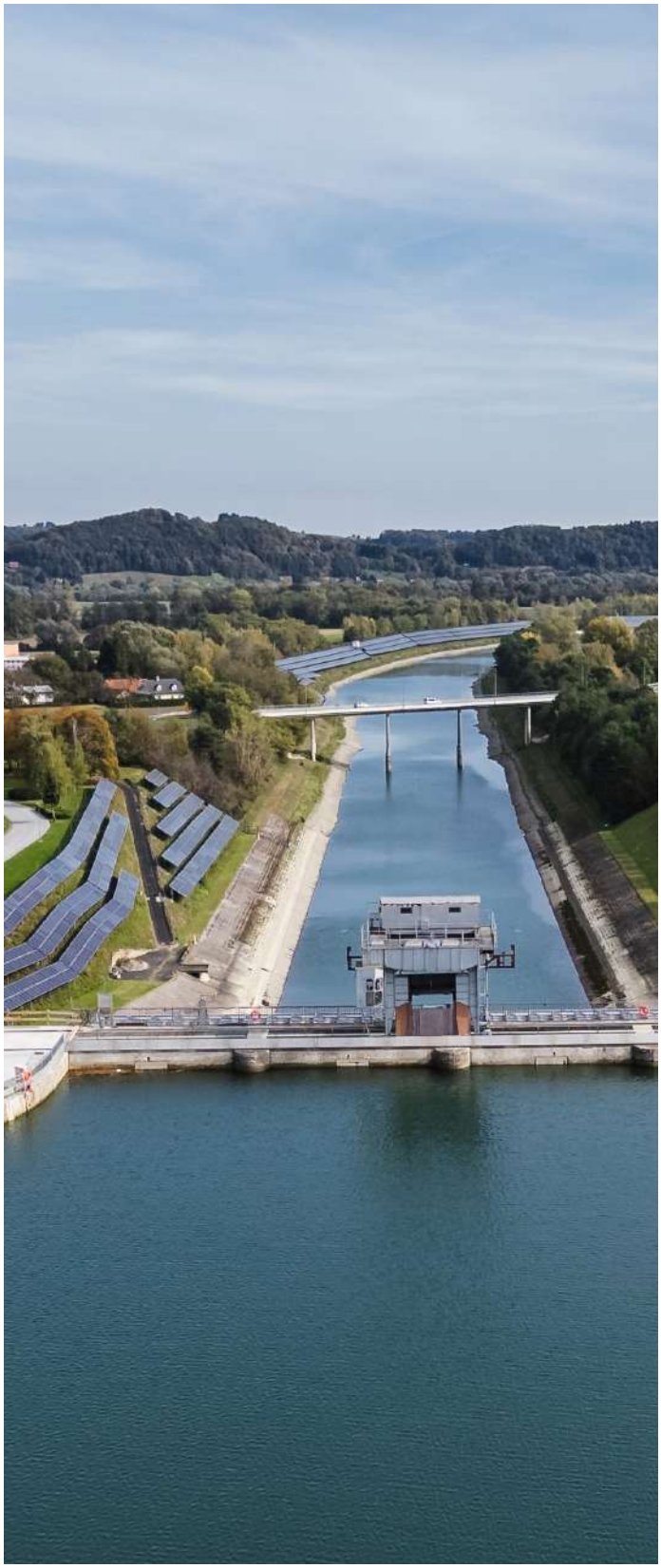
A US water demand management program estimated that the total average savings for a 2,379-square-foot single-family home range from $2,000–$5,000. The program also estimated fees to adjust meter connections, which enhance water efficiency. Across 14–48 US communities, connection fees range from $3,945 for a 1-inch meter size, $53,351 for a 4-inch meter size, and $351,132 for the largest 12-inch meter size.[222]
A 2009 case study on climate change and hydropower in Kenya found that the cost to implement water demand adaptation strategies (improved irrigation and urban water supply, expanding water storage) was a total of **$25.2 million per year**.[223]

Example benefits

Studies report a **BCR of 2.8–5.8** for measures to reduce water consumption and demand. Water demand-reduction measures typically have moderate upfront costs but generate recurring benefits such as lower operating costs. [224]



Key Takeaways



- There is a **wide range of adaptation measures available for energy assets**, and many of the adaptation measures included in this section have a BCR greater than 1 and low incremental costs. Some of the most cost-effective adaptation measures for energy assets like substations and solar farms are **asset elevation, dry floodproofing, and retention or detention ponds for flood storage.**

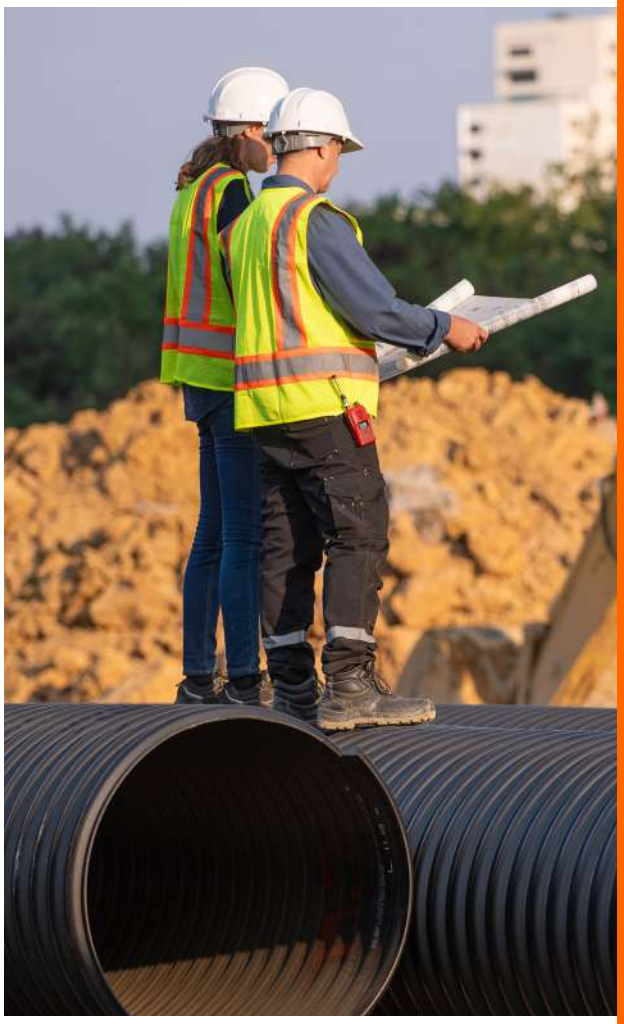
- The energy sector tends to have **strong industry engineering standards**. In many cases, energy assets are already designed with climate resilience in mind, given that they are key parts of critical infrastructure systems. However, developers face limited choices to increase and tailor their adaptation measures to their specific risk profile and appetite.

- **Almost all hard infrastructure measures are significantly more cost-effective if they are incorporated in new construction as opposed to retrofitted solutions.** As a result, it is imperative to develop resilience strategies based on future climate projections instead of past observations.

- Many operational adjustments can play a large role in increasing the resilience of energy assets. For example, modern water resource management strategies can maximize energy output of hydropower assets while reducing drought and flooding risks. Measures to increase redundancy are also often more cost-effective for distributed assets like T&D networks.

Water and Sanitation

Water and sanitation infrastructure encompasses wastewater and drinking water systems, as well as other associated electrical and control infrastructure. Access to clean water and sanitation services is a pressing issue in the region, even without the pressures of climate change. One in four people (approximately 150 million people) in LAC lives in water-scarce areas, and two out of three people lack adequate sanitation services.[225] Between 50% and 80% of wastewater in Latin America does not receive treatment before returning to waterways, and 30% of all rivers in the region are polluted by wastewater or solid waste.[226, 227] A 2016 report estimated that meeting the UN Sustainable Development Goals related to water and sanitation by 2030 in LAC would require approximately $12.208 billion per year in investments in urban areas and $1.841 billion per year in investments in rural areas.[228] Table 17 summarizes the physical impacts and financial consequences of climate hazards for the water and sanitation sector. As discussed in Chapter 3, sponsors are encouraged to **consider the geo-type of their asset's location** to determine what hazards are most relevant before diving into asset-level vulnerabilities and adaptation measures.



Roads, Sewers, and Stormwater Infrastructure

There is often significant overlap between road adaptation projects and wastewater/ stormwater infrastructure projects, especially in coastal and flood-prone cities. For example, projects to elevate roadways almost always require adjustments to sewer inverts, manholes, and pump-station inlets to match and prevent wastewater backups. Additionally, wastewater lift stations and stormwater pump stations are often sited where roads cross low-lying areas or tidal channels. For this reason, projects to enlarge culverts are often bundled with pump-station capacity or elevation upgrades.

When developing adaptation projects, sponsors should consider interdependencies across asset types to ensure projects are comprehensive and cost-effective. Combining road upgrades with wastewater/stormwater improvements in a single project can help minimize construction disruptions and costs.

Table 17. Climate hazard impacts and financial consequences for water and sanitation

Hazard	Physical Impacts	Financial Channels		Illustrative Financial Consequences
		Primary	Secondary	
Drought	Reduced reservoir levels and water availability	Revenue disruption	Cost escalation Credit deterioration	Lower billed consumption and higher pumping or supply costs
Flooding and storms	Damage to pipelines, treatment plants, and sewer systems	Cost escalation	Revenue disruption	Repair costs and temporary service interruption
Sea level rise	Saltwater intrusion into aquifers and surface water	Cost escalation	Revenue disruption	Higher treatment costs and development of alternative sources
Extreme rainfall	Contamination of water sources and sewer overflows	Cost escalation	Revenue disruption	Emergency treatment and cleanup costs

Table 18. Illustrative adaptation options for different water and sanitation assets

Adaptation Measure by Hazard — Drinking Water Assets | Wastewater Assets

Adaptation Measure	Drinking Water Assets	Wastewater Assets
Heavy precipitation & flooding (both inland and coastal)		
Harden infrastructure assets against flooding and other hazards	✓	✓
Conserve and/or restore natural habitats, especially around reservoirs	✓	✓
Implement early warning systems	✓	✓
Asset elevation	✓	✓
Dry floodproofing	✓	✓
Detention ponds		✓
Upgrade WWTPs and increase operating efficiency		✓
Utilize detention structures, grates, and valves to store and redirect excess flow		✓
Flood wall	✓	✓

Adaptation Measure	Drinking Water Assets	Wastewater Assets
Sea level rise, hurricanes, and other coastal hazards		
Harden infrastructure assets against flooding and other hazards	✓	✓
Conserve and/or restore natural habitats, especially around reservoirs	✓	✓
Implement early warning systems	✓	✓
Dry floodproofing	✓	✓
Flood wall	✓	✓
Implement saltwater intrusion barriers	✓	
Hurricane safe room	✓	✓
Pre-storm drawdown and storm flow management		✓
Build desalination plants	✓	

Adaptation Measure	Drinking Water Assets	Wastewater Assets
Drought		
Implement water demand monitoring	✓	✓
Improve leak monitoring and reduce leakage	✓	
Implement Flexi-Emas pumps	✓	
Build desalination plants	✓	
Harvest rainwater	✓	
Construct new reservoirs	✓	
Recharge reservoirs	✓	
Wildfire		
Defensible space and hazardous fuels reduction	✓	✓

Water and sanitation infrastructure, such as WWTPs and desalination plants, host energy-intensive processes and require reliable electricity to operate properly.[229] Hazards such as drought, hurricanes, extreme heat, and wildfire that impact energy systems can thus also impact water and sanitation systems. Adequate water and sanitation infrastructure is the foundation of modern society, and the interdependencies between water and other critical sectors underscore the necessity for a systems-level approach to infrastructure resilience planning in the face of climate change. In the same way that there are strict design standards for energy, for water there are often strict environmental and regulatory standards for water that may drive infrastructure improvements. Table 18 summarizes some of the key adaptation options available for drinking water and wastewater infrastructure assets.

All Assets

What Are the Costs and Benefits of Adaptation for Water and Sanitation Assets?

Adapting water and sanitation assets to climate change largely focuses on preparing infrastructure for the impacts of extreme precipitation and flooding. In particular, hardening and upsizing assets such as pipes and culverts to withstand larger and more frequent climate impacts and protecting assets with barriers and flood walls are key effective measures. This section provides example costs and benefits for water and sanitation adaptation measures **based on available literature**.

Harden infrastructure assets against flooding and other hazards

Hazards: Extreme precipitation and inland flooding | Sea level rise and coastal hazards | Hurricanes and other extreme storms | Effectiveness: **High**

Description

Hard infrastructure measures like floodproofing, upsizing pipes and tanks, and building flood barriers can protect both drinking water and wastewater assets against flooding.

Example costs

The US Economic Development Administration awarded the city of Greenville, NC, **$4.8 million** to construct a flood wall and berm around its WWTP.[230]

The cost of expanding a groundwater storage tank with a new 208,000-gallon capacity in Pennsylvania was **$1.4 million**.[231]

The city of San Francisco has started a project to upsize sewer pipes and boxes to increase flood resilience. The project plans to upsize 2,855 linear feet of sewer pipes and 3,200 linear feet of large box sewers to increase conveyance capacity. The project costs an estimated **$160 million** in total.[232]

The primary water company in Washington, D.C. is constructing a perimeter flood wall to protect one of the largest WWTPs in the world against a 500-year flood event. The total project cost is **$2.4 million**.[233]

Example benefits

In the United States, every $1 million invested in water infrastructure generates **$2.6 million** in economic output, $1.4 million in GDP, and supports ten jobs.[234]

The BCR for building a flood wall and berm around a wastewater plant in Greenville, NC, was **31:1**.[235]

Hardening infrastructure against flooding and other hazards can yield high BCRs because the upfront investment in features such as raised foundations and structural reinforcement prevents potentially catastrophic damage and long-term economic losses to water infrastructure and utilities.

Conserve and/or restore natural habitats, especially around reservoirs

Hazards: Landslides | Hurricanes | Extreme precipitation | Inland flooding

Effectiveness: **Medium**

Description

Reforestation in watersheds and areas around reservoirs can reduce sediment loading by stabilizing soil, slowing runoff, and reducing pollutants. Loss of vegetation also increases water treatment costs by millions of dollars. Managing and conserving watersheds (via integrated watershed management) can increase the adaptive capacity of LAC communities to the risks of climate change affecting water resources. Wetlands, mangroves, and other climate-sensitive coastal habitats act as natural barriers against coastal erosion and can naturally improve water quality. They can also regulate intense flows from flooding/precipitation events by storing runoff and releasing it slowly. Conserving these habitats can make water sources more resilient to climate risks.

Example costs

The cost of reforestation, including establishing nurseries and monitoring in a project scaling up water management practices for vulnerable communities in La Mojana, Colombia, is **$1,650**. The estimated plant density was 2,500 seedlings per hectare.[236]

A project in the Rio Blanco watershed in Ecuador declared priority conservation acres critical for the hydrological cycle as conservation/sustainable use. The improved management of protected forests and private conservation areas (230,000 ha) cost **$108,106** for contractual services, company, and equipment/furniture. An additional 1,000 ha of native vegetation conserved by sustainable forest management and conservation cost **$46,500**.[237]

Conserving 1,000 ha of native vegetation through sustainable forest management and conservation mechanisms in Ecuador, including hiring consultants to identify conservation areas critical for the hydrological cycle and equipment for protecting habitats, cost **$72,000** in 2018.[238]

A project in eastern China installed constructed wetlands near a WWTP to remove nutrients. It cost **$24,012/year** compared to physical upgrades to a WWTP, which cost $65,538/year.[239]

Example benefits

Assisted natural forest regeneration across eight projects in El Salvador, Honduras, and Peru was found to have a **BCR of 1–6.1.** Four tree plantations grown in Peru were shown to have a BCR of 1.7-4. Fourteen sites with agroforestry with annual and/or perennial crops had a **BCR of 1.2–4.3.** Growing and planting trees has a relatively low cost but can have long-lasting positive effects on nearby water sources by improving water quality and protecting the surrounding land from degradation. [240]

The BCR of global mangrove restoration ranges from **6.35 to 15**, demonstrating that these projects can be very cost-effective. Additionally, net gains in ecosystem services value were **$231–$725 billion**. In the Latin American and Caribbean region, many countries have particularly high BCRs, including Ecuador (**138**), Colombia (**75.4**), Costa Rica (**75.4**), and Mexico (**10.6**).[241]

Implement water demand monitoring and early warning systems

Hazards: Drought

Effectiveness: **Medium**

Description

Improve water demand and availability by monitoring and managing water demand by managing prices and using water-saving technology when water supplies are low due to extreme temperatures and droughts. Early warning systems can also be helpful for flood resilience. Under drought/heat stress, conducting stress testing on wastewater treatment biological systems can assess tolerance to heat to prepare for extreme conditions. Monitoring infrastructure integrity regularly will also prevent future costs and protect water supply.

Example costs

The design of two water district plans that incorporated climate information to improve water security in Panama in 2018 cost **$30,000** in 2018. The acquisition and installation of a network of hydro-agro-metrological stations for the plans cost **$1,950,000.**[242]

The cost of upgrading and implementing warning systems for extreme floods in a 2018 integrated water management project in Panama was **$341,000,** including maintenance, installation, and training.[243]

The City of South Bend installed a network of 150 depth/flow sensors and automated smart valves and actuators across its 600-mile wastewater network. The project cost **$7 million** in total and **$280,500** per year to operate and maintain.[244]

Example benefits

A BCA of flood early warning systems implemented in Nepal found that the BCR range from **24 to 73**, depending on the source. Early warning systems can prevent catastrophic loss of life and property, leading to high benefit-cost ratios.[245]

After deploying smart, automated sensors and gates, the city of South Bend saved **$437 million** in avoided capital investment, implying a BCR of **62:1** ($437 million in avoided costs compared with a $7 million system cost). Installing sensors can have high benefits because they reduce maintenance and monitoring costs by identifying blockages that limit sewer capacity, potentially preventing future water losses. [246]

Drinking Water Infrastructure

Which Climate Hazards Can Impact Drinking Water Infrastructure?

Drought can impact drinking water infrastructure by decreasing regional surface-water availability. In a 2023 study conducted by the IDB, 77% of Latin American water operators surveyed reported that reductions in river flow affected their operations.[247] Systems in which more than half of the drinking water is lost before it reaches the end user are also more susceptible to disruptions due to drought. 60% of drinking water produced in Haiti is lost before it reaches the end user due to undetected leaks and infrastructure inefficiencies.[248] In Brazil, the national average drinking water loss rate is about 40%.[249] These leaks and inefficiencies can be exacerbated by climate-driven damage to drinking water infrastructure.



Example:

In 2014–2015, São Paulo, Brazil, faced a severe period of drought, with the São Paulo Cantareira water supply system's storage levels reaching only 5% of capacity in March 2015.[250] A 2023 study found that due to the drought and subsequent lost revenue for water suppliers, the water sector sustained R$528 million in losses during this period.[251] In extreme cases of drought and water unavailability, communities may rely on water delivered by trucks. In Bolivia, water supplied via tanker truck costs four times as much as water delivered via piped water infrastructure, and in Peru it can cost up to 12 times as much.[252]

Extreme heat can exacerbate drought conditions by increasing evaporation rates, causing reservoir, lake, and wetland levels to decrease faster.[253] Communities in mountainous regions often rely on snowmelt and glacial melt for drinking water. As rising temperatures cause more precipitation to fall as rain, rather than snow, and cause glaciers to shrink, more communities are facing disruptions to their water systems.[254] As of 2022, Andean glaciers had retreated 30–50% over the past three decades, threatening drinking water supplies for communities in the region.[255]

Sea level rise contributes to the contamination of underground freshwater aquifers, as seawater penetrates groundwater supplies further inland, a phenomenon known as saltwater intrusion. Globally, the Caribbean is one of the most vulnerable regions to saltwater intrusion, but this phenomenon can impact almost all low-lying, coastal regions.[256] Human-caused water pollution from municipal use, industry, mining, and agriculture exacerbates the consequences of climate hazards for drinking water quality. As of 2022, 25% of rivers, lakes, and aquifers in LAC were polluted due to human activities and mismanagement.[257]

The dominant **compound climate pathway** is the **drought-flood transition**, which challenges system reliability by forcing operators to manage both source water scarcity during dry periods and the rapid influx of contaminated runoff and high sediment loads following intense rainfall.

What Are the Costs and Benefits of Adaptation for Drinking Water Assets?

Hypothetical Projects: Pump Stations

Table 19 summarizes estimates of incremental costs and BCRs for a range of climate adaptation measures for **two hypothetical pump station projects**:

1. A **small pump station** that is a local booster station on a main distribution line in a small town or rural settlement. The pump station is 1,000 sq. ft., has a daily design flow of 0.5 million gallons per day (MGD), and serves 6,000 customers. The estimated total cost for a new construction project in Brazil is approximately $900,000.

2. A **large pump station** that is a major high-service or booster station feeding a large pressure zone in a big city. The pump station is 6,000 sq. ft., has a daily design flow of 20 MGD, and serves 220,000 customers. The estimated total cost for a new construction project in Brazil is approximately $6.5 million.

BCRs for flooding adaptation measures are significantly higher for the large pump station than the small pump station due to the larger number of customers, which significantly increases the total value of the potable water service per day.

Table 19. Adaptation measures for pump stations and cost/benefit information [ix]

Small Pump Station			
Adaptation Measure	**Measure Effectiveness**	**Cost as % of Total Project Cost**	**BCR**
Asset elevation	High	8%	54
Dry floodproofing	Medium	1%	283
Detention ponds for floodwater diversion and storage	Medium	1%	392
Flood wall (5 feet tall)	High	48%	9
Hurricane safe room	Low[x]	1%	143
Defensible space and hazardous fuels reduction for wildfires	Medium	1%	13

Large Pump Station			
Adaptation Measure	**Measure Effectiveness**	**Cost as % of Total Project Cost**	**BCR**
Asset elevation	High	3%	1321
Dry floodproofing	Medium	1%	4281
Detention ponds for floodwater diversion and storage	Medium	1%	4892
Flood wall (5 feet tall)	High	16%	273
Hurricane safe room	Low[x]	1%	117
Defensible space and hazardous fuels reduction for wildfires	Medium	1%	32

Hypothetical Projects: Desalination Plants

Table 20 summarizes estimates of incremental costs and BCRs for a range of climate adaptation measures for **two hypothetical desalination plant projects**:

1. A **small desalination plant** that is a modular seawater or brackish water reverse-osmosis (RO) unit for a small coastal town or rural settlement. The plant is 10,000 sq. ft., has a design flow of 5 MGD, and serves 100,000 customers. The estimated total cost for a new construction project in Brazil is approximately $16 million.

2. A **large desalination plant** that is a large seawater RO plant for a major coastal city. The plant is 50,000 sq. ft., has a daily design flow of 30 MGD, and serves 800,000 customers. The estimated total cost for a new construction project in Brazil is approximately $70 million.

Table 20. Adaptation measures for desalination plants and cost/benefit information [xi]

Small Desalination Plant			
Adaptation Measure	**Measure Effectiveness**	**Cost as % of Total Project Cost**	**BCR**
Asset elevation	High	7%	81
Dry floodproofing	Medium	1%	429
Detention ponds for floodwater diversion and storage	Medium	1%	898
Flood wall (5 feet tall)	High	8%	64
Hurricane safe room	Low[xii]	1%	29
Defensible space and hazardous fuels reduction for wildfires	Medium	1%	49

Large Desalination Plant			
Adaptation Measure	**Measure Effectiveness**	**Cost as % of Total Project Cost**	**BCR**
Asset elevation	High	6%	240
Dry floodproofing	Medium	1%	1511
Detention ponds for floodwater diversion and storage	Medium	1%	2135
Flood wall (5 feet tall)	High	4%	339
Hurricane safe room	Low[xii]	1%	107
Defensible space and hazardous fuels reduction for wildfires	Medium	1%	83

ix See Appendix C for more details on the hypothetical project methodology and inputs.

x This measure is marked as low effectiveness because it does not affect the exposure of the asset to the hazard and only lessens the severity of the impacts of the hazard.

xi See Appendix C for more details on the hypothetical project methodology and inputs.

xii This measure is marked as low effectiveness because it does not affect the exposure of the asset to the hazard and only lessens the severity of the impacts of the hazard.

Other Drinking Water Adaptation Measures From the Literature

Other adaptation measures for drinking water assets and example costs and benefits are described below **based on available literature.**

Recharge aquifers

Hazards: Drought

Effectiveness: **Medium**

Description

Aquifer recharge stores excess water underground to maintain groundwater reserves and serve as a water reserve during droughts.

Example costs

The total capital cost for a managed aquifer recharge (MAR) scheme in Arizona, US, in 2016 was **$11,020,** and the annual operating cost was **$4,309** to recharge 30,800 cubic meters per year. The capital cost per cubic meter recharged was **$0.39,** and the operational cost per cubic meter recharged was **$0.14**.[258]

A 2014 case study in Jamaica examined a facility operating across 68 acres, capable of extracting 73,000 cubic meters of water per day. The project required a construction investment of **$8.6 million**, with relatively modest annual OPEX of **$70,000**. When normalized, the capital cost amounts to **$1.02 per cubic meter of water extracted**.[259]

The median economic cost for MAR projects in California is $410 per acre-foot per year (**$0.33 per cubic meter per year**).[260]

An aquifer storage and recovery facility and a water treatment facility were built in Hilton Head, US. The project cost **$129 million** between 1998 and 2022 and is projected to cost another **$80 million** over the next 20 years.[261]

Flood MAR was implemented in Kings County, CA, to offset groundwater overexploitation in an aquifer. The project captured high flows in a nearby river and flooded 1,000 acres of flood-resistant crops to a 15–30 cm depth. 4 million cubic meters of water were diverted. Costs to capture and apply the flood flows were **$0.03 per cubic meter**, compared to dedicated recharge basins, which cost up to **$0.90 per cubic meter**. The costs to pump groundwater for the project were **$0.05–$0.10 per cubic meter**.[262]

Example benefits

Aquifer recharge yields moderate BCRs because it turns relatively low-cost treated water into long-term storage that avoids expensive options such as new dams or desalination plants. Injection-well schemes have higher BCRs because they achieve faster and deeper storage with smaller-scale infrastructure. Below are examples from infrastructure projects that have implemented different types of aquifer recharge:

Source water MAR schemes **BCR: 2.8 (natural water)**

End-use MAR schemes **BCR: 2.8 (human consumption)**

MAR schemes using injection wells **BCR: 4.4**

MAR schemes using infiltration methods **BCR: 2.3**[263]

Construct new reservoirs

Hazards: Drought

Effectiveness: **Medium**

Description

Construct reservoirs to store water for release during intense droughts.

Example costs

An off-stream reservoir lined with high-density polyethylene, which is the most common reservoir liner, typically costs **$221,000** for 100 acre-feet storage, **$592,000** for 200 acre-feet of storage, and **$466,000** for 300 acre-feet of storage (2001 USD).[264]

The construction of a large reservoir began in 2024 and is planned for completion in 2033. The reservoir will serve 24.5 million people in California. The project includes 1.5 million acre-feet of storage, nine new dams, 12 miles of 9–32 ft pipes, and 20 million cubic yards of material. The total project construction cost is **$2.8 billion**.[265]

The city of Newark, DE, built a reservoir with a capacity of 317 million gallons. The reservoir can provide up to 5 MGD of supplemental water during periods of drought. The reservoir cost **$10 million** to construct and **$1 million** annually for operation and maintenance.[266]

Example benefits

Reservoirs can bring economic benefits. For example, the Newark reservoir generated **$9,856** in economic benefits from air pollution mitigation through tree and shrub absorption and **$103,125** from water pollution mitigation and treating stormwater. Also, the reservoir's construction was found to bring **$5,416,803** in benefits, including increasing residents' willingness to pay higher property taxes and water rates and increasing the number of avoided water purchases, and **$3,013,200** in costs, showing a net positive economic result.[267]

Harvest rainwater

Hazards: Drought

Effectiveness: **Medium**

Description

As part of the effort to decentralize water production, individual or community rainwater harvesting can be an inexpensive and effective way to collect water.

Example costs

An estimate from a project scaling up water management practices for vulnerable communities in La Mojana estimated that building a rainwater harvesting tank costs **$2,679,** including the costs of filters, gutters, and rain catchment.[268]

Example benefits

The BCR of residential rooftop rainwater harvesting has a BCR of 4, and ground surface rainwater harvesting has a **BCR of 14.8**. The BCR for rainwater harvesting is high because it relies on simple, low-cost surface-capture systems that reduce dependence on expensive centralized water supply or groundwater infrastructure. This measure has especially high benefits for developing countries without access to reliable water resources.[269]

Build desalination plants

Hazards: Drought

Effectiveness: **Medium**

Description

Building desalination plants provides a backup/additional water source and can help to decentralize water production to make it more resilient.

Example costs

The Atacama desalination plant in Chile is Latin America's largest desalination plant. It cost a total of **$500 million** in 2018. The plant has a maximum capacity of 2,630 liters of water per second, and it will provide industrial/mining facilities with water.[270]

A desalination plant in Ensenada, Mexico, was built in 2012 and cost over **$50 million**.[271]

Example benefits

A BCA of desalinated seawater in Spain estimated a **BCR of 4.05**, highlighting a positive ROI. However, the costs often outweigh the benefits of building desalination plants, unless they are located in areas without existing groundwater or surface-water storage sources. Usually, the incremental benefits of avoiding water shortages are not large enough to offset high construction and energy expenses.[272]

Implement Flexi-Emas pumps

Hazards: Drought

Effectiveness: **Low**

Description

Flexi-Emas pumps are made of PVC or polyethylene pipes and are easy to construct and adjust to control the pressure and amount of water pumped. These pumps make it easier to extract water from wells with small diameters, increasing access to improved water sources.

Example costs

In the US, a 10-meter Flexi-Emas pump costs **$20–$30,** excluding the borehold tube well.[273]

In Bolivia, the cost of a Flexi-Emas pump is **$21.40**.[274]

Materials for an Emas pump cost **$9–$33** in Uganda.[275]

Example benefits

The cost of materials and manufacturing needed to construct an Emas pump is significantly lower than other traditional pumps, such as the rope pump. The material costs for the Emas pump range from **21 to 60% of the material costs of the rope pump**.[276]

Improve leak monitoring and reduce leakage

Hazards: Drought | Hurricanes

Effectiveness: **Low**

Description

A key concern for drinking water systems is managing leakage, and insufficient monitoring can make it difficult to understand how much water is being lost. Uncontrolled leaks can also make pipes more vulnerable to damage from extreme weather events. For example, uncontrolled leaks cause soil erosion, pipe weakening, and joint failures, all of which can be exacerbated by intense rainfall and extreme heat stress. Improving leakage detection and addressing identified leaks can significantly reduce the amount of water lost from the system. Leakage reduction is a frequently used adaptation measure for water utilities, especially in LAC.

Example costs

The city of Waterbury, CT surveyed its 650 miles of water mains for **$195,000 ($300 per mile)** for leaks using acoustic monitoring. The monitoring revealed 950 acre-feet of leaks, and the value of recovered water losses exceeded the total cost of detection/monitoring.[277]

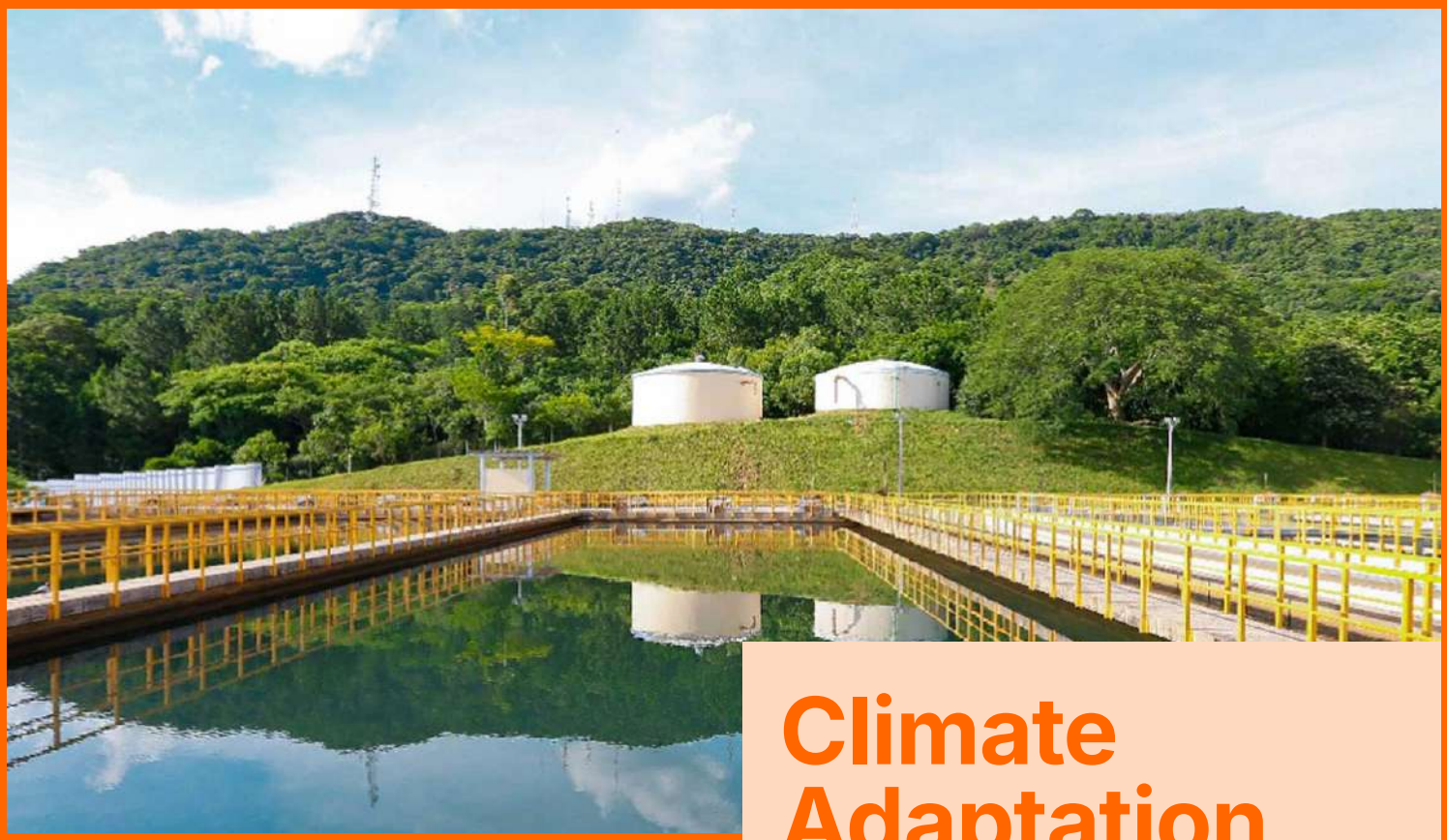
North Miami Beach, FL deployed an acoustic monitoring system (11,000 leak sensors and 38,000 communication modules) across 550 miles of pipeline. The city repaired 23 leaks and saved 27 million gallons of water and **$38,000** annually.[278]

Example benefits

Leakage reduction can decrease the frequency of pipe bursts and emergency repairs, reducing service disruptions and maintenance costs.

A global drought risk study found that reducing leakage is the most cost-effective adaptation action for approximately **60% of utilities and can reduce unsustainable water supply days more cheaply** than building new reservoirs or desalination plants.[279]

The California State Water Resources Control Board estimates that default unit repair costs are **$5,946 per main leak and $2,3330 per service line leak**. If utilities maintain and upgrade aboveground water infrastructure, these costs can be avoided.[280]



Climate Adaptation Case Study: *Corsan Project*

The Corsan Project is a $341 million climate-resilient water and sanitation investment serving approximately 7.3 million people, designed to strengthen service reliability and reduce non-revenue water losses across Rio Grande do Sul, Brazil, and financed by IDB Invest and internally generated operating cash flow. The project combines infrastructure upgrades, automation, remote leak detection, and emergency power supply to reduce water loss rates from 42.4% to 30% by 2033 while expanding sewage coverage and expanding continuity of service during extreme events. Based on 2024 production levels, achieving the target loss reduction would save approximately 77.5 million cubic meters of water annually, translating into estimated annual financial gains of $102–$132 million. This project demonstrates how embedding climate adaptation into utility asset management can deliver strong economic returns while protecting essential services and enhancing financial stability under increasing climate risk. See Appendix A for more information on this case study.



Wastewater Infrastructure

Which Climate Hazards Can Impact Wastewater Infrastructure?

Hurricanes, **heavy precipitation**, and **other storms** can pose threats to the physical infrastructure and operations of wastewater infrastructure. For example, wind from hurricanes can cause blackouts, forcing WWTPs to stop functioning. Because these facilities are generally gravity-fed and therefore located at the lowest point in the area, when operations are disrupted, sewage may be released directly into the nearest river. Flooding from hurricanes, other storms, and other heavy precipitation events can overwhelm pipe infrastructure in areas with combined sewer systems that process both wastewater and stormwater together, leading to the contamination of waterways with untreated sewage discharged without treatment.[281] Extreme rainfall events can also lead to sewer pipe collapse due to erosion and scour. In a 2023 study conducted by IDB, 66% of Latin American water operators surveyed reported that wastewater sewer collapses due to heavy rainfall affected their operations.[282]

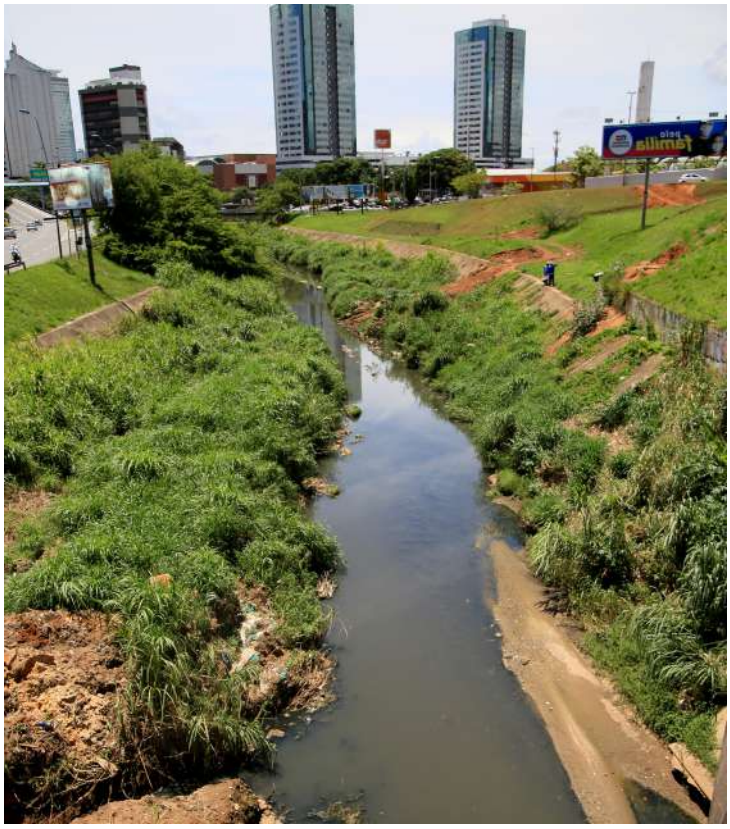


Example:

Hurricanes can cause physical damage to the pipes and infrastructure that support the water and sanitation sector. In 1998, Hurricane Mitch caused $58.0 million in damage to water and sanitation infrastructure in Honduras, where 90% or more of the population lacked access to water services in the hurricane's immediate aftermath.[283] The same hurricane caused $19.8 million in damage to the water and sanitation sector in Nicaragua, $61.1 million in damage to the sector in Guatemala, and $2.4 million in damage to the sector in El Salvador.[284] Following Hurricane Dorian in The Bahamas (2019), the water and sanitation sector recorded approximately $14.8 million in infrastructure damage, $36.6 million in service losses, and $2.3 million in additional operational costs.[285]

Precipitation-driven flooding exacerbates the consequences of inadequate wastewater management systems and strains public health infrastructure. Communities without access to proper sanitation infrastructure may dump raw sewage and trash into rivers, where flood events can spread contaminants like heavy metals, as well as diseases like cholera and leptospirosis.[286] This was the case during the floods in Rio Grande do Sul, Brazil, in 2024, when there were at least 54 confirmed cases of leptospirosis, a disease caused by a waterborne bacteria.[287] In this way, flood events that carry contaminants and diseases can have cascading impacts on social infrastructure like hospitals and health clinics.

The dominant **compound climate pathway** is the **drought-flood transition**, as prolonged dry conditions can increase the concentration of pollutants within the system, while subsequent high-precipitation events frequently overwhelm treatment capacity and trigger overflow risks.



What Are the Costs and Benefits of Adaptation for Wastewater Assets?

Whereas there are a wide range of adaptation measures for drinking water to increase the redundancy of water resources, wastewater adaptation measures focus primarily on hardening infrastructure assets to avoid disruptions during extreme weather events and increase operational efficiency. Additionally, as discussed at the beginning of this section, there is significant overlap between road adaptation measures and wastewater/stormwater improvements.

Hypothetical Projects: Lift Stations

Table 21 summarizes estimates of incremental costs and BCRs for a range of climate adaptation measures for **two hypothetical lift station projects**:

1. A **small lift station** that serves a sub-basin of a town. The station is 1,000 sq. ft., has a design flow of 0.2 MGD, and serves 2,000 customers. The estimated total cost for a new construction project in Brazil is approximately $350,000.

2. A **large lift station** that serves a major urban sewer district sub-basin. The station is 3,600 sq. ft., has a design flow of 10 MGD, and serves 100,000 customers. The estimated total cost for a new construction project in Brazil is approximately $3.15 million.

Table 21. Adaptation measures for lift stations and cost/ benefit information [xiii]

Small Lift Station			
Adaptation Measure	**Measure Effectiveness**	**Cost as % of Total Project Cost**	**BCR**
Asset elevation	High	7%	16
Dry floodproofing	Medium	3%	21
Detention ponds for floodwater diversion and storage	Medium	3%	41
Flood wall (5 feet tall)	High	120%	1
Hurricane safe room	Low[xiv]	1%	107
Defensible space and hazardous fuels reduction for wildfires	Medium	1%	12

Large Lift Station			
Adaptation Measure	**Measure Effectiveness**	**Cost as % of Total Project Cost**	**BCR**
Asset elevation	High	4%	279
Dry floodproofing	Medium	1%	662
Detention ponds for floodwater diversion and storage	Medium	1%	1150
Flood wall (5 feet tall)	High	26%	49
Hurricane safe room	Low[xiv]	1%	114
Defensible space and hazardous fuels reduction for wildfires	Medium	1%	36

xiii See Appendix C for more details on the hypothetical project methodology and inputs.

xiv This measure is marked as low effectiveness because it does not affect the exposure of the asset to the hazard and only lessens the severity of the impacts of the hazard.

xv See Appendix C for more details on the hypothetical project methodology and inputs.

xvi This measure is marked as low effectiveness because it does not affect the exposure of the asset to the hazard and only lessens the severity of the impacts of the hazard.



Hypothetical Projects: Wastewater Treatment Plants

Table 22 summarizes estimates of incremental costs and BCRs for a range of climate adaptation measures for **two hypothetical WWTP projects**:

1. A **small WWTP** located in a small town or rural settlement. The WWTP is 12,000 sq. ft., has a design flow of 1 MGD, and serves 11,000 people. The estimated total cost for a new construction project in Brazil is approximately $4 million.

2. A **large WWTP** located in an urban area. The WWTP is 80,000 sq. ft., has a design flow of 60 MGD, and serves 700,000 people. The estimated total cost for a new construction project in Brazil is approximately $300 million.

Table 22. Adaptation measures for WWTPs and cost/benefit information[xv]

Adaptation Measure	Measure Effectiveness	Small WWTP		Large WWTP	
		Cost as % of Total Project Cost	BCR	Cost as % of Total Project Cost	BCR
Asset elevation	High	8%	14	4%	43
Dry floodproofing	Medium	2%	35	1%	721
Detention ponds for floodwater diversion and storage	Medium	3%	39	1%	553
Flood wall (5 feet tall)	High	35%	3	1%	112
Hurricane safe room	Low[xvi]	1%	143	1%	119
Defensible space and hazardous fuels reduction for wildfires	Medium	1%	32	1%	64



Other Wastewater Adaptation Measures From the Literature

Other adaptation measures for wastewater assets and example costs and benefits are described below **based on available literature.**

Upgrade WWTPs and increase operating efficiency

Hazards: Extreme precipitation and inland flooding | Landslides | Effectiveness: **Medium**

Description

Heavy rain events can increase the risk of flooding, landslides, and turbidity in rivers, which can lead to the collapse or overflow of wastewater systems. Upgrading WWTPs to increase efficiency and operating capacity can help reduce sewer overflows during extreme storm events. WWTP upgrades to improve handling of sewage and process control can also enhance the ability of a plant to manage variable flows during and after storm events. Adding backup power to WWTPs can also help maintain operations during storms and grid disruptions.

Example costs

A basin-scale sanitation program in the Guayas River basin in Guayaquil, Ecuador includes improved wastewater treatment, reuse, and flood-resilient outfall designs. The WWTP improvements include tide gates, conveyance improvements, and elevated pumping. WWTP upgrades cost approximately **$5–10 million per 10–20 MGD plant capacity** increase or rehabilitation.[289, 290]

Chile treats 90% of its wastewater. A national WWTP modernization program aims to increase the resilience of the wastewater system to droughts and flash floods. WWTP improvement projects include adding anaerobic digesters and backup power to reduce disruptions during extreme weather events. Other WWTP upgrades include improving headworks and pretreatment to ensure WWTPs can handle higher-intensity runoff and debris. Upgrades to enhance energy and treatment reliability for midsize WWTPs (10–50 MGD) typically cost **$3–8 million per plant**.[291]

A WWTP modernization project in San Mateo, California, aimed to eliminate sewer overflows into San Francisco Bay, improve resilience to extreme weather, and meet stricter regulatory standards. The project expanded the capacity of the WWTP, upgraded treatment processes, added new storage and conveyance, and improved outfall resilience. The total cost was **$552 million**.[292]

Example benefits

Upgrading WWTPs has been shown to provide significant economic and environmental benefits, while keeping operation and maintenance costs low. WWTP improvements can also reduce the risk of environmental penalties or fines due to sewage overflows. A WWTP improvement project in North Macedonia, funded by the Swedish International Development Agency (SIDA), had a **BCR of 2.11** and positive environmental benefits from the project.[288]

Pre-storm drawdown and storm flow management

Hazards: Extreme precipitation and inland flooding | Hurricanes | Effectiveness: **Medium**

Description

Extreme storm events can overwhelm wastewater collection systems when storage capacity is nearly full before a storm arrives. By utilizing continuous monitoring sensors, weather forecast integration, and automated controls, utilities can proactively draw down water levels in pipes, detention basins, and tanks ahead of a storm and maximize available system capacity. Pre-staging pump stations to begin operating before peak flows arrive further reduces the risk of combined sewer overflows and system backups.

Example costs

A Florida city used Continuous Monitoring and Adaptive Control (CMAC) technology to discharge 70 acre-feet of storage from its lake system before Hurricane Irma, which prevented flooding. The cost was **$200,000.**[293]

Another Florida city is constructing a **$16 million** pump station specifically designed to drain retention ponds, remove stormwater, and redirect it into a nearby river.[294]

Example benefits

The optimization cost for a Florida city's pre-storm drawdown system was **$200,000**, compared to an estimated $8 million the city would have otherwise spent to increase capacity with additional pump stations. This implies a BCR of **40:1.**

Utilize detention structures, gates, and valves to store and redirect excess flow

Hazards: Extreme precipitation and inland flooding | Hurricanes | Effectiveness: **High**

Example costs

The Chicago Deep Tunnel project was the largest underground in-line storage system in the US. The system contains over 109 miles of tunnels and three surface reservoirs with a combined capacity of 17.5 billion gallons of water. This project has cost over $3 billion. One of the reservoirs cost **$40 million,** with an average of **$8.1 million** in maintenance costs.[295]

In Rhode Island, seven underground storage facilities and three deep rock tunnel segments cost **$467 million**. The tanks and tunnels capture sewage overflows during rain events so stored flows can be returned for treatment after the storm.[296]

A city in Virginia constructed a 50-million-gallon underground tank connected to the main sewer line and used weirs to divert flow, which contributed to minimal overflow at 10 CSO outfalls. The total project cost was about **$250 million** over ten years.[297]

Example benefits

The Chicago Deep Tunnel project (mentioned above) has saved the city of Chicago **$250 million** in flood damage reduction benefits, implying a BCR of **6.25.** Benefits such as reductions in sewer overflows by 85% and billions of gallons of stormwater and wastewater captured outweigh the costs of the Chicago Deep Tunnel project, and a similar project in a densely populated area would likely see similar benefits.[298]

Key Takeaways



- BCRs for flood adaptation measures for drinking water assets are **consistently higher for larger projects due to the greater number of customers served**, which significantly increases the total value of uninterrupted potable water service.

- **Relatively low-cost measures, such as dry floodproofing and detention ponds, frequently deliver stronger returns than more capital-intensive interventions** like flood walls, making them particularly attractive options for utilities with limited budgets.

- A **diversified approach**, combining structural protections, alternative water sources such as desalination and rainwater harvesting, and groundwater management strategies like aquifer recharge and saltwater intrusion barriers, offers the most robust protection against the range of climate risks facing drinking water systems today.

- Water infrastructure assets are often tightly linked to one another, and successful adaptation requires a **systems-thinking approach**. For example, many of the water infrastructure assets described in this section require a stable power supply, and there is significant overlap between water assets and other sectors, such as transportation. Effective climate adaptation for water and sanitation requires early and careful planning across multiple locations, organizations, and sectors.

Telecommunications

Telecommunications infrastructure includes assets such as data centers, cell towers, supporting networks, and subsea cables and their associated onshore landing stations. As of 2024, Latin America had 250,000 cell towers, with each tower serving 2,433 people on average.[299] Mobile penetration (the number of mobile connections as a percentage of the total population) was 126% in 2024 in the region.306 As of 2025, 37% of data centers in Latin America were in Brazil, 14% were in Chile, 12% were in Mexico, and 9% were in Colombia.[300] Forecasts estimate that the value of the data sector in Latin America could reach $10 billion by 2029, nearly doubling in value since 2023.[301] Investing in resilient data infrastructure will be critical for ensuring private sponsors capture this value to its fullest potential. Table 23 summarizes the physical impacts and financial consequences of climate hazards for the telecommunications sector. As discussed in Chapter 3, sponsors are encouraged to **consider the geo-type of their asset's location** to determine what hazards are most relevant before diving into asset-level vulnerabilities and adaptation measures.



Energy and Telecommunications: Interconnected Systems

Data centers also have high electricity needs, making them highly dependent on energy infrastructure and sensitive to disruptions in the energy sector. By 2035, data centers could consume 5% of Latin America's electricity. In Chile, energy demand from data centers could increase eightfold between 2025 and 2032. These projections demonstrate the ways in which the energy sector will have to respond to growing demand from data centers and highlight the interconnected nature of critical infrastructure systems.

Given how intertwined these infrastructure systems are, many of the adaptation strategies included in this section are tailored to telecommunications assets but are closely connected to energy systems.





Table 23. Climate hazard impacts and financial consequences for telecommunications

Hazard	Physical Impacts	Financial Channels		Illustrative Financial Consequences
		Primary	Secondary	
Hurricanes and storms	Damage to towers, fiber networks, switching equipment	**Cost escalation**	Revenue disruption	Restoration costs and network outages
Flooding	Damage to underground fiber and switching infrastructure	**Cost escalation**	Revenue disruption	Repair costs and temporary service interruption
Power outages	Shutdown of telecom equipment due to electricity loss	**Revenue disruption**	Cost escalation	Emergency backup power and service interruption
Extreme heat	Equipment stress and cooling system overload	**Cost escalation**	Credit deterioration	Higher OPEX and equipment replacement
Drought	Cooling constraints for water-cooled data centers	**Cost escalation**	Revenue disruption	Increased cooling costs or operational limitations

Most telecommunications adaptation strategies are focused on building redundancy and enhancing reliability. *Table 24* summarizes some of the key adaptation options available for telecommunications infrastructure assets.

Table 24. Illustrative adaptation options for different telecommunications assets

Adaptation Measure by Hazard	Data Centers	Communications Networks
Heavy precipitation & flooding (both inland and coastal)		
Early warning systems	✓	✓
Rainwater drainage systems	✓	
Modular data centers	✓	
Automated failover systems	✓	
Decentralized cloud infrastructure	✓	
Solar-powered data centers	✓	
Robust backup power solutions		✓
Hardening communications lines and improving redundancy		✓
Sea level rise, hurricanes, and other coastal hazards		
Saltwater-resistant materials	✓	✓
Modular data centers	✓	
Automated failover systems	✓	
Decentralized cloud infrastructure	✓	
Solar-powered data centers	✓	
Robust backup power solutions		✓

Adaptation Measure by Hazard	Data Centers	Communications Networks
Drought		
Rainwater storage systems	✓	
Efficient cooling technologies	✓	
Wildfire		
Automated failover systems	✓	
Decentralized cloud infrastructure	✓	
Solar-powered data centers	✓	
Fire-resistant equipment		✓
Localized microgrids		✓
Defensible space	✓	✓



All Assets

What Are the Costs and Benefits of Adaptation for Telecommunication Assets?

It is important for asset managers, designers, and planners to take into account the costs and benefits associated with certain adaptation measures to better protect assets from climate hazards. The following adaptation measures can be applied to all types of telecommunications assets, from data centers to cell towers. Most telecommunications adaptation strategies are focused on building redundancy and enhancing reliability. This section provides example costs and benefits for telecommunications adaptation measures **based on available literature**.

Monitoring and early warning systems

Hazards: Landslides

Effectiveness: **Low**

Description

Implementing climate monitoring systems (such as air quality, heat, or flood sensors) can provide early warning of climate-related events to protect critical telecommunications infrastructure. For landslides in particular, implementing geotechnical and remote-sensing monitoring (Global Navigation Satellite System (GNSS), radar) with automated thresholds can detect slope instability near cell towers to reduce the risk of infrastructure damage.

Example costs

A wireless sensing system for land movement monitoring and landslide detection estimated that land deformation monitoring typically costs **$300,000 per site** and low-cost GPS chips cost $100 per sensor in 2016.[302]

A 20-sensor low-cost network was installed in Virginia to monitor flood inundation. The hardware cost **$2,000 per sensor unit**; operating costs were **$800 per sensor** per year to operate them, and data management cost **$12,500 per year**.[303]
In a low-cost landslide monitoring system, a single base station and rover unit operating for 3 months costs **$1,800**, as of 2019.[304]

A complete landslide monitoring setup can cost between **$50,000 and $500,000**, depending on terrain complexity. Annual maintenance is 15–25% of the initial investment.[305]

The United Nations has spent around **$3.1 billion** between 2023 and 2027 on early warning systems and notifications for climate- and weather-related risks. Spending **$800 million** on early warning systems in developing countries would avoid losses of **$3 billion to $16 billion per year**.[306]

Monitoring and early warning systems (continued)

Example benefits

Overall, the BCRs for early warning measures are relatively high because moderate investments in monitoring, forecasting, and simple sensors can prevent large disaster-related losses. However, benefits are limited by response capacity and local infrastructure/geographical limits.

Using a slope stability risk model reduced the probability of landslide occurrence, and the **benefits outweighed the costs by a ratio of 2.7–1.307**

Researchers have estimated that low-income countries could experience potential benefits with a **BCR ranging from 4 to 35.**[307]

The BCR of improving Multi-Hazard Early Warning System (MHEWS) is **1:9.** For every $1 invested in MHEWS, an average of $9 in net economic benefits can be realized.[308]

The BCR for low-cost flood inundation sensors has been found to be **1.4:1**.[309]

Defensible space for wildfires

Hazards: Wildfires | Drought

Effectiveness: **Medium**

Description

Maintaining a cleared and low-fuel buffer zone by removing vegetation makes wildfires less likely to occur and protects tower structures and telecommunications equipment. This can make cell service more reliable under wildfire risk associated with climate change.

Example costs

Clearing light brush costs **$800–$3,800/ha**.[310]

Clearing moderate brush/small trees costs **$6,000–$10,000/ha**.[311]

Clearing heavy brush/mixed forest costs **$8,000–$15,000/ha**.[312]

Example benefits

Creating defensible spaces will prevent additional firefighting and rebuilding costs if telecommunications infrastructure is damaged or destroyed by a wildfire. For example, in California, for every dollar invested in home hardening (which involves creating a defensible space and using fire-resistant materials), the **total economic activity returned would be about $1.70.** Other research suggests that creating defensible spaces provides up to **$8 in avoided costs** per dollar invested.[313]

Saltwater-resistant materials

Hazards: Sea level rise | Coastal flooding | Hurricanes

Effectiveness: **Medium**

Description

Corrosion-resistant building materials such as stainless/galvanized steel and composite materials can extend asset life and help ensure that telecommunications equipment remains online due to sea level rise and coastal storms due to climate change.

Example costs

Small stainless steel enclosures for telecommunications equipment (such as cabinets) typically cost **$500–$2,000 per unit**. Large stainless steel cabinets at a data center scale can cost **$2,000–$10,000**.[314]

Example benefits

Studies estimate that **25–30% of annual corrosion costs could be saved** if management practices like using saltwater-resistant materials were used because the materials can last longer and potentially withstand more flooding and precipitation.[315]

Data Centers

Which Climate Hazards Can Impact Data Centers?

Drought can impact data centers due to their high water needs to cool their internal systems. Some data centers require two liters of water per kWh of electricity used.[316] Despite this vulnerability, some drought-prone regions are seeing significant data center investments. For example, Santiago de Querétaro, Mexico, was experiencing exceptional drought in 2024 and had 1,000 MW of data center capacity planned.[317]

Other hazards, such as **landslides**, **wildfires**, and **sea level rise,** can affect data centers that are in vulnerable areas. The research team could not identify any publicly reported cases of these hazards impacting data centers in Latin America at the time of writing. This does not mean, however, that these hazards could not impact data centers in the future.

The dominant **compound climate pathway** is the **heat-and-drought** pathway, which limits the availability of water necessary for cooling and reduces the efficiency of air conditioning systems, increasing the risk of thermal shutdowns.

Example:

In some cases, data center sponsors are experiencing regulatory and reputational challenges to building data centers in drought-prone regions. In 2020, Google received permission to develop a $200 million data center in Santiago, Chile. In 2025, however, the Chilean government partially revoked the permits it had previously approved due to local concern over water scarcity.[318]

What Are the Costs and Benefits of Adaptation for Data Centers?

This section provides example costs and benefits for data center adaptation measures **based on available literature**.

Rainwater drainage and storage systems

Hazards: Drought

Effectiveness: **Low**

Description Implement efficient drainage infrastructure to capture, filter, and reuse rainwater for cooling and non-potable uses. This will reduce reliance on central water supplies and improve resilience to water stress and drought.

Example costs

The city of Quincy, WA, and Microsoft partnered on a data center water reuse project in 2021 that has reduced the amount of potable water needed for data center cooling and increased drought resilience. Various water sources were used, including treated industrial wastewater, Columbia River Basin Project water, and municipal reclaimed water. The total project cost was **$31 million**.[319]

Setting up a rainwater harvesting system for a commercial facility similar to a data center typically costs between **$2 and $5 per sq. ft.**, depending on the facility size.[320]

Example benefits

An example of a 2021 UK project that retrofitted a building with sustainable drainage systems provided a net value to the client of $134,006 over a 10-year period, compared with the installation costs of **$52,262**. The ROI was achieved in 3 years.[321]

In some of Google's data centers that have implemented recirculating water multiple times in cooling systems, a **50% reduction in water usage** compared to traditional cooling systems.[322]

Efficient cooling technologies

Hazards: Extreme temperatures

Effectiveness: **Medium**

Description Deploying high-efficiency cooling systems like liquid/immersion cooling or hot/cold aisle containment will reduce energy use and keep equipment safe during high temperatures.

Example costs

A hot-aisle/cold-aisle layout is one of the oldest and best ways to save energy and cool data centers. It works by lining up server racks in alternating rows with cold-air intakes facing each other to form a cold aisle and the hot-air exhausts facing each other to form the hot aisle. The total cost for hot aisle/cold aisle containment is **$125** per linear foot. For example, a 10,000-square-foot facility with 400 racks in 20 rows has an average of 8,682 kW of total facility power consumption and would cost a total of **$110,000**.[323]

Air-side economizers bring cool air from outdoors and distribute it to servers, while hot air from inside is directed outdoors. The design and construction cost of an air-side economizer in California is **$662,000**.[324]

Example benefits

Cooling savings are 10–35% after applying efficient cooling technologies. When hot-aisle/cold-aisle containment is used in combination with variable-speed fan drives, **fan energy usage is reduced by 20–25%, and chiller energy use by 20%**.[325]

Modular data centers

Hazards: Extreme heat | Hurricanes and extreme storms | Wildfires

Effectiveness: **Medium**

Description

Modular data centers are easy to install, relocate, or expand. They can be sited in lower-risk locations and located near renewable energy resources, which also improves resilience to energy disruptions. Modular data centers can deliver capacity within a 3-4-month delivery window, which is more than six times faster than traditional designs.

Example costs

Case studies from a private company, Schneider Electric, published in 2012, estimate that it costs **$10 per watt** to build a modular data center. For individual, containerized facility modules, the cost is expected to be around **$2 per watt**. In London, it costs **$706,500** for 500 kW of power and cooling, which is **$1.8 per watt**.[326]

A 2025 report estimates that each power module for a prefabricated modular data center, which is the most expensive type of modular data center, costs **$750,000–$1 million** per power module, depending on the configuration. Other major types of modular data centers, such as an information technology module, cooling module, and an all-in-one module, cost **$625,000, $499,000, and $466,000**, respectively.[327]

Example benefits

Based on findings from 451 Research, companies could experience a **10–30% savings** on CAPEX from using modular data centers instead of a traditional build. This is because modular data centers have 20% lower construction costs and take less time to build.[328]

Automated failover systems

Hazards: Hurricanes and extreme storms

Effectiveness: **Medium**

Description

Equip data centers with automated failover systems that switch to alternative power sources and networks in case of disruptions.

Example costs

Switched Automatic Transfer Switch (ATS) units distribute power to receptacles from redundant plugs. If the primary power source fails, secondary power sources will take over. One unit with a 100–120 VAC voltage costs **$935;** 240–200 VAC voltage costs **$1,155–$1,430**.[329]

Example benefits

High availability failover systems are a risk-reduction investment. Data center outages can be expensive, with downtime costs reaching around $9,000 per minute, and over **$500,000** per hour. Failover systems prevent or reduce these high costs.[330]

Decentralized cloud infrastructure

Hazards: Hurricanes and extreme storms | Heavy precipitation and inland flooding

Effectiveness: **Medium**

Description

Decentralized cloud infrastructure distributes data center workloads across a network, which reduces points of failure. For example, if one data center is impacted by extreme weather events or flooding, other "nodes" can take over.

Example costs

Virtualization enables data centers to use fewer servers, decreasing energy consumption and making data centers more resilient by reducing reliance on physical servers and infrastructure. Total savings from implementing virtualization (2010) were **$281,366**. 3-year total ownership costs of virtualization were **$205,712**. A data center with virtualization costs **$16,965**, server provisioning costs **$1,980**, and server administration costs **$55,080**.

A study from Cisco estimated that a virtualized server costs around **$2,000** to deploy, compared to $7,000 for a standard physical server with 2 CPUs.[331]

Example benefits

An Energy Star report detailed that virtualization enables the repurposing or removal of existing servers, which can save **$500 annually** in energy costs and **$1,500** in hardware maintenance costs. In a 2010 study, a server upgrade with virtualization led to almost **$150,000** in direct cost savings and more than **$130,000** in indirect cost savings because electricity consumption decreased and reduced the need for additional energy infrastructure.[332]

Solar-powered data centers

Hazards: Hurricanes and extreme storms

Effectiveness: **Medium**

Description

Solar-powered data centers keep up with data centers' high energy demand by providing a reliable, clean, and locally available energy source.

Example costs

The typical costs of solar for large-scale utility projects typically ranged from **$29–$92 per MWh** (2024).[333]

A fuel cell-powered microgrid and data center project in Connecticut cost $1 billion (2020). A data center microgrid with a 340 MW solar farm on 700 acres in Arizona cost **$3 billion** to build.[334]

Example benefits

By incorporating solar panels, data centers can use stored or generated energy during peak hours, which can generate **savings of 15–30%**. An energy company installed a 1.1 MW solar array that offset 94% of a data center's energy usage annually, resulting in a substantial decrease in utility expenses. Demand charges were reduced by 15% to 40%.[335]

Communications Networks

Which Climate Hazards Can Impact Communications Networks?

Extreme heat can disrupt the refrigerated huts at the base of telecommunications towers that house the computers that control cell traffic. On hot days, if these huts cannot stay below a certain temperature, the computers may shut down or fail, disrupting services.[336] Extreme heat can also pose health risks for outdoor workers tasked with maintaining and repairing cell towers.

Sea level rise and other coastal hazards can impact cell towers and communications networks along coasts. Saltwater flooding can corrode metal cell tower structures, and erosion can destabilize the foundations of cell towers and other communications assets.

Example:

Coastal flooding and other coastal hazards can damage communications networks. A 2023 study estimated that a coastal flooding event with a 0.01% annual probability (sometimes referred to as a 1-in-a-100-year flood) could result in approximately $1 million in damages to cell towers in some parts of Brazil by 2080 under a high-emissions scenario (RCP8.5).[337]



Hurricanes and extreme storms can produce high winds that can damage cell towers and can have detrimental impacts on communications networks. In the 2017 hurricane season, 50% of mobile network operators in the Caribbean were directly impacted by hurricanes and associated disruptions and damages.[338]

Example:

Hurricanes Irma and Maria in 2017 damaged 90% of telecommunications infrastructure in Puerto Rico, representing approximately $1.2 billion in damages. For context, in 2017, mobile operators in the Caribbean brought in $5.1 billion in total revenue, meaning the losses just in Puerto Rico from these two hurricanes that occurred over the span of one month were roughly equivalent to the value of 20% of the sector's total revenue generated in one year in the Caribbean.[339] After Hurricane Dorian in The Bahamas in 2019, post-disaster assessments estimated $42.1 million in telecommunications infrastructure damages and $54.4 million in service losses. Many of the losses were linked to the absence of commercial electricity supply and the time required to restore communications networks.[340]



The dominant **compound climate pathway** is the **wildfire-landslide pathway,** as fire-related loss of vegetation along corridor infrastructure can trigger subsequent slope instability that damages towers, physical cabling, and access roads.

What Are the Costs and Benefits of Adaptation for Communications Networks?

This section provides example costs and benefits for communication network adaptation measures **based on available literature**.

Harden communication lines and improve redundancy

Hazards: Hurricanes and extreme storms | Heavy precipitation and inland flooding | Wildfire

Effectiveness: **Medium**

Description

Hardening communications lines can upgrade communications infrastructure with protective design features (e.g., undergrounding, water-resistant cabling, wind- and impact-resistant poles/towers) that are more resilient to extreme weather and other climate-related hazards. Create multiple, redundant network paths that use different physical routes (underground, overhead, satellite) to ensure that if one part of the network is disrupted, services can continue through alternate pathways.

Example costs

The cost of undergrounding broadband line segments can be **$83,160 per mile**.[341]

A 5.5-mile segment of line was buried at a cost of **$11,570 per mile**, or **$57,850 total.**[342]

Satellite backup internet is estimated to cost **$50–$300/month**, and dedicated internet backup is estimated to cost users **$1,000+/month in 2025**.[343]

The cost of underground broadband telecommunication lines is $55,440 more than overhead lines.

Example benefits

Installing underground line infrastructure has a **BCR of 0.3**. Typically, undergrounding lines brings higher BCRs in densely populated areas. The very high capital and construction costs of burying lines are only partially offset by avoided damage and outage costs, especially in areas with lower customer density.[344]

Fire-resistant equipment

Hazards: Wildfire

Effectiveness: **Medium**

Description

Using fire-resistant equipment like cables, enclosures, and support structures can prevent critical communications equipment from going out of service during wildfires and can allow for open communication among emergency management teams.

Example costs

A private company estimates that armored plenum fiber-optic cable costs **$1.6 per foot.**[345]

Example benefits

Using fire- and waterproof telecommunication cabinets reduces the risk of failure and damage to telecommunications equipment from extreme temperatures, humidity, and flooding. Telecommunications cabinets reduce maintenance and repair costs, minimize downtime, and extend equipment lifespan, protecting overall CAPEX.[346]

Robust backup power solutions

Hazards: Hurricanes and extreme storms

Effectiveness: **Medium**

Description

Standby generators and reliable batteries allow communications networks to maintain service during outages caused by climate-related hazards.

Example costs

On average, small (30 kW) natural gas generator units typically cost **$15,000–$25,000**, mid-range 60–100 kW generators cost between **$30,000 and $60,000**, and high-capacity 500 kW generators cost **$100,000–$500,000** or higher.[347]

Example benefits

The average cost of telecommunications network downtime is **$9,000 per minute**. Adding backup power solutions such as generators can prevent or reduce these costs.[348]

Localized microgrids

Hazards: Hurricanes and extreme storms, Wildfire, Extreme heat

Effectiveness: Medium

Description

Installing renewable-powered microgrids around critical communication network areas (e.g., cell towers) allows those areas to operate separately from the main grid during climate-related outages.

Example costs

Estimates from the US Department of Energy indicate that equipment and installation account for **75% of the total microgrid cost**, **construction management accounts for 15%, and design and engineering account for 10%**. On average, US microgrids cost **$2 million–$5 million per MW** to build as of 2024.[349]

NREL estimated that commercial/industrial microgrids cost **$2,470,900–$4,900,100**, utility microgrids cost **$2,323,800–$3,219,800**, and a microgrid controller costs **$6,200/MW-$470,000/MW**, with a mean of **$155,000 (2018).**[350]

Example benefits

Developing renewable microgrids avoids grid capacity charges and upgrade contributions that yield a **20–40% reduction in operating expenses**. Additionally, installing microgrids can make energy supply more resilient by reducing outage risks.[351]

Key Takeaways

Fundamentally different adaptation approaches are required for distributed assets like communication networks as opposed to highly concentrated and expensive assets like data centers:

- **Adaptation measures for distributed assets typically rely on relatively low-cost measures** such as early warning systems, fire-resistant cables, and undergrounding cables. These measures are often paired with a second set of measures that aim to build system-wide redundancy. Maintenance measures such as ensuring defensible space around cell phone towers and data cables can further reduce vulnerability.

- While the demand for new data centers is increasing rapidly, there **is limited data available on the impacts of climate hazards and the effectiveness of adaptation measures for data centers**. Technology is also evolving rapidly. For example, **new cooling technologies** are reducing energy and water demand, increasing the resilience of data centers to drought, heat, and other disruptions to the energy system.

Telecommunications and energy sectors are tightly linked as they both provide services across large areas and often use similar infrastructure (such as cables). Telecommunications assets also rely on a stable power supply. Thus, it is often helpful to think about climate resilience to telecommunications assets alongside the critical energy assets in the area.



Social Infrastructure

IDB Invest defines social infrastructure as the infrastructure of social care, encompassing the health and education sectors.[352] Disruptions to social infrastructure can have cascading economic consequences. In 2024, nearly 30 million students in LAC experienced climate-related school disruptions.[353] The World Bank estimates that every additional year of educational attainment translates to an increase of 9–10% in future income.[354] Disruptions to education systems due to climate change can therefore have long-term economic consequences, perpetuating cycles of poverty and disincentivizing business investment. In 2023, the World Health Organization declared climate change to be the most significant public health challenge of the 21st century.[355] *Table 25* summarizes the physical impacts and financial consequences of climate hazards for the social infrastructure sector. As discussed in Chapter 3, sponsors are encouraged to **consider the geo-type of their asset's location** to determine what hazards are most relevant before diving into asset-level vulnerabilities and adaptation measures.

Table 25. Climate hazard impacts and financial consequences for social infrastructure

Hazard	Physical Impacts	Financial Channels		Illustrative Financial Consequences
		Primary	Secondary	
Extreme heat	Reduced facility efficiency, equipment stress, service disruption (e.g., hospital overload, school closures)	**Cost escalation**	Revenue disruption	Higher energy and cooling OPEX; accelerated equipment replacement CAPEX; reduced service capacity affecting availability payments or performance-based funding
Heavy precipitation & flooding (inland and coastal)	Asset damage, service shutdowns, access disruption for users and staff	**Cost escalation**	Revenue disruption	Emergency repair and reconstruction CAPEX; temporary service interruption; short-term loss or delay of availability-based payments; increased insurance costs
Sea level rise, hurricanes, and coastal hazards	Recurrent storm damage, chronic asset degradation, increased downtime	**Cost escalation**	Credit deterioration	Rising lifecycle CAPEX; increased maintenance frequency; pressure on public budgets or project balance sheets; deterioration of financial ratios and credit profile
Wildfire	Asset damage, smoke-related shutdowns, increased health demand, disruption of supporting systems	**Cost escalation**	Revenue disruption	Repair and replacement CAPEX; surge in operating costs; temporary service interruption; increased insurance premiums and potential coverage constraints

Because health and education infrastructure are supported primarily through buildings (hospitals, health clinics, schools, and universities), most of the adaptation measures relevant to this sector are centered on hardening buildings against hazards, such as by elevating critical equipment to protect against flooding or installing hurricane-safe rooms. Sponsors can draw on international standards and certifications,

such as the Building Resilience Index, the Building Research Establishment Environmental Assessment Method (BREEAM), and Excellence in Design for Greater Efficiencies (EDGE) green building certification, to systemically assess, tier, and signal resilience and sustainability performance across social infrastructure assets.[356], [357], [358] These frameworks provide standardized metrics and checklists and a verified structure for social infrastructure projects. Table 26 summarizes some of the key adaptation options available for social infrastructure assets.

Table 26. Illustrative adaptation options for social infrastructure assets

Hazard	Adaptation Measure
Extreme heat	Window ventilation system, fans, or other cooling systems
	Solar panel system
Heavy precipitation & flooding (both inland and coastal)	Building or asset elevation
	Flood wall
	Dry floodproofing
	Detention ponds for floodwater diversion and storage
	Nature-based flooding solutions
Sea level rise, hurricanes, and other coastal hazards	Wind-resilient building shape and roof design
	Hurricane safe room
	Solar system
Wildfire	Fire-resistant materials and design
	Defensible space and hazardous fuels reduction

Which Climate Hazards Can Impact Social Infrastructure?

Heavy precipitation and flooding can damage the physical infrastructure of hospitals and health clinics and can drive public health challenges that stress already fragile healthcare systems. Across Latin America, an estimated 70% of hospitals are in areas that are highly susceptible to flooding, earthquakes, or hurricanes.[359] In Colombia, 20% of health facilities are exposed to flooding.[360] Hazards such as extreme heat and heavy precipitation can overlap, exacerbating other health risks, like mosquito-borne diseases. Environmental suitability for dengue transmission in Latin America has increased by 35% over the past decade due to rising average temperatures and more frequent extreme precipitation events.[361] During the 1997–1998 El Niño flooding season, Peru, Ecuador, Argentina, and Uruguay saw a 200% increase in hospital admissions for children with diarrhea, as compared to the previous five years, due to an increase in disease transmission correlated with flooding conditions.[362] Heavy precipitation and

inland flooding can damage school buildings and can make students' routes to school unsafe, leading to extended periods of school closures.[363] In Brazil, flooding was the leading cause of climate-related educational disruptions in 2024.[364]

Example:

Heavy precipitation and flooding can damage the physical structure of health clinics and hospitals, leading to costly replacement and repair needs. In 2017, El Niño-driven flooding in Peru caused $413 million in damages to the health sector and $819 million in damages to the education sector.[365] Hazards such as extreme heat and heavy precipitation can overlap, exacerbating other health risks, like mosquito-borne diseases, and stressing an already vulnerable health care system. A 2018 study estimated that in Brazil alone, annual costs associated with dengue transmission were approximately $1.4 billion, mostly due to health care OPEX and loss of worker productivity.[366]

Sea level rise and coastal hazards can threaten the physical infrastructure of hospitals and schools through flooding and erosion. Building hospitals and schools to withstand these disruptions is vital to ensuring the success of investments in the region's social infrastructure. Coastal exposure is material for the health sector; the United Nations Population Fund reported in 2024 that 41 million people in LAC live in low-elevation coastal areas exposed to storms and flooding, placing 1,448 hospitals at significant risk.[368]

Wildfires can damage the physical structures of hospitals in exposed areas, necessitating costly repairs and equipment replacements. This hazard can also have negative public health consequences, increasing the risk of cardiovascular and respiratory illnesses and compounding existing chronic conditions, thus increasing OPEX for hospitals and health clinics.[369] The increasing severity and frequency of public health crises as a result of climate change are placing more demand on the region's health systems, increasing demand for hospital beds, respirators, medication, and other critical equipment and resources.

Example:

As wildfires become more frequent and severe across the region, more people are exposed to poor air quality as a result, increasing risks of cardiovascular and respiratory illnesses, as well as exacerbating existing chronic conditions. Such exposures come with serious consequences for health care sector spending; one study estimated that wildfires in Brazil between January and August 2024 cost the health care sector $14.6 million.[367]

Hurricanes and extreme storms can damage the physical structures of hospitals and health clinics due to flooding and high wind speeds. An estimated 70% of hospitals are in areas that are highly susceptible to flooding, earthquakes, or hurricanes.[370] In 2025, an estimated 477,000 pupils experienced disrupted schooling due to damaged or closed schools in Cuba, Haiti, and Jamaica following Hurricane Melissa.[371] After

Hurricane Dorian in The Bahamas, damage to the education sector was estimated at $72.4 million, while damage to the health sector was estimated at $37.7 million.[373] In Colombia's 2010–2011 La Niña emergency, 3,083 educational institutions and 13,225 classrooms were affected, nearly 800,000 students were left without classes or faced disruptions in educational services, and 14 educational centers plus 119 classrooms were used as temporary shelters.[374]

Extreme heat can have direct negative impacts on public health outcomes, further stressing the region's already vulnerable health infrastructure and increasing OPEX. Researchers have found that the number of yearly hospitalizations could increase under climate change due to the negative consequences of extreme heat on health. As previous health crises like the COVID-19 pandemic have shown, increases in hospitalization rates can stress health care systems by increasing demand for hospital beds and other resources. On June 5, 2024, the Mexican Health Ministry reported 90 heat-related deaths as the result of a record-breaking heatwave in Mexico City.[375] Extreme heat also poses a threat to educational infrastructure by creating uncomfortable or unsafe indoor conditions. School buildings that do not have proper air conditioning or ventilation can become uncomfortably or dangerously hot during extreme heat events, inhibiting students' ability to learn or even leading to school closures. In 2024, extreme heat was the leading cause of climate-driven school disruptions globally.[376]



Example:

Exposure to extreme heat can have negative health consequences, further stressing Latin America's already vulnerable health care system. In Latin American countries, there was an average 140% increase in heat-related deaths between 2013 and 2022, as compared with the period from 2000 to 2019. These deaths can have negative economic consequences, straining health care systems and negatively affecting workforces. A 2025 study found that heat-related deaths in three study sites in Brazil between 2004 and 2018 represented a cumulative burden of $60.3 billion.[372]

Many **compound climate pathways** could impact social infrastructure assets, but the **dominant pathways** are the **heat and drought** and **wildfire-landslide** pathways. Combining heat and drought can strain facility operations by increasing cooling and water demand while simultaneously elevating the prevalence of heat-sensitive public health issues and respiratory conditions. The wildfire-landslide pathway can destroy surrounding landscapes and air quality, pose risks to building integrity, and increase operational stress on facilities responsible for emergency healthcare and community services.

What Are the Costs and Benefits of Adaptation for Social Infrastructure?

Hypothetical Projects: Hospitals

Table 27 summarizes estimates of incremental costs and BCRs for a range of climate adaptation measures for **two hypothetical hospitals**:

1. A **small, rural hospital** that is 22,600 sq. ft. and serves 3,000 customers per year. The estimated total cost for a new construction project in Brazil is approximately $2.6 million.

2. A **large, urban hospital** that is 600,000 sq. ft. and serves 450,000 customers per year. The estimated total cost for a new construction project in Brazil is approximately $70 million.



Table 27. Adaptation measures for hospitals and cost/benefit information[xvii]

Adaptation Measure	Measure Effectiveness	Small Hospital		Large Hospital	
		Cost as % of Total Project Cost	BCR	Cost as % of Total Project Cost	BCR
Asset elevation	High	13%	2	15%	2
Dry floodproofing	Medium	5%	2	4%	5
Detention ponds for floodwater diversion and storage	Medium	1%	16	1%	48
Flood wall (5 feet tall)	High	27%	0.8	6%	5
Hurricane safe room	Low[xviii]	7%	65	2%	65
Defensible space and hazardous fuels reduction for wildfires	Medium	6%	4	1%	15

xvii See Appendix C for more details on the hypothetical project methodology and inputs.
xvii This measure is marked as low effectiveness because it does not affect the exposure of the asset to the hazard and only lessens the severity of the impacts of the hazard.

Hypothetical Projects: Schools

Table 28 summarizes estimates of incremental costs and BCRs for a range of climate adaptation measures for **two hypothetical schools**:

1. A **small, rural elementary school** that is 50,000 sq. ft. and serves 300 students. The estimated total cost for a new construction project in Brazil is approximately $2.15 million.

2. A **large, urban high school or college** that is 400,000 sq. ft. and serves 2,000 students. The estimated total cost for a new construction project in Brazil is approximately $17 million.

Table 28. Adaptation measures for schools and cost/benefit information [xix] [xx]

Adaptation Measure	Measure Effectiveness	Small School		Large School	
		Cost as % of Total Project Cost	BCR	Cost as % of Total Project Cost	BCR
Asset elevation	High	6%	0.5	8%	0.5
Dry floodproofing	Medium	2%	1	2%	1
Detention ponds for floodwater diversion and storage	Medium	1%	5	1%	9
Flood wall (5 feet tall)	High	7%	0.5	2%	2
Hurricane safe room[xx]	Low	5%	378	4%	379
Defensible space and hazardous fuels reduction for wildfires	Medium	4%	4	1%	12

Other Adaptation Measures From the Literature

Other adaptation measures for social infrastructure assets and example costs and benefits are described below **based on available literature.**

xix See Appendix C for more details on the hypothetical project methodology and inputs
xx The hurricane safe room adaptation measure has a significantly higher BCR for schools rather than hospitals as the FEMA BCA Tool assumes a higher value for protecting a school structure than an institution structure, like a hospital..

Building or asset elevation

Hazards: Extreme precipitation and flooding

Effectiveness: **High**

Description

Elevating critical equipment or assets above flood levels and ensuring the first-floor design elevation is above the 100- or 500-year floodplain for new construction projects can significantly reduce exposure to flooding.

Example costs

FEMA reported in 1998 that elevating a building by 0.6 meters costs between $180 and $510 per m². FEMA no longer publishes dollar values for building elevation cost estimates due to the wide variation of costs depending on time, location, project size, and materials. However, building elevation is typically considered an expensive adaptation measure. Elevating assets tends to be significantly more costly when completed as a retrofit rather than as part of a new construction project.[377, 378]

A 2023 IDB Invest study of Jamaica, Barbados, and Trinidad and Tobago found that the cost of elevating a structure can be **$2,300 for a 464-square-meter warehouse**.[379]

Elevating heating, ventilation, and air conditioning (HVAC) systems, plumbing, and electrical meters can cost **$6,000 or more**.[380]

Example benefits

Asset elevation is typically highly effective because it completely removes the structure from the area of flooding exposure, essentially eliminating flood risk. Studies indicate that elevating buildings has a high **BCR of 12–69** due to these benefits.[381]



Floodproofing and floodwater diversion and storage measures

Hazards: Extreme precipitation and inland flooding | Hurricanes

Effectiveness: **Medium**

Description

This measure involves diverting floodwater from a body of water into a wetland, floodplain, canal/ditch, pipe, or other conduit (e.g., tunnels, wells) and storing it in reservoirs, floodplains, wetlands, or other storage facilities. Floodwater diversion and storage projects typically combine multiple adaptation measures, such as flood walls, culvert upsizing, and NBS such as wetland restoration. Depending on the scale of the project, floodwater diversion and storage projects can have significant land and permitting requirements, especially if they involve NBS. For buildings, floodwater diversion and storage projects may include floodproofing, temporary or permanent flood barriers, or pump systems to remove floodwater from properties.

Example costs

Installing a sump pump or other similar, small-scale water pump can cost between **$100 and $400**.[382]

Permanent dry floodproofing measures such as a long-lasting waterproof sealant coating or membrane up to 3 feet typically cost **$8–$12 per sq. ft**.[383]

Temporary flood wall systems typically cost **$50–$150 per sq. ft**. Permanent flood walls average **$150 per linear foot** plus labor to install. The height and material of the permanent flood wall can significantly influence the total cost.[384]

The US Army Corps of Engineers (USACE) invested $1.6 billion in a large-scale flood risk project in San Juan and Guaynabo in Puerto Rico. The project included multiple floodwater diversion and storage measures, including deepening and widening tributaries to allow for more efficient water flow, rebuilding bridges to remove obstructions during flooding events, and constructing flood walls and levees to reduce flooding.[385]

Example benefits

Overall, floodproofing measures tend to have moderate to high BCRs because relatively modest investments in low-cost retrofits (such as floodproofed walls, shields, and backflow valves) or localized storage and diversion structures can avoid large economic losses by cutting downtime, protecting buildings, and reducing damage bills, particularly in frequently flooded areas. In dense urban or highly exposed settlements, the same measures yield even higher returns. Below are diverse examples that demonstrate the benefits and costs.

A 2025 study evaluated the effectiveness of wet floodproofing measures for schools in the Dominican Republic. Wet floodproofing included using external plastering to make walls impervious, adding shields for openings with ground sills, and backflow valves. The study found that under a 0.25-meter flood scenario, wet floodproofing measures successfully reduced the service interruption time by 35 days in rural areas and by 58 days at the province level.[386]

The USACE Puerto Rico flood project mentioned above is reported to provide over **$125 million** in annual economic benefits through avoided flood damages and will reduce flood risk for over 250,000 residents.[387]

The 2023 IDB Invest study of Jamaica, Barbados, and Trinidad and Tobago found that, for a single-family residential building, installing flood doors has an **ROI of 127**, while permanent flood barriers have an **ROI of 81**.[388]

Nature-based solutions

Hazards: Extreme heat | Extreme precipitation and inland flooding | Hurricanes

Effectiveness: **Medium**

Description

There is a wide range of NBS that can be implemented to reduce flooding, heat, and drought impacts. NBS for flooding typically involve using natural systems like soil and plants to store, infiltrate, or evapotranspirate captured water and to either reuse it or release it more slowly into the existing drainage or sewer system. Example strategies include bioretention basins/ponds, green roofs, permeable pavement, and urban trees. For social infrastructure assets, pervious surfaces and grass, trees, and rain gardens can be used around buildings to reduce flooding, as well as ambient temperatures during heatwaves. Planting native species that are well adapted to local conditions can also help increase resilience to drought.

Example costs

A 2023 article reported that green roofs can cost **$1 per m²** to install in Brazil.[389]

The Chesapeake Bay Trust reports that rain gardens can cost **$4–$35 per sq. ft.** to install, depending on the size and other site characteristics.[390]

The 2023 IDB Invest study of Jamaica, Barbados, and Trinidad and Tobago found that the cost of water retention and infiltration systems for a residential building is **$650**.[391]

Example benefits

Generally, nature-based solutions for social infrastructure assets deliver high ROIs because they use relatively low-cost construction or retrofit measures that generate recurring savings through reduced water use, lower energy demand, and potentially avoided stormwater infrastructure.

The 2023 IDB Invest study reports a **high ROI of 518–943** for water retention and infiltration systems for residential buildings.[392]

In Brazil, a study on low-cost favela green roofs found that green roofs successfully reduced surface temperatures by up to 22°C compared to adjacent bare roofs.[393]
A 2024 US urban forestry study found that for each $1 spent on urban tree canopy expansion can yield $1.4–$3.1 in benefits due to energy, stormwater, and air quality benefits.[394]

Wind-resilient building shape and roof design

Hazards: Hurricanes | Wind

Effectiveness: **Medium**

Description

Constructing or retrofitting buildings to secure the building envelope and integrity during a wind event can increase resilience to hurricanes and other strong wind events. For example, separating the veranda roof from the building roof can reduce the risk of wind uplift. Another option is to install hurricane shutters or hurricane roof clips and ties to reduce wind damage during storms. Additionally, U-shaped and L-shaped buildings should be avoided, as these shapes amplify wind loads at interior corners. Separating buildings can also allow the wind to safely pass through them.

Example costs

The 2023 IDB Invest study of Jamaica, Barbados, and Trinidad and Tobago found that the cost of installing hurricane/wind roof clips and ties or hurricane shutters can be **$180–$1,900** for a 70 m² residential building or **$1,200–1,800** for a 464 m² warehouse.[395]

Example benefits

The 2023 IDB Invest study found that, for a single-family residential building, installing hurricane/wind roof clips and ties and hurricane shutters tends to be significantly more cost-effective than installing impact-resistant windows and doors. Hurricane/wind roof clips and ties have a **very high ROI of 2,400–4,411**; hurricane shutters have an ROI of 51, and impact-resistant windows and doors have a *negative* ROI of -24. However, **for hurricane resilience improvements, the size and type of building being retrofitted can significantly affect the ROI.** For example, in the case of a warehouse, the ROI of hurricane/wind roof clips and ties is much lower (0–260) than for a residential building, and the ROI for impact-resistant windows and doors is positive (140) instead of negative. For both a residential building and a warehouse, the study found that constructing the roof out of concrete has a negative ROI (from -53 to -70).[396]

Fire-resistant building materials

Hazards: Wildfire

Effectiveness: **Medium**

Description

Using non-combustible materials for both new and existing buildings can provide structural protection and reduce damage during wildfires.

Example costs

An Australian study from 2018 found that the cost for retrofitting a home with wildfire-resilient materials averaged **$19,000** and that the average cost of preparation for retrofitting is **$8,000**.[397]

A 2024 US study found that fire protection for a composite building (one made up of lots of different types of materials) can cost between **4% and 12% of total construction costs**.[398]

Example benefits

Studies indicate that fire-resistant and non-combustible materials have a **BCR of 34** because moderate increases in upfront construction or retrofit costs are outweighed by very large reductions in property loss and business interruptions, especially in high-risk wildfire areas.[399]

A 2017 report by the US National Institute of Building Sciences estimated that wildfire-resilient building retrofits can produce **$4 of savings for every $1 of additional cost**.[400]

Window ventilation systems, fans, or other cooling systems

Hazards: Extreme heat

Effectiveness: **Low**

Description

Designing windows that open fully can promote cross-ventilation and help lower indoor temperatures during extreme heat events. Installing fans can also help circulate air throughout the building. Adding shade structures around buildings can also help decrease the amount of direct sunlight the building receives and minimize cooling needs.

Example costs

IDB reports that installing a window ventilation system adds no additional cost to school projects when incorporated from the beginning.[401]

Example benefits

Studies indicate that installing fans has a **BCR of 24–50**, and installing shading has a **BCR of 2–4**. Fans and shading are relatively low-cost, depending on the size of the infrastructure asset, and deliver reductions in risk to occupant safety, energy use, and health-service costs. This is especially important in schools and health facilities where occupant safety is critical.[402]

Solar panel system

Hazards: Extreme weather events

Effectiveness: **Low**

Description

Installing solar panels on building roofs can increase energy efficiency and provide backup power supply, helping reduce power disruptions during extreme weather events.

Example costs

In 2023, the World Bank spent $15 million on a project in Jamaica to develop climate-resilient school infrastructure, including solar panel microgrids for the construction of one secondary school.[403]

In California, San Benito Health Foundation is a 1579-square-meter health clinic that is almost entirely powered by a **$1.7 million solar microgrid and battery system**.[404]

In Puerto Rico, Hospital del Niño partnered with Tesla to install a **$1 million solar microgrid** following Hurricane Maria.[405]

Example benefits

Installing solar panels has a **BCR of 1.5-6**. Solar panel installation has a range of BCRs because costs vary based on location, which determines sun exposure and construction viability. However, the upfront cost of solar panels is offset by long-term reductions in electricity costs.[406, 407]

Rainwater harvesting

Hazards: Drought

Effectiveness: **Low**

Description

Installing a rainwater harvesting system can increase heat and drought resilience by collecting water for drinking or irrigation. Rainwater harvesting can also reduce flooding by capturing and storing excess rainwater during storms.

Example costs

In Mexico City, rainwater harvesting systems installed by the nonprofit organization Isla Urbana cost between **$300 and $4,000**.[408]

The 2023 IDB Invest study of Jamaica, Barbados, and Trinidad and Tobago found that the cost of a rainwater collection system can be **$240** for a 70-square-meter residential building and **$8,600** for a 464-square-meter warehouse.[409]

Example benefits

The 2023 IDB Invest case study found that the ROI for rainwater harvesting varies significantly depending on the asset type. For example, rainwater harvesting for a single-family residential building has an **ROI of 1,600–2,769** compared to an **ROI of 202** for rainwater harvesting for a warehouse. Therefore, asset size is correlated to the project costs and overall benefits and costs.[410]

Key Takeaways



- While all climate adaptation measures are highly sensitive to the exposure of the specific asset of interest, **social infrastructure assets are also characterized by dramatically varying costs of repair or replacement, the impacts of closures and operational disruptions, and ties to the public sector.** These differences manifest in large differences in the financial characteristics of the same adaptation measure for different assets.
- Both education and health care facilities often rely on payments from (semi-)public institutions. As a result, **private sponsors will likely need to engage the public sector** in conversations about climate resilience and emergency planning while planning climate adaptation measures for social infrastructure assets.
- In practice, many sponsors will likely need to **combine multiple measures and pair them with operational measures** such as detailed emergency plans, secured supply chains, and collaborations with local utilities and public institutions to safeguard social infrastructure assets.

05

Assessing the Financial Impacts of Climate Adaptation

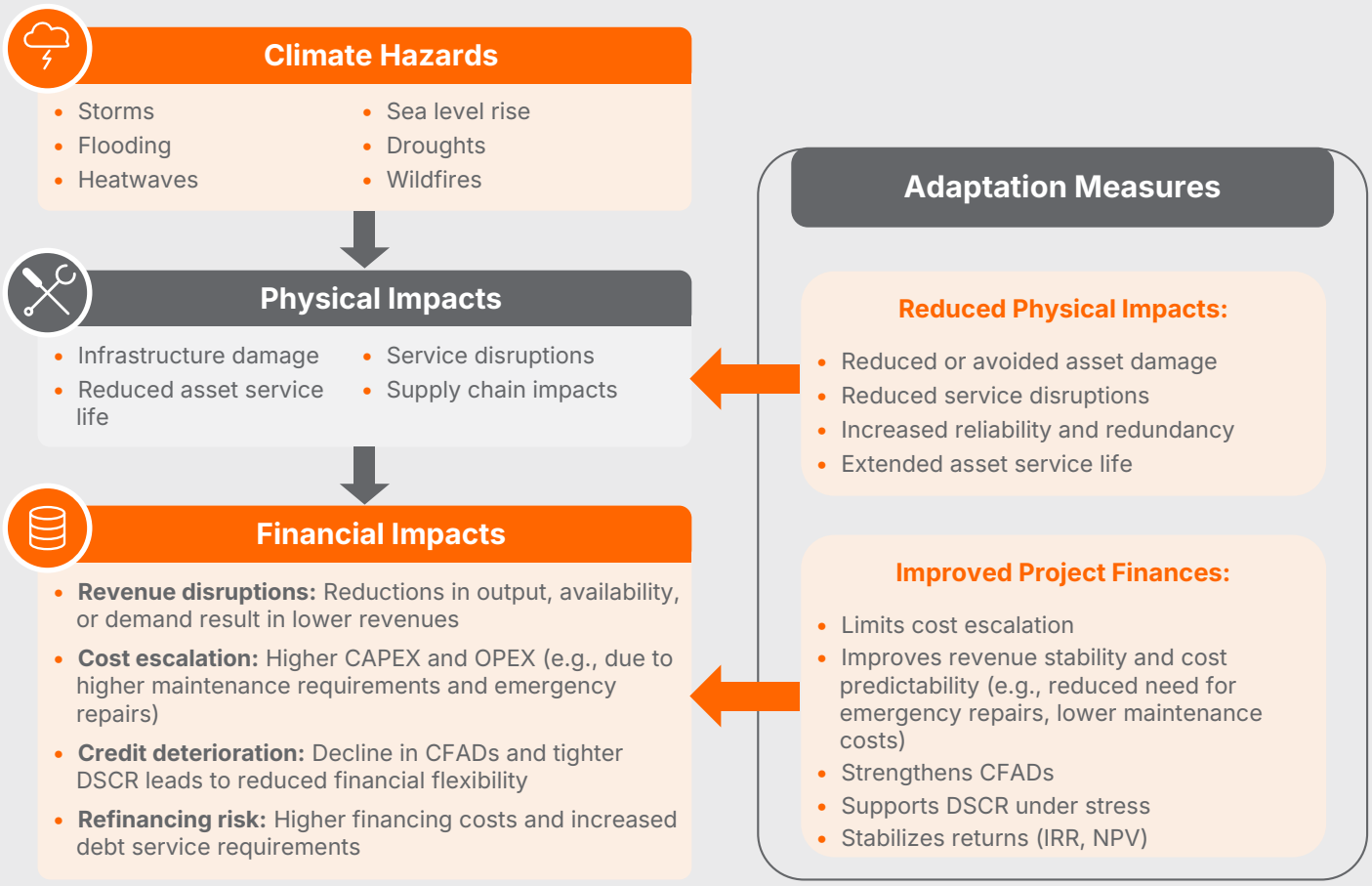
Measures at the Project Level

The previous chapters lay the groundwork for understanding climate change trends, infrastructure vulnerabilities, and adaptation costs and benefits in LAC. As discussed in Chapter 4, although BCAs are helpful for comparing adaptation measures, they do not indicate how adaptation costs and benefits directly affect an asset's balance sheet and its top and bottom lines. **This chapter marks the transition from high-level BCAs to project-level financial decision-making.**

Once an adaptation measure has been identified as economically justifiable through a BCA, a project-level analysis is needed to translate adaptation measures into concrete financial inputs that can be incorporated into a project's financial model. The starting point is to define the investment in terms of project-specific CAPEX (e.g., upfront costs of implementing resilience measures) and OPEX (e.g., changes in maintenance costs, insurance costs, and energy use). Adaptation measures may also affect asset life and replacement cycles, which are critical for long-term financial performance.

With these inputs defined, developers and sponsors can assess how climate risks and adaptation measures affect project cash flows (see Figure 7)**.** This involves quantifying how disruptions, damage, and operational changes translate into financial variables such as revenue, OPEX, and CAPEX. These effects are then incorporated into a standard project-finance model to evaluate key metrics, including cash flow available for debt service, debt service coverage ratios, internal rates of return (IRRs), and net present value (NPV).[411] This step provides a useful understanding of how climate risks influence bankability, covenant compliance, and expected returns.

Figure 7. Overview of how climate hazards affect project operations and finances, and how adaptation measures can reduce impacts and increase financial returns



Importantly, the financial model also serves as the testing ground for financing solutions. While Chapter 6 introduces financial instruments to manage residual climate risks, their effectiveness must be assessed within the same modeling framework. Instruments such as guarantees, concessional financing, insurance, or liquidity facilities ultimately affect financial performance by altering cash flow timing, reducing volatility, or improving financing terms. In practice, these instruments are evaluated by stress testing their impact on the project's cash flow profile and their ability to meet financing requirements under different scenarios and facilitate the implementation of adaptation measures.[412], [413]

The purpose of this chapter is to provide a structured approach to this financial translation. It shows how to move from project-specific cost inputs to financial model outputs and how to interpret the results from investor and lender perspectives. The analysis also identifies residual risks that remain after adaptation measures are implemented. These residual risks, particularly those affecting cash flow stability and financing conditions, form the basis for the selection and structuring of financial instruments, which are discussed further in Chapter 6.

5.1 Infrastructure Cash Flows

Once climate risks and adaptation measures have been translated into project-specific financial inputs, the next step is to evaluate how these changes affect the project's financial performance. This evaluation is carried out through the structure of the project's cash flows and the financial metrics derived from them.

Infrastructure projects can be financed through different structures, which vary primarily in how risk is allocated between the project, the debt providers, and the equity sponsors. The two most common approaches are corporate financing and project finance:

- **Corporate Financing:** Funding is based on the company's overall creditworthiness, with lenders having full recourse to the company's broader asset base if a project underperforms.
- **Project Finance:** Funding is non-recourse or limited-recourse, meaning lenders rely mainly on the cash flows generated by the project itself for repayment.[414], [415], [416]

Corporate Finance in LAC

Although this chapter focuses on project finance, it is important to recognize that a significant share of infrastructure in LAC is financed at the corporate level. In these cases, climate-related impacts may be absorbed across a broader portfolio, rather than directly at the asset level. However, the underlying analytical framework remains consistent across both approaches, as financial performance ultimately depends on the stability and predictability of cash flows.

The distinction between these mechanisms matters because, in project finance, stable and predictable project cash flows are essential for debt repayment, while corporate financing allows lenders to depend on the company's other assets if project revenues fall short. Across all financing structures, sponsors and lenders assess whether a project can generate sufficient cash flow to cover its costs, meet its financing obligations, and deliver acceptable returns.[417], [418] What differs is the extent to which lenders can rely on external support if those cash flows fall short.

The subsequent sections focus on project finance, reflecting its central role in privately financed infrastructure, where it typically represents approximately 60–90% of investment value.[419], [420], [421], [422] Within this structure, financial performance is assessed through the structure of cash flows and the metrics derived from them. In project finance, this structure is formalized through a cash flow waterfall, which defines how revenues are allocated across OPEX, CAPEX, debt service, and equity distributions. Because repayment depends on these cash flows, their stability and predictability become the central determinants of bankability. Lenders therefore assess not only the base-case performance of the project but also how cash flows behave under stress scenarios. Even relatively small changes in revenues, OPEX, or CAPEX, including those resulting from climate risks or resilience measures, can materially affect the project's ability to meet its financial obligations.[423], [424]

The cash flow structure is then translated into a set of financial metrics that allow sponsors and lenders to assess risk and return in a standardized way. The following sections introduce these concepts in more detail, beginning with the structure of the cash flow waterfall and then explaining how key financial metrics are used to evaluate infrastructure projects.

Project Finance Cash Flow Waterfall

The cash flow waterfall provides a structured view of how project revenues are allocated across competing uses and financial obligations. As shown in **The cash flow waterfall is the structure through which climate risks translate into financial outcomes.** Climate hazards affect project performance by disrupting the drivers of revenue, increasing operating and capital costs, and introducing volatility into cash flows. These effects propagate through the waterfall, determining the project's ability to service debt and generate returns.

Table 29, revenues are applied sequentially according to a predefined priority, ensuring that essential costs and senior financial commitments are met before any residual cash is distributed to equity sponsors. This sequencing reflects the seniority of claims and is a defining feature of project finance, as it ensures that debt obligations are prioritized over equity returns.[425], [426], [427]

The cash flow waterfall is the structure through which climate risks translate into financial outcomes. Climate hazards affect project performance by disrupting the drivers of revenue, increasing operating and capital costs, and introducing volatility into cash flows. These effects propagate through the waterfall, determining the project's ability to service debt and generate returns.

The waterfall therefore begins with project revenues, which are determined by the project's contractual and operational characteristics. Depending on the sector, these may include payments under power purchase agreements, user-based revenues such as tolls or tariffs, or availability payments from a public counterparty. The level and stability of these revenues depend on factors such as demand, asset availability, and counterparty performance. Climate-related disruptions directly affect these drivers, for example through reduced output, temporary service interruptions, or shifts in demand. Conversely, adaptation measures that improve asset resilience, such as flood protection or redundancy, help stabilize revenues by reducing the frequency and duration of such disruptions.. The table below summarizes how each stage of the cash flow waterfall is exposed to climate risk and why it matters for financial performance. [xxi]

xxi In practice, project finance structures may include additional reserve accounts and financing features that modify the timing and distribution of cash flows. These are discussed in Chapter 6, as they are part of financial structuring rather than core cash flow generation.

Table 29. Cash flow waterfall for project finances

	Stage	Description	Financial Relevance
1	**Revenue**	Income generated by the project (e.g., tariffs, PPA payments, tolls)	Primary exposure to climate risk
2	**Operating Expenditures (OPEX)**	Costs required to operate and maintain the asset (e.g., routine maintenance, staffing, energy, and insurance)	Often partially fixed, limiting flexibility
3	**Taxes**	Statutory payments to authorities that must be met regardless of project performance	Mandatory outflows
4	**Maintenance and Lifecycle Costs**	Expenditures required to sustain asset performance over time, including additional CAPEX to replace or reconstruct assets in the future	Critical for long-term viability
5	**Cash Flow Available for Debt Service (CFADS)**	Cash remaining after operating and required expenditures to meet debt service obligations	Key measure of repayment capacity
6	**Debt Service**	Interest and principal repayments (paid from available CFADS)	Fixed obligation; determines default risk
7	**Equity Distributions**	Residual cash available to sponsors	Most sensitive to shocks

The impact of climate risks and adaptation measures on each stage of the cash flow waterfall after revenue is described below:

- **OPEX:** Climate risks can **increase operating costs and cost volatility** (e.g., higher energy use, more frequent maintenance), while adaptation helps **reduce the need for emergency repairs** and **lower the variability of maintenance costs**, even if adaptation measures do not eliminate baseline operating expenses. [428]

- **Taxes and Required Lifecycle Expenditures:** Climate impacts can **accelerate asset degradation**, increasing lifecycle maintenance and replacement needs, whereas resilience measures can **extend asset life and lower long-term lifecycle cost**s despite higher upfront spending.[429], [430]

- **CFADS:** CFADS reflects how revenues and costs combine to determine the project's capacity to service its debt and, ultimately, its bankability.[431], [432] Climate-related revenue shocks and cost increases can **weaken debt-servicing capacity**, while adaptation that improves **revenue stability and cost predictability** directly strengthens CFADS and bankability.

- **Debt Service:** Debt service payments are fixed and contractual, and failure to meet them can trigger covenant breaches or default.[xxii] Climate-driven cash flow volatility **heightens default risk**; adaptation reduces this risk indirectly by **improving cash flow reliability**, which lenders closely scrutinize.[433], [434]

- **Equity Distributions:** As the residual cash flow, equity returns **are highly sensitive to climate-related volatility in revenues, costs, and CAPEX**, making adaptation measures that **reduce volatility** especially valuable for stabilizing returns over time.

Linking Financial Risk Channels to the Cash Flow Waterfall

The cash flow waterfall provides the structure through which project revenues are allocated, and financial performance is determined. The financial risk channels introduced in Chapter 4, revenue disruption, cost escalation, credit deterioration, and refinancing risk, can be directly mapped to specific components of this structure.[435] This mapping is described below:

- **Revenue disruption** affects the top line of the waterfall. Reductions in output, availability, or demand translate directly into lower revenues. Because many project costs are fixed, even relatively small reductions in revenue can lead to disproportionate declines in CFADS, placing immediate pressure on DSCR in stress periods (e.g., flooding that reduces toll road traffic, lowering revenues and CFADS while debt service remains fixed, thereby tightening DSCR and increasing the risk of covenant breaches or default).

- **Cost escalation** operates through increases in OPEX and CAPEX. Higher maintenance requirements, emergency repairs, and accelerated asset deterioration increase OPEX and CAPEX, reducing CFADS. These effects are often persistent and can compound over time, weakening both lender metrics and equity returns.

- **Credit deterioration** reflects the impact of sustained pressure on financial performance. When CFADS declines and DSCR tightens, projects may face covenant constraints, reduced financial flexibility, loan agreement defaults, or rating pressure, including from credit rating agencies such as Moody's, S&P, and Fitch. While this channel is not a separate line item in the waterfall, it is the result of cumulative stress on cash flows and directly affects financing conditions and investor confidence.

- **Refinancing risk** affects the lower portion of the waterfall through changes in financing terms. Increased uncertainty around future cash flows can lead to higher financing costs, shorter tenors, or reduced leverage at refinancing. These changes increase debt service requirements or reduce distributable cash flow, with direct implications for both DSCR and equity outcomes.

xxii In practice, debt service profiles can be structured in different ways to align with expected cash flows, including mechanisms such as sculpted repayment schedules, grace periods, or back-ended amortization. While these structuring approaches can provide additional flexibility and improve resilience to variability in cash flows, they do not eliminate the underlying exposure to climate-related shocks and are therefore not explored in detail here.

Taken together, these channels describe how climate risks propagate through the financial structure of a project. In practice, impacts are rarely isolated to a single channel. A single event can simultaneously reduce revenues, increase costs, and affect financing conditions, with combined effects that are amplified through the cash flow waterfall.[436], [437]

Adaptation measures interrupt these transmission pathways.[438], [439] **By reducing the frequency and severity of disruptions, limiting cost escalation, and improving the predictability of cash flows, adaptation strengthens CFADS, supports DSCR under stress, and stabilizes IRR and NPV over time.**

How Lenders and Sponsors Evaluate Infrastructure Cash Flows

Building on this framework, the cash flow structure described above provides the basis for evaluating how climate risks affect project performance. These cash flows are translated into a set of financial metrics that allow lenders and sponsors to assess whether a project remains viable under changing conditions. While both groups rely on the same underlying cash flows, they focus on different aspects of risk, particularly in the context of climate-related disruptions.

Lender Perspective

From a lender perspective, **the primary concern is whether the project can continue to meet its debt service obligations when exposed to climate stress.** This reflects the limited upside available to lenders and their focus on downside protection. The key question is therefore not whether the project performs well under expected conditions, but whether it remains resilient under adverse scenarios such as reduced output, temporary shutdowns, or increased operating and repair costs.[440], [441]

This assessment is captured through the **DSCR**, which compares the cash available for debt service to scheduled debt payments. It provides a measure of the project's ability to absorb shocks and maintain debt service capacity under stress. Climate risks affect this ratio by reducing revenues, increasing OPEX, and, in some cases, requiring additional CAPEX that increases debt service requirements. These effects reduce the margin available to service debt, meaning that a decline in DSCR represents a direct financial manifestation of climate risk.

In practice, lenders define minimum DSCR thresholds at financial close, typically in the range of 1.2 to 1.4 times, depending on the risk profile of the project.[442], [443] The critical test, however, is not the base case but the behavior of DSCR under stress. Lenders assess whether climate-related shocks, such as extreme weather events or long-term shifts in operating conditions, could cause the ratio to fall below covenant levels. If this occurs, it may trigger restrictions on distributions, require corrective measures, or, in severe cases, lead to default. **A project is therefore considered bankable only if it can maintain adequate debt service coverage under plausible (climate) stress scenarios.**

Investor Perspective

While lenders focus on the ability to withstand downside risk, **sponsors assess how climate risk affects returns.** Equity sponsors are primarily concerned with the level, timing, and variability of cash flows available for distribution. Their main

performance indicator is the **IRR**, which reflects the expected return on invested capital.

Climate risk affects IRR through several channels:

- Reductions in revenue, whether due to lower output, reduced demand, or service interruptions, directly lower cash flows.
- Increases in OPEX, such as higher maintenance or insurance expenses, further reduce available cash.
- Additional CAPEX, including those required for repair or adaptation, can increase upfront investment and reduce future distributions due to an increase in debt service.

These effects not only reduce overall returns but can also delay cash flows, which has a disproportionate impact on IRR.

In addition to IRR, sponsors consider **NPV**, which measures the absolute value created by the project. Climate risks can reduce NPV by lowering expected cash flows or increasing uncertainty around future performance.[444], [445] However, for sponsors, variability is as important as average outcomes. Because equity distributions are residual in the cash flow waterfall, they are more exposed to volatility than debt service. Even if a project continues to meet its debt obligations, climate-related disruptions can significantly reduce or delay equity returns.

Cost of Capital and Project Bankability

The effects described above ultimately translate into the cost of capital required by both lenders and equity sponsors. Each group requires a return commensurate with the perceived risk of the project. For lenders, higher perceived risk, including that arising from climate-related uncertainties, is reflected in higher interest rates or more conservative lending terms, such as reduced leverage. For equity sponsors, increased uncertainty in the level and timing of residual cash flows raises the required return on equity.

Together, these effects increase the project's overall cost of capital, typically measured as the **weighted average cost of capital (WACC).** As climate risks reduce revenues, increase costs, or introduce greater volatility, both the cost of debt and the cost of equity may rise, leading to a higher WACC.

This has direct implications for project viability. A higher cost of debt increases required interest payments, which must be serviced from project cash flows. If the cost of capital becomes too high, the project may no longer be able to generate sufficient cash flow to cover its debt service obligations, particularly under stress scenarios. In such cases, even if the project is operationally viable, it may not be financially bankable. **Adaptation measures can help mitigate this effect by improving the stability and predictability of cash flows.** By reducing the frequency and severity of disruptions, limiting cost volatility, and strengthening CFADS, these measures support more stable debt service coverage and reduce the likelihood that cash flows fall below required debt service levels. This benefits both lenders and sponsors:

- For **lenders**, this lowers the probability of default and potential losses, allowing them to offer financing at lower interest rates or with higher leverage.

- For **equity sponsors**, more stable and predictable cash flows reduce uncertainty around the level and timing of distributions, lowering the risk premium required to compensate for volatility and downside risk, and thereby reducing the cost of equity.

At the same time, there may be cases where, even with adaptation measures, the residual risk remains too high. In such situations, lenders may require interest rates that the project cannot sustain, reduce financing volumes, or decline to provide financing altogether. Where this occurs, developers may need to seek alternative financing solutions, such as risk-transfer mechanisms, concessional finance, guarantees, or other risk-sharing mechanisms, as further discussed in Chapter 6.

5.2 Case Studies

This section applies this framework to two hypothetical, illustrative case studies, showing how climate risks and adaptation measures affect project cash flows and financial metrics in practice.

Highway Case Study: Toll Road Concession

Project Overview and Financial Structure

The project consists of a 16-km toll road concession in a LAC corridor with revenues generated through user-paid tolls. Because the project relies entirely on traffic volumes and continuous availability, its financial performance is highly sensitive to operational disruptions.

The road passes through terrain that includes river crossings and sloped areas that are exposed to heavy rainfall and landslides. These characteristics make the project relevant for examining the financial implications of extreme precipitation. The financing structure reflects a standard project-finance setup, in which debt service obligations are fixed and must be met from operating cash flows, while equity returns depend on the residual cash generated after all senior obligations are satisfied. Under these conditions, even relatively short interruptions to service can propagate quickly into financial stress.



Climate Hazard and Transmission Channels

The dominant climate hazard affecting the project is **extreme rainfall**, which leads to flooding and landslides along critical segments of the corridor. The financial importance of this hazard lies in the fact that it affects both the revenue-generating capacity of the asset and its cost structure at the same time. This example of extreme rainfall affecting a road was chosen because extreme rainfall is a common issue across many of the geo-types in LAC (see *Table 1* for the hazards affecting each geo-type).

When heavy rainfall events occur, sections of the road become partially or fully impassable. Traffic is diverted or halted, and toll collection declines sharply. Because revenues are directly linked to usage, this reduction is immediate and concentrated during disruption periods. At the same time, physical damage to drainage systems, embankments, and pavement surfaces requires emergency intervention. Repair works increase both CAPEX and OPEX, while ongoing maintenance requirements also rise, including the need to keep culverts clear, maintain drainage capacity, and manage nature-based solutions designed to reduce erosion and runoff impacts. Repeated exposure further contributes to higher insurance costs and sustained increases in maintenance expenditures.

These operational effects translate directly into financial outcomes. Lower revenues combined with higher costs reduce the cash available to service debt, while debt service itself remains unchanged.

This creates pressure on the DSCR, increases the likelihood of covenant breaches, and constrains the ability to distribute cash to equity. Over time, repeated disruptions not only reduce overall returns but also introduce volatility that affects both lender confidence and investor appetite.

Scenario Structure and Assumptions

To isolate these effects, three scenarios are modeled. The Base case reflects normal operating conditions. The Base case reflects normal operating conditions without climate disruption. The Climate Stress scenario is based on IPCC scenarios and introduces a forward-looking increase in rainfall-related events, while the Adapted scenario incorporates a package of resilience measures designed to reduce the frequency and severity of impacts.

Under Climate Stress, the project experiences an average of 0.5 disruptive events per year. Each event lasts approximately two weeks and results in a loss of around 80% of daily revenue during the closure period. In addition, each event triggers emergency repair costs of approximately $15 million. These assumptions are calibrated to reflect a level of disruption that is financially material, consistent with projected increases in precipitation intensity in exposed corridors.

In the Adapted scenario, the project incorporates a set of resilience measures focused on drainage capacity, slope stabilization, and structural protection. These measures increase initial capital expenditure by approximately $25 million and add modestly to annual OPEX through enhanced maintenance and monitoring. However, they reduce event frequency, duration, and severity by approximately half, materially lowering both revenue loss and repair costs.

Financial Results

The resulting financial outcomes show a clear divergence between scenarios *(see Table 30)*, reflecting how climate impacts propagate through the project's cash flow structure.

In the Base case, the project generates stable revenues and maintains strong financial performance, with no covenant pressure and consistent distributions to equity. Under Climate Stress, revenues decline by approximately 13% on average due to repeated closures, while OPEX increases due to repair activity and insurance effects. This reduces CFADS, while debt service obligations remain largely fixed. As a result, coverage ratios fall below required thresholds, leading to multiple years of covenant breaches. In this scenario, the project fails to meet standard bankability criteria, and equity returns are significantly reduced, with NPV turning negative.

Table 30. Toll road case study financial outcomes

Metric	Base	Climate Stress	Adapted
Revenue	**26**	**22.5**	**25.2**
OPEX	-8.6	-7.6	-8.4
CFADS	**17.4**	**14.9**	**16.8**
Debt Service	-12	-16.2	-12.7
Equity Cash Flow	**5.4**	**-1.3**	**4.1**
Min DSCR	1.45x	**0.92x**	1.32x
Equity IRR	14.8%	7.2%	13.1%
Equity NPV	+22	**-8**	+16
Bankable	**Yes**	**No**	**Yes**

In contrast, the Adapted scenario restores much of the lost performance. Although capital costs are higher and debt service increases accordingly, revenues recover to near-Base levels as closures become less frequent and less severe. OPEX also stabilizes, as major repair events are largely avoided. The result is a recovery in CFADS sufficient to maintain covenant compliance, eliminate sustained breaches, and restore positive returns to equity.

Cash Flow Interpretation

The key insight from the results lies in the non-linear relationship between operational disruption and financial performance. A reduction in revenue of around 13% translates into a significantly larger reduction in available cash flow because a large share of costs remains fixed. This amplification effect is typical in infrastructure assets, where operating leverage is high, and flexibility on the cost side is limited.

At the same time, the rigidity of debt service obligations means that any reduction in cash flow immediately affects coverage ratios. Even when reserves are available, they can only partially absorb the impact of repeated disruptions. Once cash flow falls below a certain threshold, the financial structure becomes unstable, and the project enters a cycle of covenant breaches and restricted distributions.

The Adapted scenario demonstrates that restoring operational stability is more effective than attempting to manage financial stress after it occurs. By reducing the frequency and severity of disruptions, the resilience measures improve the entire cash flow profile, rather than addressing individual symptoms. This leads to more stable coverage ratios, fewer drawdowns on reserves, and more predictable distributions to equity.

From a lender perspective, the Climate Stress scenario represents a project that cannot sustain its debt obligations under plausible downside conditions. The repeated breaches of coverage thresholds indicate that the project would either require restructuring or would fail to secure financing at the outset. The Adapted scenario, by contrast, restores sufficient headroom to meet lender requirements, effectively transforming a non-bankable project into a bankable one.

From an investor perspective, the difference between scenarios is equally pronounced. The Climate Stress case shows a sharp reduction in returns and a shift from positive to negative value, driven by both lower cash flows and increased volatility. The Adapted case recovers most of the lost return, with only a modest reduction relative to the Base case. This indicates that the primary benefit of resilience investment lies not in increasing upside, but in protecting against downside scenarios that would otherwise erode value.

Residual Risk and Link to Financial Structuring

Despite the improvements achieved through adaptation, some level of risk remains. Extreme events can still exceed the design thresholds of climate-adapted projects, thereby causing disruption, particularly if they occur early in the project lifecycle. In addition, the possibility of clustered events or unforeseen climate patterns introduces uncertainty that cannot be fully eliminated through engineering measures.



These residual risks are typically characterized by low probability but high impact. They represent the portion of exposure that cannot be fully mitigated through physical measures and must instead be managed through a combination of financial structuring, risk transfer, or risk acceptance. In practice, this involves determining which risks can be absorbed within the project's financial capacity and which require additional mechanisms.

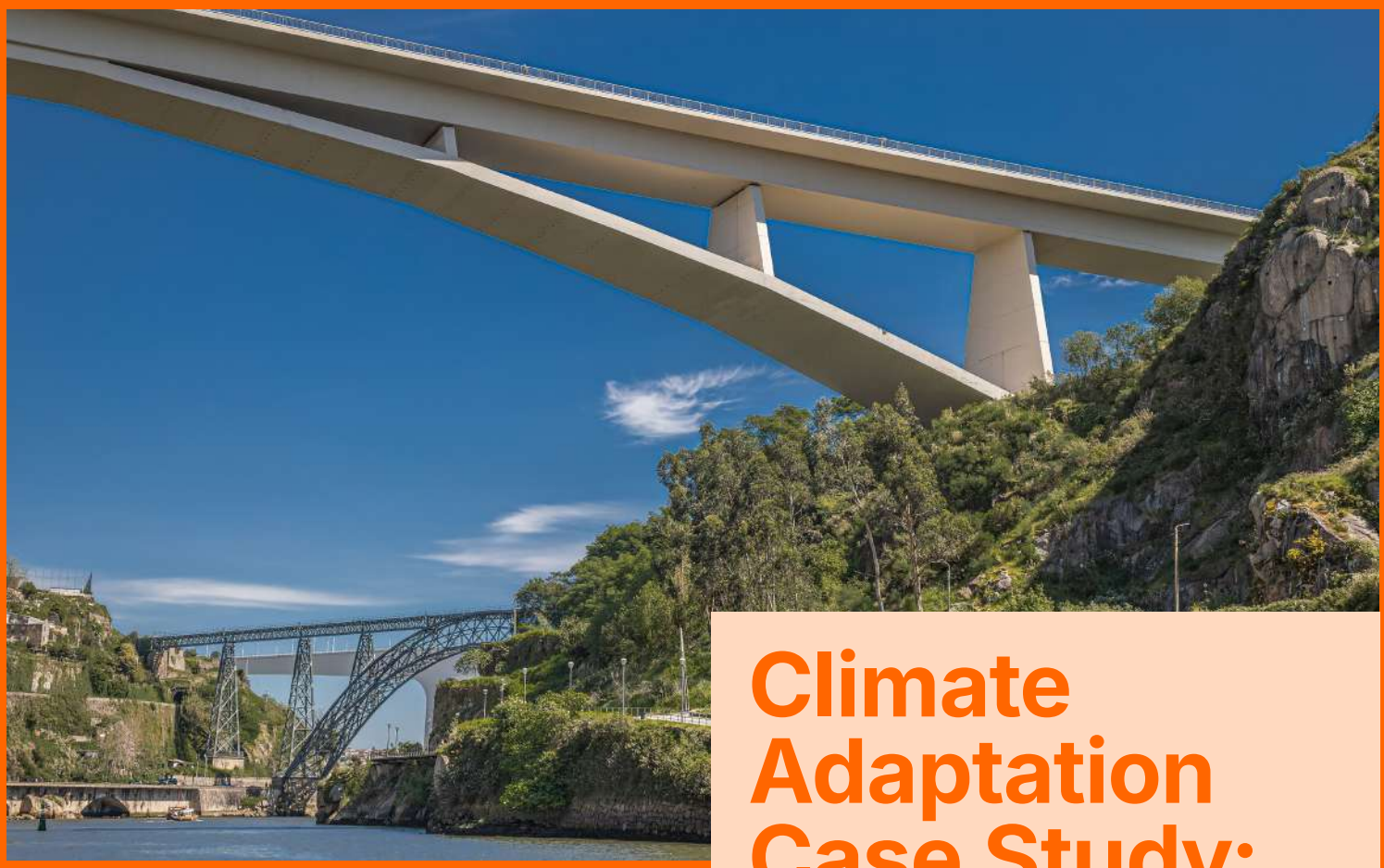
For sponsors and lenders, the key decision is not whether risk remains, but how it affects cash flow stability and bankability. This requires a structured assessment of three elements: (i) the severity of remaining disruptions to revenue and costs, (ii) the resulting impact on CFADS and DSCR under stress scenarios, and (iii) the extent to which these impacts can be absorbed within existing financial buffers.

Financial structuring tools can be used to manage this residual exposure. These include mechanisms that provide liquidity during disruption periods, transfer risk to external parties, or protect against extreme tail events. At the same time, a portion of risk may remain unmitigated where the cost of further protection exceeds the expected benefit, and is therefore explicitly accepted within the project's risk allocation.

Based on this assessment, projects can be categorized into residual risk tiers that reflect how remaining climate exposure affects cash flow stability and bankability under stress scenarios. At a high level, these tiers range from projects where CFADS remains sufficient to maintain DSCR above covenant thresholds to those where residual volatility leads to covenant pressure or breaches. This classification provides a practical decision framework for sponsors: first assess the financial impact of climate risk after adaptation, then determine whether the project remains bankable on a standalone basis, and finally identify whether additional financial instruments are required to address remaining risks.

The identification of this residual risk layer therefore provides the basis for the selection and design of financial instruments. The next chapter builds on this analysis by formalizing these residual risk tiers and translating them into specific financing strategies and instrument choices.





Climate Adaptation Case Study: *Brazil Pro-Roads*

The Brazil Pro-Roads Project is a $200 million road resilience program designed to strengthen the long-term performance of Bahia State's public road network in the face of increasing floods, landslides, extreme rainfall, heat, and sea level rise. The project is financed by the World Bank, the Brazilian government, and private capital through performance-based contracts and integrates climate risk analysis into road design, rehabilitation, and long-term maintenance to reduce impacts from future climate hazards. Adaptation measures include resilient drainage and hydraulic design, slope stabilization, heat-resistant pavements, and improvements to maintenance schedules based on climate projections. A BCA for the initial phase of the project indicates an NPV of $294.5 million and an IRR well above the estimated opportunity cost of capital. This project demonstrates how embedding resilience into asset management and maintenance contracts can deliver strong economic returns while improving transport reliability. See Appendix A for more information on this case study.



Solar Case Study: Utility-Scale Solar

Project Overview and Financial Structure

This hypothetical case study examines a utility-scale solar PV project to illustrate how climate risks affect financial performance under a contracted revenue model. The project consists of a 300 MW solar PV plant located in a coastal area exposed to hurricanes or a flood-prone area in LAC. Electricity is sold under a long-term power purchase agreement at a fixed tariff, which provides price certainty over the life of the project.

Unlike the toll road case, revenues are not driven by demand but by energy delivered. This shifts the primary exposure from traffic risk to availability risk, meaning that any disruption to generation directly affects revenue. The plant includes inverter stations, a substation, and internal cabling systems, all of which are vulnerable to flooding and water-related damage.

The project is financed under a standard structure in which debt service obligations are fixed and must be met from operating cash flows, while equity returns depend on the residual cash generated after all senior obligations are satisfied. Under normal conditions, the contracted revenue structure creates the appearance of stability. However, this stability depends on the ability to consistently generate and deliver electricity over time.

Climate Hazard and Transmission Channels

The dominant climate hazard affecting the project is **extreme rainfall or hurricanes** leading to localized flooding. This hazard is financially material because it disrupts generation and delivery rather than demand. This example was chosen because it is a common issue across many of the geo-types in LAC *(see Table 1 for the hazards affecting each geo-type)*.

When flooding affects inverter stations or substation components, parts of the plant are forced offline. This reduces the amount of electricity generated and delivered. Because the project is contractually obligated to supply a defined share of output, shortfalls in generation reduce revenue and can trigger penalty mechanisms. As a result, the financial impact is not limited to lost production but is amplified by contractual effects.

At the same time, physical damage to electrical equipment increases OPEX and may require additional capital expenditure for repair or replacement. Repeated exposure to such events can also increase insurance costs and maintenance requirements over time.

These operational effects translate directly into financial outcomes. Lower revenues combined with higher costs reduce available cash flow, while debt service remains fixed. This compresses coverage levels, increases the likelihood of covenant breaches, and restricts distributions to equity. The result is a deterioration in both lender metrics and investor returns, driven not only by average performance but also by the volatility introduced by disruption events.

Scenario Structure and Assumptions

Three scenarios are considered. The Base case reflects normal operating conditions without climate disruption. The Climate Stress scenario introduces recurring flood-related outages, while the Adapted scenario incorporates resilience measures designed to reduce flood exposure.

Under Climate Stress, the project experiences approximately 0.4 disruptive events per year, equivalent to one event every two to three years on average. Each event results in partial outages lasting around two months, during which affected parts of the plant operate at significantly reduced

capacity. Output losses during these periods are substantial, and repair costs are incurred following each event.

In the Adapted scenario, resilience measures are implemented, including elevation of critical equipment, reinforcement of substation structures, and improved drainage systems. These measures increase upfront capital expenditure and modestly raise OPEX. However, they significantly reduce the frequency, duration, and severity of disruption events, leading to improved operational continuity.

Financial Results

The resulting financial outcomes show a clear divergence between scenarios (see Table 31), reflecting how climate impacts propagate through the project's cash flow structure.

In the Base case, the project generates stable revenues and maintains strong financial performance, with no pressure on coverage levels and consistent equity returns. Under Climate Stress, revenues decline by approximately 13% due to reduced generation and associated penalties, while operating costs increase due to repair and maintenance requirements. This reduces CFADS, while debt service obligations remain largely fixed. As a result, coverage ratios fall below required thresholds, leading to multiple years of covenant breaches. In this scenario, the project fails to meet standard bankability criteria, and equity returns are significantly reduced, with NPV turning negative.

In contrast, the Adapted scenario restores much of the lost performance. Although capital costs are higher and debt service increases accordingly, revenues recover to near-Base levels as outages become less frequent and less severe. Operating costs also stabilize, as major repair events are largely avoided. The result is a recovery in CFADS sufficient to maintain covenant compliance and restore positive returns to equity.



Table 31. Solar case study financial outcomes

Metric	Base Case	Climate Stress	Adapted
Revenue	28.4	24.8	27.6
OPEX	(8.4)	(7.2)	(8.2)
CFADS	20.0	17.6	19.4
Debt Service	(13.3)	(20.7)	(14.4)
Equity Cash Flow	6.7	(3.1)	5.0
Min DSCR	1.50x	**0.85x**	1.35x
Equity IRR	13.5%	6.5%	12.0%
Equity NPV ($ million)	+28	**-12**	+22
MOIC	2.3x	1.3x	2.1x
Bankable	Yes	No	Yes

Cash Flow Interpretation

The solar case highlights that disruptions to generation have a direct and amplified effect on financial performance. A relatively small number of outage periods can materially affect annual output, particularly when they occur during high-generation months.

The presence of contractual penalties further amplifies the impact. When output falls below expected levels, the project loses revenue from reduced generation and may incur additional financial penalties. This creates a non-linear relationship between operational disruption and revenue loss, similar to the amplification effect observed in the toll road case.

Because OPEX is only partially flexible, the reduction in revenue leads to a disproportionate decline in available cash flow. Fixed debt service obligations mean that any reduction in cash flow directly affects coverage levels. Once these fall below required thresholds, the project enters a period of financial stress characterized by restricted distributions and increased default risk.

The Adapted scenario shows that stabilizing generation is more important than marginal improvements in average performance. By reducing variability, the resilience measures improve the entire cash flow profile and restore financial stability.



Interpretation From a Financing Perspective

From a lender perspective, the Climate Stress scenario demonstrates that a contracted revenue structure does not guarantee financial stability. Although price risk is mitigated, the project remains exposed to physical disruption risk. When generation is interrupted, the resulting loss of revenue and increase in costs can be sufficient to undermine debt service capacity.

The Adapted scenario restores the level of stability required for financing. Coverage levels return above covenant thresholds, and the project becomes financeable under standard terms. This underscores that, even in contracted projects, physical resilience is a prerequisite for bankability.

From an investor perspective, the difference between scenarios is driven by downside risk. The Climate Stress case results in a significant reduction in returns and negative value creation, while the Adapted case recovers most of the lost performance. The reduction in returns relative to the Base case is modest, indicating that resilience primarily serves to protect value rather than enhance it.

Key Takeaways

- In a utility-scale solar project, climate risk is transmitted primarily through disruptions to generation capacity. Flooding reduces output, triggers contractual penalties, and increases OPEX, resulting in a compression of cash flow that can quickly undermine financial viability.
- **The case demonstrates that a long-term contract structure does not insulate the project from physical climate risk. Without adaptation, the project is unable to meet lender requirements under stress conditions. With adaptation, operational stability is restored and financial performance recovers, highlighting the critical role of resilience in sustaining both bankability and investor returns.**
- As in the highway case study, adaptation significantly reduces risk but does not eliminate it entirely. Residual exposure remains, particularly in extreme scenarios that exceed design thresholds or introduce liquidity pressures. Where projects continue to fall short of bankability criteria after resilience measures have been implemented, additional structuring solutions become necessary. Questions such as how to manage residual risk, stabilize cash flows, and restore financing feasibility are addressed in the next chapter through the application of financial instruments such as guarantees, concessional financing, and reserves.
- Building on these case studies, the analysis now expands to other infrastructure sectors to examine how climate risks affect financial performance under different revenue models and operating conditions. While the highway and solar examples illustrate the core transmission mechanisms in demand-based and contracted projects, similar dynamics apply across energy, water and sanitation, telecommunications, and social infrastructure.
- The following sections therefore assess these sectors in a more systematic way, focusing on how climate-related disruptions translate into changes in revenue, OPEX, capital expenditure, and ultimately financial metrics under different project structures.



5.3 Sector Analysis

The case studies above demonstrate how climate risks and adaptation measures translate into project-level financial performance under different revenue models. Climate impacts are transmitted through a consistent set of mechanisms, affecting revenues, OPEX, and CAPEX, and ultimately the stability of project cash flows. These effects are reflected in key financial metrics, with pressure on CFADS and DSCR typically emerging first, followed by impacts on IRR and NPV through reduced and more volatile equity distributions.

These results build directly on the financial risk channels introduced in *Chapter 4*, namely revenue disruption, cost escalation, credit deterioration, and refinancing risk. In this chapter, these channels are translated into the cash flow waterfall, showing how physical disruptions propagate through revenues, costs, and debt service obligations. The case studies illustrate how relatively moderate operational disruptions can result in disproportionate financial impacts due to the fixed nature of costs and financing obligations.

The same transmission logic applies across infrastructure sectors, although the relative importance of each channel depends on the revenue model and contractual structure. Demand-based assets are primarily exposed to revenue disruption, while contracted assets are more sensitive to availability and performance risks. In other sectors, cost escalation or counterparty-related risks may dominate, depending on how risks are allocated between private and public stakeholders.

This section extends the analysis across the five priority infrastructure sectors. The focus is on tracing how the previously identified financial channels translate into changes in revenues, OPEX, CAPEX, and ultimately financial performance under different sector conditions.

Across sectors, climate risk becomes financially material when it affects the stability and predictability of cash flows. These effects are amplified through the cash flow waterfall and reflected in DSCR and equity returns. Adaptation measures improve outcomes by reducing disruption and stabilizing cash flows, but residual risks remain and must be considered in financing and structuring decisions.

The following sections apply this framework to each sector.

Transportation

Transport infrastructure is particularly sensitive to climate risk because financial performance depends heavily on the stability of traffic volumes and asset availability. As illustrated in the toll road case study, disruptions to availability translate directly into revenue loss, while many OPEX and debt service obligations remain fixed. This dynamic makes revenue disruption the dominant transmission mechanism in many transport projects.

In user-pays models, such as toll roads or port terminals, revenues are directly linked to traffic volumes or throughput. Under this model, the private partner and its lenders bear demand risk associated with how many users pay to use the asset.[446] When disruptions reduce traffic or cargo flows, revenues decline immediately while many OPEX and debt service obligations continue. This compresses CFADS and tightens DSCR in stress periods, with secondary impacts on IRR and NPV driven by reduced and more volatile equity distributions.

Transport projects financed through availability-payment or government-pays structures face a

different risk transmission mechanism. In these projects, payments are linked to the availability or performance of the infrastructure rather than to traffic volumes. Project cash flows therefore depend primarily on the reliability of payments from the public counterparty rather than on user demand.[447] However, in these structures, it is also critical to demonstrate that the project complies with required KPIs; otherwise, governments can deduct penalties from the payments. Climate shocks can affect such projects indirectly if disasters place fiscal pressure on governments and weaken payment reliability, introducing elements of credit deterioration. They can also affect the project directly through cost escalation. Even where revenues are contractually protected, extreme heat, flooding, landslides, storm surge, or erosion can raise routine maintenance costs, accelerate asset deterioration, and require more frequent repairs and inspections. If these additional costs are not fully compensated, margins tighten, reducing CFADS and placing pressure on DSCR.

Ports and airports often face exposure to both revenue disruption and cost escalation. Operational shutdowns reduce throughput-based revenues, while storm damage or flood impacts increase repair and maintenance expenditures. Transport disruptions also generate wider economic losses by delaying deliveries and reducing connectivity across supply chains.[448] At the project level, these combined effects increase volatility in cash flows, weakening DSCR in disruption years and reducing IRR and NPV.

Over longer time horizons, climate risk can contribute to refinancing risk. Increased volatility in traffic flows or lifecycle costs may lead lenders to demand higher spreads, shorter tenors, or additional credit support at refinancing, affecting both financing conditions and project valuation. Adaptation measures mitigate these effects by reducing the frequency and severity of disruptions. Improvements in drainage, slope stabilization, and asset protection reduce both revenue losses and repair costs, stabilizing CFADS and supporting DSCR under stress while improving the predictability of equity returns.

Energy

Energy infrastructure is exposed to climate risk primarily through its dependence on reliable generation and delivery of electricity. As illustrated in the solar case study, which is based on a long-term PPA, contractual price stability does not eliminate risk. Instead, it shifts the primary exposure from price and demand variability to availability risk. Projects selling electricity under long-term PPAs typically benefit from stable contractual revenues (World Bank Group, 2014). However, this stability depends on the ability to consistently generate and deliver electricity. When climate hazards cause outages or damage critical components, generation falls below contracted levels, reducing revenues and potentially triggering penalties. As shown in the solar case, this can lead to a simultaneous loss of output and additional financial obligations, compressing CFADS and tightening DSCR. The resulting reduction and increased variability in cash flows also weaken IRR and NPV.

Projects with merchant exposure face greater sensitivity to revenue disruption. Climate shocks can reduce output while increasing price volatility, exposing the project to both volume and price risk. This combination increases variability in CFADS and leads to more pronounced impacts on DSCR, IRR, and NPV.

Projects operating under single-buyer or government-purchaser models can experience a different type of transmission mechanism. In some cases, electricity in these systems is purchased by a state-owned utility that bears market risk on behalf of the system. Climate shocks can therefore

reach project cash flows not only through physical disruptions but also through the financial condition of the purchasing utility, making counterparty credit risk a key consideration and introducing additional uncertainty in cash flow stability.[449]

T&D operators face yet another financial profile. Their revenues are often regulated or tariff-based, meaning that climate hazards primarily affect their finances through cost escalation rather than lost electricity sales. Severe storm damage to transmission networks can generate large emergency repair and restoration costs, as illustrated by the widespread destruction of transmission lines and poles in Puerto Rico following Hurricane Maria and in Jamaica following Hurricane Melissa.[450]

Hydrological stress can also affect broader electricity markets. In Chile, for example, drought has affected both hydropower output and thermal plants that rely on cooling water, contributing to changes in electricity supply conditions and generation costs.[451] These dynamics can indirectly affect project revenues and cost structures, with implications for both lender metrics and investor returns.

Adaptation measures such as equipment protection, redundancy, and improved system design reduce outage duration and repair costs. While they increase upfront CAPEX, they stabilize CFADS, support DSCR, and reduce volatility in investor returns.

Water and Sanitation

Water and sanitation infrastructure differs from other sectors in that it is less frequently financed through fully non-recourse project-finance structures. Compared to energy, transport, and telecommunications, investment is typically led by the public sector, with private participation often embedded in hybrid arrangements such as concessions or PPPs. As a result, project cash flows are more closely linked to regulated tariffs, public transfers, and payment guarantees than to fully autonomous revenue streams. This shifts the financial transmission of climate risk toward cost escalation and credit-related channels.

Water utilities operating under tariff-funded models are exposed to revenue disruption when drought reduces water consumption. Conservation measures and restrictions lower billed volumes while most OPEX remain fixed.[452], [453] This reduces available cash flow and weakens the project's ability to meet financial obligations, particularly where tariffs cannot adjust in response to declining volumes.

Regulatory structures amplify this effect. Where tariffs are regulated, higher operating or capital costs cannot always be passed through immediately. This creates a lag between cost increases and revenue adjustments, compressing margins and weakening financial performance.[454] In practice, this means that climate-related cost shocks are absorbed within the utility's financial structure before they can be reflected in tariff revisions.

Extreme events introduce significant cost escalation. Damage to pipelines, treatment systems, and intake structures increases CAPEX and OPEX, often on a large scale. After Hurricane Maria, Dominica's post-disaster needs assessment reported $24.0 million in damages and $39.73 million in losses in the water and sanitation sector, including pipelines washed away, intake systems blocked with debris, and treatment infrastructure damaged.[455] These costs reduce available cash flow and weaken overall financial performance.

Water projects that depend on municipal or government payments introduce an additional

exposure pathway through public-sector credit conditions. In such structures, lenders rely on the financial strength of the public authority responsible for payment obligations. If disasters weaken municipal or sovereign finances, the risk of delayed payments or contract renegotiation increases, introducing uncertainty in cash flows and affecting the project's ability to meet its financial commitments and maintain investor confidence.[456]

Projects serving low-income or rural users often rely on subsidies or viability gap funding to remain financially viable. These transfers can become more uncertain when governments face fiscal stress following disasters, increasing volatility in cash flows, and weakening financial returns over time. Additionally, subsidies typically do not take into account higher costs due to climate risks. The private sector has to incorporate these additional risks in its models to fully close the viability gap.

Puerto Rico illustrates how public-sector credit conditions can affect infrastructure financing. The Puerto Rico Aqueduct and Sewer Authority reported how public-sector credit conditions can affect infrastructure financing. The Authority described a planned long-term bond issuance that could not proceed following credit downgrades affecting the government and its public corporations. This demonstrates how deteriorating credit conditions can constrain refinancing options and affect long-term project value.[457]

Adaptation measures such as flood protection, redundancy, and improved system design can reduce damage and stabilize operations. By limiting cost escalation and reducing service disruptions, these measures improve cash flow predictability and support more stable financial performance. However, given the continued reliance on public funding and regulated revenues, residual risks remain closely linked to fiscal capacity and institutional resilience.

Telecommunications

The financial implications of climate risk in telecommunications depend on the asset's position in the value chain, with cost escalation typically dominating for infrastructure assets and revenue disruption becoming more important closer to end users.

Telecommunications tower companies often operate under long-term lease agreements with mobile network operators. These contracts provide relatively stable baseline revenues because tower operators are typically paid fixed or contractually escalated lease charges for hosting equipment, rather than being paid directly based on short-term fluctuations in traffic volumes. As a result, climate shocks do not usually cause an immediate collapse in tower revenues. Instead, financial pressure tends to appear first through the cost escalation and liquidity channels, as operators incur restoration costs, deploy backup power, and harden infrastructure after extreme events. These costs reduce CFADS and can affect DSCR where recovery is delayed.

By contrast, retail telecommunications providers and internet service providers sit closer to end users and are more exposed to revenue disruption when prolonged outages reduce service availability or trigger customer losses.[458], [459] In these cases, both revenue and cost channels are affected, increasing cash flow volatility and weakening IRR and NPV.

Data centers have another revenue structure. Their revenues are often secured through long-term hosting or colocation agreements, but operational continuity depends on reliable electricity supply and cooling capacity. Because cooling systems can require significant water or electricity inputs, disruptions to these resources can increase OPEX or temporarily constrain operations, affecting both

revenue and cost profiles and reducing overall cash flow stability.

Adaptation measures such as redundancy, backup systems, and infrastructure hardening reduce outage risk and improve operational continuity. These measures stabilize CFADS and support more resilient DSCR and investor outcomes.

Social Infrastructure

In social infrastructure, the financial transmission of climate risk differs from other sectors because projects are typically funded through public-sector budgets or availability-based payment structures rather than direct user-fee revenues. As a result, climate impacts are transmitted less through immediate revenue loss and more through cost escalation and pressure on public finances, making cost escalation and credit deterioration the dominant channels.

Most hospitals, schools, and public buildings are budget-funded, meaning that climate shocks primarily affect financial performance by increasing expenditure requirements rather than reducing income. Governments must often finance emergency response, temporary continuity measures, repairs, and reconstruction before long-term funding is mobilized. Post-disaster financing typically unfolds in two phases: an urgent recovery phase followed by a larger but less time-sensitive reconstruction phase.[460] This creates short-term liquidity pressure and uncertainty in funding flows, which can affect the timing and reliability of payments. However, it is important to note that most privately managed social infrastructure assets must comply with KPIs, and if these are not met due to climate or other risks, public entities can partially deduct payments to concessionaires.

These pressures can be particularly acute where budget flexibility is limited. In Colombia, budget reallocations provided an immediate source of liquidity, but constitutional and legal rigidities constrained their use; 86% of the 2010 national budget could not be reallocated during the La Niña 2010–2011 event.[461] Even where the state is the ultimate payer, this can result in a temporary gap between disaster impacts and the availability of funding.

Insurance can help reduce this gap, but only where coverage is meaningful. In Colombia, insured losses historically represented a small share of total damages, with only 4.5% of losses from the 2010–2011 La Niña event covered.[462] As a result, reconstruction costs continue to fall largely on public reserves, contingent credit, budget reallocation, or borrowing, concentrating financial stress on sovereign and sub-sovereign balance sheets.

A distinct financing structure arises when social infrastructure is developed under availability-payment PPPs. In these arrangements, government payments linked to asset or service availability form the primary revenue source for the private partner. While this provides relatively stable contractual cash flows at the project level, the underlying exposure remains linked to public-sector liquidity and fiscal capacity. Climate shocks that weaken fiscal conditions can therefore affect payment reliability, introducing variability in project-level cash flows and financial performance.

Adaptation measures reduce the scale of damage and the need for emergency spending, improving both asset resilience and public financial stability. By limiting cost escalation and smoothing funding requirements, these measures support more stable cash flows, strengthen DSCR, and reduce volatility in investor returns.

06

Framework for Financing *Climate Adaptation Measures*

Chapter 5 established how climate hazards affect infrastructure projects financially and showed that adaptation measures can substantially improve these outcomes. **This chapter picks up where the Chapter 5 analysis leaves off and introduces a toolkit of financial instruments that serve two linked purposes:**

1. **Financing the project's capital expenditure**, including the incremental CAPEX required for adaptation, and
2. **Managing the residual climate risk** that remains once adaptation measures are in place.

The focus throughout this chapter is project finance, consistent with the structure used in Chapter 5, with balance-sheet instruments flagged where they are more commonly used for corporate borrowers such as regulated utilities and tower operators.

The organizing logic is a **matching principle.** Because climate risk reaches projects through specific financial transmission channels, the choice of financial instrument should address the dominant channel(s) affecting the project's cash flows.[463] A toll road exposed primarily to revenue disruption calls for revenue stabilization or liquidity instruments. A project exposed to counterparty credit risk calls for guarantees or credit enhancement. A project facing recurring extreme events calls for risk-transfer mechanisms. In practice, most projects are exposed to more than one channel and require a combination of instruments, but the matching principle keeps the structuring exercise anchored to the specific financial vulnerabilities identified in Chapter 5 rather than to generic instrument labels.

This chapter is organized as follows:

Section 6.1 Financial Instrument Toolkit

Introduces the six families of financial instruments covered in this chapter. See Appendix D for more detailed descriptions and examples of each family of financial instruments.

Section 6.2 Sector Patterns

Applies the matching principle sector by sector, building on the cash flow analysis in *Chapter 5.*

Section 6.3 Practical Three-Step Decision Framework: Classify, Assess, and Match

Provides a three-step decision framework (Classify, Assess, Match) for selecting instruments in practice.

Section 6.4 Other Factors Affecting Instrument Selection

Addresses the contextual factors that shape instrument feasibility.

Section 6.5 Case Studies

Applies the framework to the toll road and solar case studies introduced in *Chapter 5.*

Section 6.6 From Financial Structuring to Risk Transfer

Describes the difference between risk allocation within a capital structure and risk transfer.

6.1 Financial Instrument Toolkit

This section introduces six families of financial instruments used in climate-resilient infrastructure transactions. Each family is defined below, and the transmission channel(s) each family primarily addresses and the component(s) of the cash flow waterfall on which each family acts are specified. Full descriptions, including structure, contractual features, and worked examples, are in Appendix D: Financing Instruments for Climate-Resilient Infrastructure. In most transactions, several families are combined, with the specific mix determined by the project's residual risk profile and the dominant transmission channel(s) identified in Chapter 5.

How Can KPIs Support Effective Use of Financial Instruments

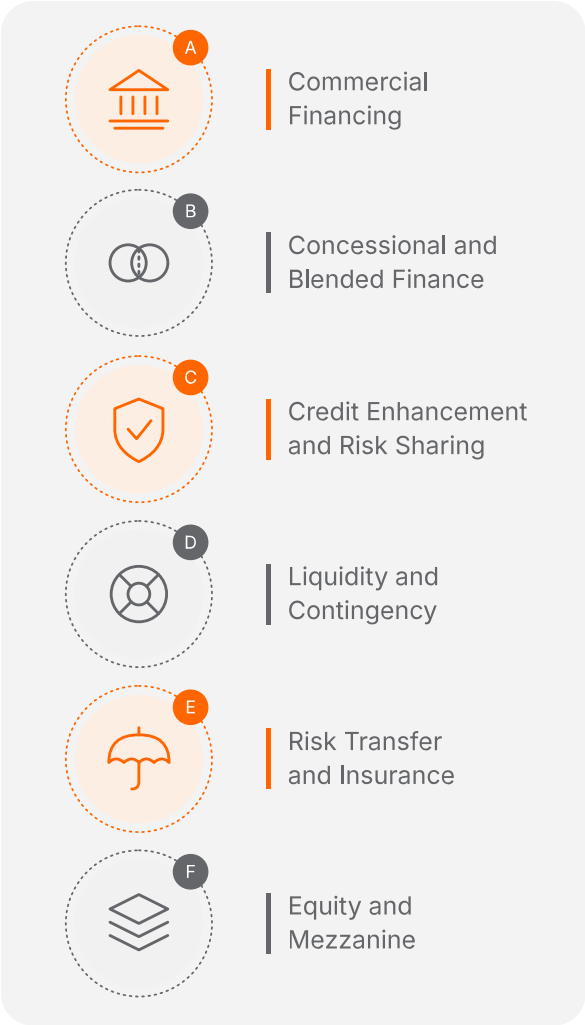
1 **Process KPIs:** These metrics evaluate preparatory activities (e.g., implementing adaptation plans) and include outcome-focused metrics that measure resilience results.

2 **Outcome KPIs:** These measure tangible resilience results (e.g., reduced service disruptions during extreme weather) and demonstrate whether adaptation measures deliver improvements in operational resilience.

Together, process and outcome KPIs can serve as measures for sponsors that signal progress toward resilience outcomes [473]



The six financial instrument families are:



1. *Commercial Financing*

Commercial financing comprises senior project-finance loans, syndicated bank debt, use-of-proceeds bonds (green and blue), sustainability-linked loans (SLLs) and sustainability-linked bonds (SLBs), and results-based financing mechanisms. These instruments form the base layer of the capital structure and fund the bulk of project CAPEX, including adaptation CAPEX, at market terms.[464] They do not address transmission channels directly. Rather, they make the project financeable in the first place, and their pricing and tenor reflect how lenders assess the project's residual climate risk and its capacity to sustain CFADS and DSCR under stress. Commercial financing instruments actively manage residual climate risk. They do not exist solely to fund CAPEX; they can also reward achievement of adaptation KPIs that sustain cash flows and maintain DSCR under climate stress.

2. *Concessional and Blended Finance*

Concessional and blended finance instruments comprise concessional loans, blended finance structures, MDB/DFI A/B loans, subordinated debt and mezzanine financing, first-loss capital, and viability gap funding.[465, 466] These instruments make CAPEX affordable when a project's cash flow cannot support commercial financing terms. They work in two ways. A concessional loan charges a lower interest rate and allows a longer repayment period than a commercial loan, which directly reduces annual debt service and leaves more CFADS available to cover the senior debt. A first-loss or subordinated tranche sits below the senior lenders in the cash flow waterfall. In practice, this means that when CFADS is distributed in the waterfall, senior lenders receive their scheduled interest and principal first. Any remaining cash then flows to the subordinated or first-loss layer, which is paid only if enough cash is available. If the project underperforms and CFADS falls short, the subordinated layer receives less than its scheduled return, or nothing at all, while senior lenders continue to be paid in full. In a default scenario, the subordinated tranche absorbs losses against its principal before any loss reaches senior debt. That loss-absorption role reassures senior lenders, who can then lend at better rates or for longer tenors than they would on a standalone basis. The net effect is a lower WACC and stronger

DSCR headroom, which is particularly useful for adaptation CAPEX, where the benefit is partly externalized, or the payback exceeds commercial tenors, and for projects where credit deterioration or refinancing risk is material.

3. *Credit Enhancement and Risk Sharing*

Credit enhancement instruments comprise partial credit guarantees, partial risk guarantees, and political risk insurance.[467, 468] They work by having a third party, typically an MDB or political risk insurer, promise to step in and pay lenders if a specific type of default occurs. A partial credit guarantee covers a defined portion of debt service if the borrower defaults for any reason. A partial risk guarantee covers losses caused specifically by a government's failure to meet its obligations, such as not honoring a concession contract or a payment guarantee. Political risk insurance covers losses from events like expropriation or currency transfer restrictions. No cash changes hands unless the triggering event occurs. In the waterfall, these instruments do not appear as a line item in normal years; they sit alongside the debt service line as a backstop. Their economic effect is to reduce the probability and severity of loss to senior lenders, which translates into better pricing, longer tenors, and access to sponsors (such as institutional bond buyers) who would not lend without the guarantee.

4. *Liquidity and Contingency*

Liquidity and contingency instruments comprise debt service reserve accounts (DSRAs), Major Maintenance Reserve Accounts (MMRAs), standby and contingent credit facilities, climate-resilient debt clauses, and sovereign contingent instruments such as the World Bank's Catastrophe Deferred Drawdown Option (Cat DDO).[469, 470] These instruments work like cash buffers that the project can draw on when revenues fall short or unexpected costs arise. A DSRA is a ring-fenced account holding enough cash to cover typically six to twelve months of debt service; if revenues dip, the reserve covers debt service while the project recovers. An MMRA serves a related but distinct purpose: it accumulates cash over time to fund large, periodic maintenance and lifecycle expenditures, such as pavement overlays, turbine overhauls, or pump replacements, that would otherwise create sharp spikes in CAPEX and distort CFADS in the year they occur. Regular contributions to the MMRA are treated as an operating outflow in the waterfall, which smooths the cost of major maintenance across the project life and protects DSCR in the years when the work is actually carried out. In the context of climate risk, MMRAs are particularly relevant where adaptation introduces additional long-cycle maintenance needs or where climate stress accelerates asset degradation. A standby credit facility is a pre-arranged loan that the project can draw on if needed, without having to negotiate new financing under stress. Climate-resilient debt clauses allow a borrower to defer debt service after a qualifying disaster, and a Cat DDO gives a sovereign immediate access to pre-approved concessional financing when a disaster strikes. In all cases, the instruments address the gap between CFADS and scheduled debt service: when CFADS temporarily falls below what the project owes, these buffers provide the cash that prevents a covenant breach or default.

5. *Risk Transfer and Insurance*

Risk-transfer instruments comprise indemnity insurance, parametric insurance, and Cat bonds. They address revenue disruption and cost escalation from extreme events by transferring defined portions of loss to the insurance or capital markets in exchange for a premium. Within the waterfall, these instruments restore revenues or offset repair CAPEX and elevated OPEX, stabilizing CFADS under stress. The mechanics of these instruments, including how parametric triggers are designed and how they compare to indemnity cover, are discussed in Chapter 7.

6. *Equity and Mezzanine*

Equity and mezzanine instruments comprise sponsor equity, DFI and climate fund equity, and preferred equity and mezzanine financing. Sponsor equity is the capital the developer puts at risk in the project; it sits at the bottom of the cash flow waterfall, meaning equity holders are paid only after operating costs, taxes, debt service, and all reserves have been funded. If cash flows are strong, equity captures the upside; if climate risk materializes and compresses CFADS, equity absorbs the shortfall, which is why residual climate risk is visible most sharply in IRR and NPV. Mezzanine and preferred equity sit between senior debt and sponsor equity in the waterfall. They take their returns after senior lenders are paid but before common equity, accepting higher risk than senior debt in exchange for a higher return. DFI equity and mezzanine layers bridge the gap between what senior lenders will provide and what sponsors can or will contribute, absorbing losses before senior lenders and improving the senior tranche's credit quality.[471]

Balance-Sheet Applications

Several instruments in the toolkit are more commonly deployed on a corporate or public balance sheet than in project finance. Corporate green bonds, SLBs, and SLLs are typically issued by regulated utilities, tower operators, concession holding companies, and other infrastructure corporates that raise capital at the entity level rather than through a ring-fenced special purpose vehicle (SPV). At the sovereign level, contingent instruments such as the Cat DDO and climate-resilient debt clauses are structured against the public balance sheet rather than against a specific asset.[472] Balance-sheet applications are flagged sector by sector in Section 6.2 where they are material to the instrument mix.

6.2 Sector Patterns

Chapter 5 analyzed how the four transmission channels play out differently across sectors, reflecting the underlying revenue model, counterparty structure, and hazard exposure of each. This section builds on that analysis by identifying which instrument families from the toolkit are most commonly deployed in each sector, and where balance-sheet financing dominates over project finance. **The aim is not to prescribe a single financing package per sector, but to show how the matching principle introduced at the start of this chapter applies when the dominant transmission channel is known.**

Across all sectors, the base of the capital stack is broadly similar:

- **Senior commercial debt**, typically a project-finance loan or a bond, provides the bulk of long-term financing and is the instrument most sensitive to climate-driven changes in DSCR and CFADS.
- **Sponsor equity** sits below the debt in the cash flow waterfall and absorbs residual volatility in IRR and NPV.

The climate-responsive instruments discussed in each sector sub-section below are layered on top of this base to address the specific transmission channels that make commercial debt unaffordable, insufficient, or unavailable on standalone terms. In practice, most resilient infrastructure transactions combine senior commercial debt and sponsor equity with one or more of these specialized instruments; the sector sub-sections below focus on that specialized layer because it is where sector-specific structuring decisions are made.

Transportation

Risk Channel and Financial Impact

Chapter 5 identified transport as primarily exposed to revenue disruption in user-pays models (toll roads, ports, airports), with availability-payment structures shifting the exposure toward cost escalation and counterparty credit risk. Instrument selection follows from this split.

Instrument Selection

For transport projects exposed primarily to **revenue disruption**, instruments that stabilize revenues or provide liquidity during disruption periods are



particularly relevant, because they protect CFADS and support DSCR under stress. These instruments are layered onto a base of senior commercial debt and sponsor equity. Potential mechanisms include:

- **Minimum revenue guarantees:** These guarantees activate when revenues collected by the concessionaire fall below predetermined levels and are commonly used in transport PPPs to mitigate demand risk.[474] In practical terms, this means that if traffic volumes fall substantially below expectations, the government compensates the concessionaire for part of the revenue shortfall.

- **Liquidity mechanisms:** These mechanisms include reserve accounts and contingent credit facilities. Rather than replacing lost revenues permanently, liquidity mechanisms provide cash that allows projects to continue servicing debt and maintaining operations during temporary disruption periods, absorbing short-term CFADS shortfalls without triggering covenant breaches.

Where exposure arises primarily through **counterparty credit risk**, as in availability-payment concessions, financial instruments focus on strengthening payment security rather than stabilizing demand:

- **Partial risk guarantees** can protect lenders if the public authority fails to make contracted availability payments.

- **Sovereign guarantees and related risk-mitigation mechanisms** can also elevate the creditworthiness of the contracting agency and reduce investor exposure to non-payment risk.[475]

Structuring

Complex transport projects exposed to multiple financial channels, or with residual climate risk that remains material after adaptation, **may require blended financing structures** that combine commercial financing with guarantees, concessional loans, or other credit enhancement mechanisms to improve the risk-return profile and mobilize private capital.

Energy

Risk Channel and Financial Impact

Chapter 5 showed that contracted revenue under a long-term PPA does not eliminate climate risk: it shifts exposure from price and demand to availability. The solar case study demonstrated that flood-related outages can compress CFADS below covenant thresholds even under a fixed tariff, with equity IRR and NPV deteriorating sharply. **Instrument selection in the energy sector therefore depends on the interaction between climate hazards and the project's revenue structure.**

Instrument Selection

Projects with **long-term PPAs and strong offtakers** can often access **conventional project-finance instruments** such as commercial project loans or green bonds because contractual revenues provide lenders with predictable cash flows.

Where climate hazards create **moderate residual risk of disruption**, **additional liquidity reserves or insurance products** may be used to manage temporary revenue interruptions and stabilize CFADS.

Projects exposed to **counterparty credit risk**, such as those selling electricity to financially constrained public utilities, may require instruments that strengthen payment security. **Sovereign guarantees and similar credit enhancement mechanisms** can elevate the creditworthiness of the contracting agency and reduce investor exposure to non-payment risk.[476]

Structuring

Where projects face higher residual climate risk or weaker revenue security, blended finance structures may be required to attract private investment. Blended finance uses concessional capital, guarantees, or other risk-sharing instruments to improve the risk-return profile of projects that might otherwise be considered too risky for commercial financing, enabling senior commercial debt to participate alongside concessional tranches.[477]

Financial Instruments for Hydropower

Because hydropower provides such a large share of electricity generation in LAC, drought risk can be systemic rather than project-specific. When hydrological stress affects entire river basins or power systems, project-level instruments alone may not be sufficient to stabilize the sector. Broader measures such as diversification of generation sources, regional risk-sharing mechanisms, or contingent public financing may therefore complement project-level financial structures.[478, 479]

Water and Sanitation

Risk Channel and Financial Impact

Chapter 5 showed that water infrastructure is less frequently financed through fully non-recourse project finance, with investment typically led by the public sector and tariff adjustments often lagging cost increases. The result is that climate shocks tend to reach water projects primarily through **cost escalation and credit deterioration**, rather than through revenue disruption in the same way as transport. Financing structures in the sector therefore often combine guarantees, subsidies, and concessional capital to stabilize project cash flows and maintain DSCR under stress.

Instrument Selection

Partial credit guarantees can improve financing terms by covering a defined portion of debt service shortfalls or repayment obligations, thereby reducing lender credit risk. Partial risk guarantees protect lenders and sponsors against specific government-related events that undermine a project's ability to generate or receive expected cash flows, such as public-sector non-payment, breach of contractual obligations, or adverse regulatory action.[480]

Where tariff revenues alone are insufficient to make water projects financially viable, governments may provide **viability gap funding or targeted subsidies** to maintain affordability while preserving bankability.[481] This is common across LAC, where tariffs often do not achieve full cost recovery. In several Caribbean countries, tariffs charged by state-owned utilities fail to cover the full operating and capital costs of service provision, making ongoing government support necessary to sustain service delivery.[482]



Water scarcity can also increase the need for **concessional capital** in island and water-stressed systems. The Food and Agriculture Organization classifies countries such as Barbados and Antigua and Barbuda as water-scarce, with renewable freshwater availability below 1,000 cubic meters per person per year (FAO, 2016).

Structuring

In these contexts, water projects may need a combination of bond financing, public payment support, and credit enhancement to become bankable. Peru's Huascacocha water transfer PPP illustrates this approach. The project raised approximately S/321 million (about $116 million) through a project bond, while revenues were supported by government payment certificates issued by the public offtaker. This structure helped create a more predictable payment stream for the concessionaire and lenders, supporting financing despite the project's reliance on public-sector demand.[483]

Telecommunications

Risk Channel and Financial Impact

Chapter 5 distinguished three patterns within telecommunications:

1. Tower operators with long-term tenancy contracts exposed primarily to cost escalation and liquidity pressure after extreme events;
2. Retail and data center providers exposed to short-term revenue disruption during outages; and
3. Public telecommunications infrastructure dependent on fiscal capacity.

Instrument selection differs across these segments. Regulated tower operators and integrated telecoms typically raise capital on their balance sheet rather than through project finance, so several of the instruments discussed here are more commonly deployed at the corporate level.

Instrument Selection

Telecommunications tower portfolios supported by long-term tenancy contracts can often sustain **commercial bank debt or bond financing**, because baseline revenues are underpinned by multi-year lease agreements with mobile network operators. In such cases, the main resilience challenge is usually not an immediate collapse in contracted revenue, but ensuring that operators have sufficient liquidity to fund restoration, maintain service continuity, and finance infrastructure hardening after extreme events**. Liquidity reserves, committed contingency financing arrangements, and financing for resilience capital expenditure** can therefore play an important role in protecting CFADS and supporting timely repair CAPEX.

For telecommunications providers whose revenues depend more directly on continuous service provision to consumers, the primary financial vulnerability is **short-term revenue interruption** during network outages. **Financing structures that emphasize liquidity** buffers and restoration financing can therefore help stabilize operations and cash flows after disasters.

Data centers face a related challenge centered on **operational continuity**. Investments in redundancy, backup power systems, and cooling capacity can reduce vulnerability to electricity outages and extreme heat. Financial structures may therefore emphasize **resilience capital expenditure and contingency liquidity**.

Structuring

Public telecommunications infrastructure may require additional policy and financial support. Disaster-contingent financing mechanisms, including state-contingent debt clauses that temporarily defer debt service after major disasters, can provide immediate liquidity relief when governments face large reconstruction costs. These mechanisms have been used in sovereign debt instruments to create fiscal space following disasters.



Social Infrastructure

Risk Channel and Financial Impact

Chapter 5 showed that social infrastructure is typically funded through public budgets or availability-based payment structures, with climate shocks transmitted less through project revenues than through pressure on public finances.

Instrument Selection

Cost escalation and credit deterioration are the dominant channels, and the relevant financial instruments therefore operate primarily at the sovereign or sub-sovereign level rather than at the individual asset level. Financial instruments in social infrastructure are usually most relevant when they address public-sector liquidity first and reconstruction funding second. Immediate post-disaster financing needs are typically best met through **pre-arranged contingent financial arrangements**, including contingent credit lines and insurance, because these can make financing available quickly and reduce delays associated with budgetary procedures.[484]

Structuring

When bigger shocks occur, there is a need not just for quick access to funds, but also for resources to support rebuilding efforts. To meet these needs, **governments can structure disaster risk financing instruments in layers**: reserve funds for lower-cost, higher-probability events; contingent financing or sovereign risk transfer for higher-cost, lower-probability shocks; and insurance to help finance repairs and reconstruction where markets are sufficiently mature and affordable.[486] The most relevant financing package for social infrastructure is therefore often layered in this way, with reserves or budget reallocations covering smaller shocks, contingent liquidity addressing the immediate post-disaster period, and borrowing or risk-transfer instruments handling large reconstruction needs. The next section examines how physical adaptation changes the need for these instruments and the range of financing options available.

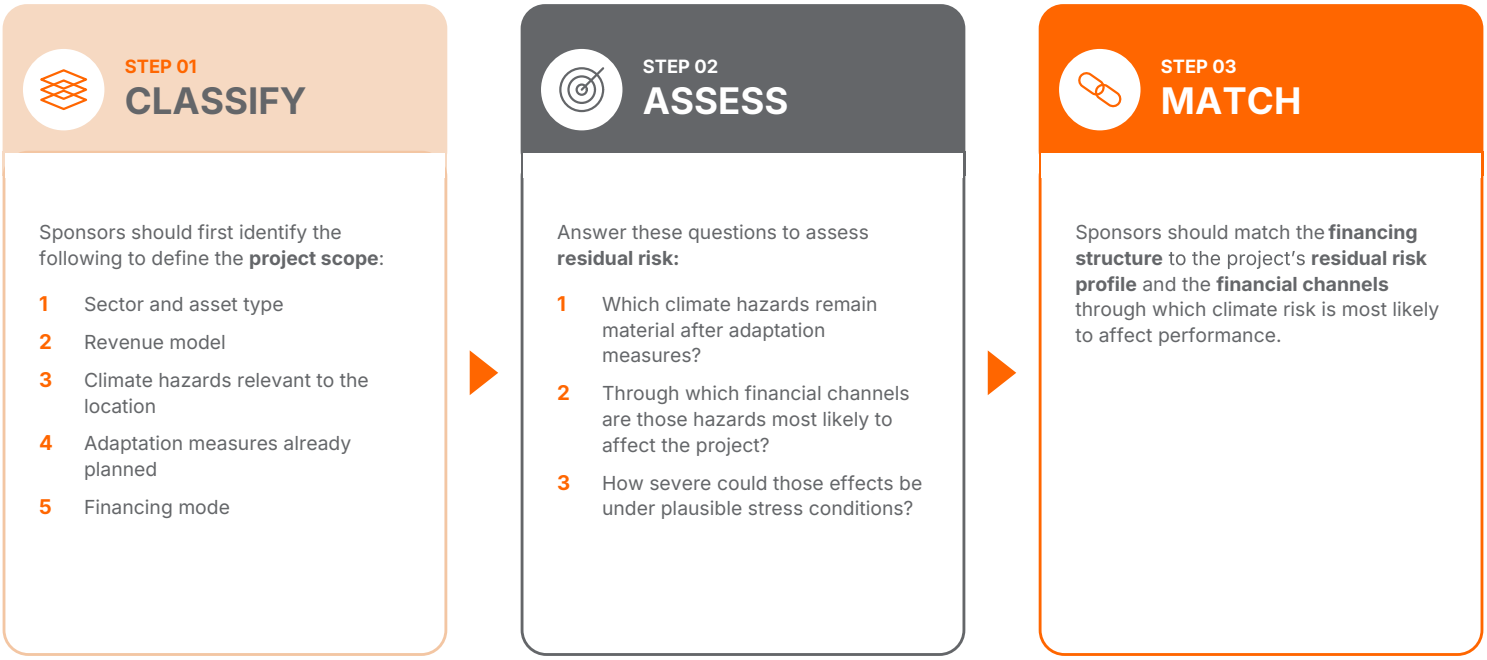
Example Contingent Financial Arrangements: Colombia

Colombia's disaster risk management report states that contingent loans such as the World Bank Cat DDO give the government **immediate and timely access to liquidity in case of a national disaster.** The report also states that the government had a $150 million contingent credit line and requested full disbursement in December 2010 due to the effects of La Niña 2010–2011. At the regional level, the IDB's Contingent Credit Facility provides a further public-liquidity instrument aligned with this sector. It offers parametric natural disaster coverage of up to $300 million or 2% of GDP, whichever is less, with proceeds reserved for extraordinary government expenditures during the post-event emergency period.[485]

6.3 Practical Three-Step Decision Framework: Classify, Assess, and Match

The preceding sections set out the logic linking climate hazards to project cash flows and financing needs. This section translates that logic into a practical framework for transaction structuring. **The objective is not to prescribe a single instrument for each project, but to narrow the field to financing structures that fit the project's climate exposure, cash flow model, and residual risk after adaptation (see Figure 8).**

Figure 8. Three-step decision framework: Classify, assess, match



Sponsors can leverage this guide to apply the three-step framework:

1. **Classify:** Chapter 3 provides an overview of climate change trends in LAC and can help sponsors identify which climate hazards are relevant to their location. Chapter 4 can then be used to understand asset-specific vulnerabilities and select appropriate adaptation measures.

2. **Assess:** Chapter 5 provides a structured approach to help sponsors move from project-specific cost inputs to financial model outputs. This chapter can be used to understand how climate risks and adaptation measures affect financial performance.

3. **Match:** Chapter 6 provides a financial instrument toolkit to help sponsors match the financing structure to the project's residual risk profile and the financial channels through which climate risk is most likely to affect performance. This chapter can be used to match the appropriate financing structure.



Step 1: Classify

The first step is to classify the project so that the financing analysis begins from the correct baseline. Before selecting any financial instrument, the project should be defined along five dimensions:

- Sector and asset type
- Revenue model
- Climate hazards relevant to the location
- Adaptation measures already planned
- Financing mode

The **sector and asset type** establish the basic parameters of the analysis: whether the project is in energy, water, transport, or another sector, and what kind of asset is being financed, such as a generation facility, a transmission line, a treatment plant, or a road concession. These determine which risks are structurally relevant and which financing approaches are commonly applied.

The **revenue model** is especially important, and the same type of project can carry very different revenue exposures depending on how it is structured. A power project may sell electricity at spot market prices, making it sensitive to both generation volumes and price volatility, or it may operate under a long-term PPA that provides contracted revenues but still leaves the developer exposed if it cannot generate or deliver. A water or transport asset may operate under a regulated tariff regime, a concession with volume-linked revenues, or an availability-payment structure where the public sector pays regardless of usage. Each arrangement implies a different risk profile, even for assets that are otherwise technically identical. Identifying which revenue mechanism applies, and whether more than one is active simultaneously, is therefore a prerequisite for meaningful risk assessment.

Hazard exposure must also be defined in project-specific terms. Coastal assets may face hurricanes, storm surge, coastal flooding, and sea level rise, while inland assets may be more exposed to river flooding, landslides, drought, or extreme heat. Sponsors can use Chapter 3 of this

guide to determine which hazards are most relevant based on the geo-type of the asset location.

Planned adaptation measures must be incorporated at this stage as well, because financing should be matched to the risk that remains after physical resilience measures are taken into account, rather than to the unmitigated hazard. Sponsors can use Chapter 4 of the guide to understand asset-specific vulnerabilities at the project site and select appropriate adaptation measures.

Financing mode determines which instruments are available and how they are deployed. Project finance, consistent with the focus of this chapter and Chapter 5, involves a ring-fenced SPV repaid from project cash flows. Corporate-balance-sheet financing raises capital at the entity level and is common for regulated utilities, tower operators, and infrastructure holding companies. Public-balance-sheet financing sits at the sovereign or sub-sovereign level and is typical of social infrastructure and large-scale public works. Several instruments in the toolkit (Section 6.1) are more commonly deployed in one mode than another.

Step 1 therefore establishes the analytical baseline for financing: what the asset is, how revenues are generated, which hazards are material, how much of that risk is already being reduced through adaptation, and which financing mode is in scope.

Step 2: Assess

Once the project has been classified, the next step is to assess how climate risk is likely to affect financial performance after planned adaptation measures are taken into account. The purpose of this step is to move from a descriptive understanding of hazard exposure to a decision-useful view of residual financial risk. Sponsors can use Chapter 5 of this guide to understand how climate risks and adaptation measures affect financial performance.

This assessment should examine three questions:

1. Which climate hazards remain material after adaptation measures are incorporated?
2. Through which financial channels are those hazards most likely to affect the project: revenue disruption, cost escalation, credit deterioration, refinancing risk, or some combination of these?
3. How severe could those effects be under plausible stress conditions?

At this stage, the analysis should translate physical climate exposure into financial terms. That may include estimating expected damage, likely downtime, potential revenue loss, cost increases, pressure on debt service, and the implications for refinancing or payment reliability. Where sufficient data are available, the analysis may also include quantitative metrics such as expected annual loss, value at risk, and projected debt service coverage under stress scenarios. Where data are more limited, a structured qualitative assessment may still be sufficient to identify the dominant financial vulnerabilities.

The result should be a practical classification of residual risk as Low, Moderate, or High, together with the identification of the dominant transmission channel or channels through which that residual risk reaches the project's financial performance. This pair of outputs drives the matching step: the residual risk level indicates how much structuring support is needed, and the dominant channel indicates which instruments to reach for.

Step 2 therefore determines not only whether climate risk remains, but whether the remaining exposure is material enough to shape financing choices, and through which channels it does so.

Step 3: Match

The final step is to match the financing structure to the project's residual risk profile and the financial channels through which climate risk is most likely to affect performance. The aim is not to identify one instrument in isolation, but to assemble a financing structure that fits the project's residual risk profile. Sponsors can use this chapter (Chapter 6) to match appropriate financial instruments.

The matching logic has two layers. The dominant channel identifies which instrument families to reach for; the residual risk level determines how intensively they are deployed. Table 32 maps each transmission channel to the primary instrument families and specific instruments that address it, with cross-references to Section 6.1 and Appendix D.

Table 32. Crosswalk from transmission channels to instrument families

Transmission Channel	Primary Instrument Families	Specific Instruments	Appendix D Sub-Sections
Revenue disruption	Liquidity and contingency Credit enhancement Risk transfer	Debt service reserve accounts, standby and contingent credit facilities, minimum revenue guarantees, availability-payment structures, parametric and indemnity insurance	D C E
Cost escalation	Liquidity and contingency Risk transfer	MMRAs, standby and contingent credit facilities, indemnity insurance, parametric insurance for extreme events	D E
Credit deterioration	Credit enhancement Concessional and blended finance	Partial credit guarantees, partial risk guarantees, political risk insurance, subordinated debt and mezzanine, first-loss capital, MDB/DFI A/B loans	C B
Refinancing risk	Credit enhancement Concessional and blended finance Liquidity and contingency	Partial credit guarantees, climate-resilient debt clauses, Cat DDO, concessional loans with extended tenors, A/B loans	C B D

The overall financing logic is as follows. Projects with lower residual climate risk and more stable revenues can generally rely more heavily on conventional commercial financing. As residual risk increases, projects typically require more liquidity protection, more risk transfer, more credit enhancement, or a greater role for concessional or public support.

For projects with low residual risk, financing may be based primarily on standard commercial instruments because expected cash flows remain relatively stable even under climate stress. Depending on the revenue model and credit profile, this may include commercial project-finance loans, infrastructure bonds, green bonds, or SLLs. In these cases, climate resilience still matters, but it is more likely to influence pricing,

investor confidence, and access to capital than to determine basic bankability.

For projects with moderate residual risk, the financing structure often needs to combine commercial capital with instruments that absorb part of the remaining downside risk. Relevant tools may include MDB A/B loan structures, partial credit guarantees, subordinated debt from climate-focused funds, contingent liquidity facilities, and parametric insurance. These instruments do not eliminate the underlying climate exposure, but they can help stabilize debt service, improve lender confidence, and provide liquidity after disruption events.

For projects with high residual risk, conventional commercial financing may not be sufficient on a standalone basis. In such cases, the financing package may require concessional loans, first-loss capital, grant support for adaptation measures, public guarantees, and catastrophe risk backstops. The purpose of these instruments is to absorb risks that private lenders or sponsors are unlikely to accept without substantial support, particularly where climate shocks could materially impair revenues, increase costs, or disrupt repayment capacity.

Some instruments relevant at the moderate and high tiers may operate at the sovereign or public-balance-sheet level rather than directly at the project level. This is especially important where governments remain the ultimate financial backstop after climate shocks, whether through reconstruction spending, public payment obligations, or sector-wide liquidity support. Instruments such as contingent credit facilities, disaster risk financing arrangements, or climate-resilient debt clauses may therefore be highly relevant even where the immediate asset-level financing structure appears project-based.

Step 3 aligns the financing package with the project's remaining climate-related vulnerabilities. In most cases, resilient infrastructure transactions rely on a combination of instruments rather than a single financing tool.

6.4 Other Factors Affecting Instrument Selection

The three-step framework in Section 6.3 helps identify which instruments are broadly suited to a project's residual climate risk, dominant transmission channel, and cash flow profile. In practice, however, final instrument selection is also shaped by transaction-specific constraints. Contractual terms, regulatory frameworks, public-sector capacity, political conditions, and sponsor objectives can all narrow the set of instruments that are feasible in a given case. **This section highlights the main contextual factors that can affect whether an otherwise suitable instrument can actually be deployed.**

Contractual Constraints: Existing contractual arrangements may limit the ability to introduce climate resilience features after financial close. Long-term PPP concession agreements negotiated before climate risks were fully incorporated into project structuring may not accommodate resilience upgrades, climate-contingent payment mechanisms, or force majeure provisions suited to slow-onset impacts. In practice, this means that instrument suitability is not determined only by risk profile, but also by whether the contractual framework can support the required allocation of risk, payment flexibility, and upgrade obligations. For new transactions, climate-related provisions should therefore be incorporated from the outset, including explicit climate risk allocation, provisions for resilience upgrades, renegotiation triggers, and force

majeure definitions that reflect relevant hazard types.

Credit and Financing Conditions: Climate risk can also affect instrument selection through credit conditions. Even where a project's operating model appears sound, lenders and sponsors may price climate exposure through stricter DSCR covenants, shorter tenors, wider spreads, or additional credit support requirements. Conversely, stronger climate risk assessment and adaptation planning may support lender confidence by demonstrating that downside risks to CFADS have been identified and addressed. The practical implication is that climate resilience influences not only the need for particular instruments, but also the terms on which financing can be raised.

Political, Regulatory, and Social Context: Instrument selection must also reflect the broader political, regulatory, and social environment in which the project operates. Government policy stability, tariff-setting frameworks, permitting processes, community acceptance, and macro-fiscal conditions all affect financing viability. In LAC, infrastructure conflicts have often been shaped not only by technical or financial issues, but also by politicization, weak upstream analysis, and community opposition. An instrument that is theoretically suitable may therefore still be impractical if it depends on tariff increases that are politically infeasible, public guarantees that are fiscally constrained, or contractual arrangements that lack social legitimacy.

Equity and Sponsor Considerations: Instrument selection is also influenced by the return expectations and risk tolerance of sponsors and equity providers. Climate risk affects equity directly through dividend volatility, impairment risk, and the potential need for additional capital injections after major shocks, with corresponding pressure on IRR and NPV. Projects with higher residual climate risk may therefore require either higher expected returns or sponsors with a greater willingness to accept long-dated or development-oriented risk. This can create a role for DFIs, impact sponsors, climate-focused funds, or other mission-driven capital providers alongside purely commercial sponsors. From a sponsor perspective, resilience measures are relevant not only because they reduce physical risk, but also because they help protect long-term asset value and the durability of equity returns.

6.5 Case Studies

The case studies below build directly on the financial model introduced in Chapter 5 and the structuring framework developed in Section 6.3. Each case illustrates how specific financial instruments are used to address the dominant constraint preventing a project from reaching financial close.

Rather than introducing new project types, the cases use the same underlying project structures from Chapter 5 and compare scenarios: base conditions, climate stress, partial adaptation, and adaptation combined with financial instruments. This allows the effect of financial structuring to be isolated and assessed in a consistent way. The first two cases continue the toll road and solar projects introduced in Chapter 5. The third case presents a high-risk variant of the highway project, in which adaptation alone is insufficient and a blended finance structure becomes necessary.

The objective is to demonstrate how targeted instruments translate into improvements in DSCR, CFADS, bankability, and IRR, and to show how these effects differ depending on the underlying transmission channels.



Highway Toll Road Concession

This case continues the toll road concession introduced in Chapter 5. It applies the framework to a transport project where revenue disruption remains the dominant constraint after partial adaptation. It represents a typical moderate-residual-risk situation, where physical resilience improves performance but does not fully restore bankability.

Under partial adaptation, the project benefits from reduced disruption, with revenue losses declining from 13% to 8%. This improves CFADS and DSCR, but the minimum DSCR remains at 1.10x, below the covenant threshold. Covenant breaches persist and the project remains unfinanceable on commercial terms.

The remaining constraint is therefore not overall performance, but downside revenue volatility in stress years, which directly affects CFADS and DSCR. This identifies revenue disruption as the binding transmission channel and provides a clear basis for instrument selection.

The financing response follows directly from this diagnosis. A minimum revenue guarantee is introduced to stabilize revenues in the worst years, combined with an enhanced DSRA to address temporary liquidity shortfalls. The improved risk profile also allows for a modest reduction in the cost of debt.

In practice, minimum revenue guarantees are typically provided by the public sector under the concession agreement, as they represent a contingent fiscal commitment linked to demand risk. In some cases, they may also be supported or structured with the involvement of development finance institutions, particularly where fiscal capacity is constrained.

The cost of the guarantee is usually structured as a periodic fee or embedded in the overall concession terms. In this case, the annual cost is modest, on the order of $0.05 to $0.10 million per year, and is largely offset by the reduction in debt service resulting from improved credit conditions. The economic value of the instrument lies less in the direct cash transfer and more in its effect on DSCR in downside scenarios.
A key consideration is timing. Securing a minimum revenue guarantee typically requires government approval and negotiation as part of the concession agreement or financing package. This process can take several months and, in some jurisdictions, significantly longer due to fiscal approval procedures and contingent liability assessments. As a result, while the instrument improves bankability, it may extend the time required to reach financial close.

The impact of these instruments is summarized below in Table 33.

Table 33. Highway toll road: Impact of financial instruments

Metric	Partial Adaptation	With Financial Instruments	Effect
Min DSCR	1.10x	1.32x	Covenant restored
Equity IRR	10.2%	13.0%	Above hurdle
Covenant breaches	3 years	0	Eliminated
Lock-up years	5	0	Removed

The improvement in DSCR is driven primarily by the revenue guarantee, which stabilizes CFADS in the worst-performing years. The DSRA provides an additional buffer, ensuring that debt service can be maintained even during temporary disruptions.

The cash flow waterfall confirms this mechanism. In stress periods, the minimum revenue guarantee (MRG) provides a top-up to revenues, while reserve releases ensure continuity of debt service. This stabilizes the lower end of the cash flow distribution, which is the binding constraint for lenders.

This case illustrates a key principle: when the binding constraint is revenue volatility, targeted instruments that stabilize CFADS can restore bankability. However, these instruments come with tradeoffs in terms of negotiation complexity and timing, which must be factored into structuring decisions.

Utility-Scale Solar Under Power Purchase Agreement

This case continues the utility-scale solar project introduced in Chapter 5. It illustrates a project where the primary constraint is not revenue volatility in the traditional sense, but a combination of operational risk and the cost of capital. Under a long-term PPA, revenues are contractually secured, but climate-related disruptions still affect generation and therefore CFADS. In addition, the cost of financing plays a critical role in determining whether DSCR meets lender requirements.

Under partial adaptation, the project benefits from improved resilience, with revenue losses reduced from 13% to 6%. This leads to a meaningful improvement in CFADS and DSCR. However, the minimum DSCR remains at 1.10x, below the covenant threshold. While the project performs adequately in most years, it remains vulnerable in downside scenarios and cannot reach financial close on commercial terms.

The binding constraint in this case is therefore the cost of capital, which keeps debt service at a level that compresses DSCR in stress conditions. This differs from the highway case, where revenue volatility was the primary issue.

The financing response reflects this diagnosis. A concessional loan is introduced to replace a portion of the commercial debt, reducing the overall cost of financing. This is combined with an enhanced DSRA to provide liquidity during temporary disruptions, an MMRA to manage lifecycle maintenance costs, and parametric insurance to limit exposure to extreme events.

The MMRA works by setting aside cash during normal operating years to fund large, periodic maintenance expenditures that the solar plant will incur over its life, such as inverter replacements, substation overhauls, and module cleaning and repair programs. Rather than paying for these

expenditures in a single year and creating a sharp drop in CFADS and DSCR when the work is carried out, the project makes regular contributions to the MMRA during normal years. The contributions are treated as an operating outflow in the cash flow waterfall, which smooths the cost of major maintenance across the project life. When the expenditure is actually carried out, the work is funded from the MMRA rather than from that year's operating cash flow, protecting CFADS and DSCR in the maintenance year. In the context of climate risk, the MMRA is particularly relevant here because flood exposure and extreme heat can accelerate degradation of inverters and electrical equipment, increasing both the scale and frequency of lifecycle maintenance requirements.

In practice, concessional financing is typically provided by multilateral development banks or development finance institutions. These lenders offer capital at below-market rates and longer tenors, reflecting their development mandate. In this case, approximately 30% of the debt is provided as concessional financing, significantly reducing the overall debt service burden.

The cost of concessional financing is embedded in its pricing structure. Interest rates are typically several hundred basis points below commercial rates, and longer tenors further reduce annual debt service. While these instruments may involve fees or conditions, their net effect is a reduction in the WACC. This translates directly into improved DSCR and higher equity returns. However, concessional financing also affects transaction timelines. Securing such financing typically requires detailed appraisal processes, alignment with development objectives, and coordination with other lenders. This can extend the time to financial close by several months, particularly where multiple institutions are involved.

The impact of the instrument package is summarized below in Table 34.

Table 34. Utility-scale solar PV: Impact of financial instruments

Metric	Partial Adaptation	With Financial Instruments	Effect
Min DSCR	1.15x	**1.38x**	**Covenant restored**
Debt service	High	**Reduced**	**Primary driver**
Equity IRR	10.0%	**13.5%**	**Fully restored**
Lock-up years	4	**0**	**Eliminated**

The improvement in DSCR is driven primarily by the concessional loan, which reduces annual debt service and increases the margin available under stress scenarios. The DSRA provides additional liquidity support, while the MMRA smooths maintenance-related cash flow variability over time. Parametric insurance limits the impact of extreme events, further reducing downside risk.

In the cash flow waterfall, CFADS is unchanged by the concessional loan, since it is determined by the project's revenues and operating costs rather than by its financing terms. What changes is the debt service line below CFADS: a lower interest rate and longer tenor reduce scheduled debt service, so the ratio of CFADS to debt service (DSCR) improves, and more cash remains

available for equity distributions. Unlike the highway case, where revenue support was the key driver and CFADS itself was lifted by the MRG, here the improvement comes from lowering the financing burden that CFADS has to cover.

This case highlights an important distinction. When the binding constraint is the cost of capital rather than revenue volatility, concessional financing is the most effective instrument. It improves both DSCR and IRR by reducing debt service and increasing the share of cash flows available to equity.

At the same time, the use of concessional financing introduces tradeoffs. It can increase transaction complexity and extend the time to financial close, and it may involve conditions related to environmental or development objectives. These factors must be considered alongside the financial benefits.



High-Risk Highway Variant: Blended Finance Required

This case presents a high-risk variant of the highway project, in which the climate exposure is more severe than in the base case of the highway toll road concession project. It illustrates a situation where climate exposure remains significant even after substantial adaptation measures are implemented, placing the project in the high residual risk category described in Section 6.3, Step 3. It shows that neither adaptation nor a single financial instrument is sufficient to restore bankability, and that a layered financing structure is required.

Under the adaptation-only scenario, the project incorporates a comprehensive resilience package. This reduces revenue losses from 25% to 10%, representing a significant improvement. However, the increased capital expenditure required for adaptation raises the overall financing requirement, and the resulting debt service remains high. As a result, the minimum DSCR remains at 0.97x, below 1.0x, meaning that the project is unable to service debt in the worst years. The project therefore remains unfinanceable.

The binding constraint in this case is structural. Both revenue volatility and cost escalation remain material, and the overall risk profile exceeds what commercial lenders can accept.

The financing response reflects this. Rather than targeting a single constraint, the structure redistributes risk across multiple layers of capital. Concessional financing is introduced to reduce the cost of capital, first-loss capital is used to absorb downside risk, and an MRG stabilizes revenues. A partial credit guarantee further improves the credit profile of the senior debt.

Each of these instruments is typically provided by a different type of stakeholder. Concessional financing is generally provided by multilateral development banks or development finance institutions. First-loss capital is often provided by climate funds or impact sponsors willing to accept higher risk in exchange for development impact. Revenue guarantees are provided by the public sector as part of the concession framework, while credit guarantees are typically issued by development institutions.

The role of these instruments becomes clear when viewed through the cash flow waterfall. Project revenues first cover operating costs, after which CFADS is available for debt service. Senior lenders are paid first, followed by concessional lenders, subordinated capital providers, and finally equity.

In stress scenarios, where revenues decline significantly, the structure ensures that losses are absorbed before they reach senior debt. Reserve accounts provide initial liquidity. If this is insufficient, first-loss capital absorbs the next layer of losses. The MRG stabilizes revenues at a floor level, and concessional financing reduces the overall debt service burden. As a result, senior lenders continue to be repaid even under adverse conditions.

The impact of this structure is summarized below in Table 35.

Table 35. High-risk highway variant: impact of blended finance structure

Metric	Adaptation Only	With Blended Structure	Effect
Min DSCR	0.97x	**1.30x**	**Bankability restored**
Bankability	Not feasible	**Achieved**	**Enabled**
Equity IRR	4.5%	**9.2%**	**Improved but constrained**
Covenant breaches	Persistent	**Eliminated**	**Risk reduced**

The improvement in DSCR reflects the combined effect of all instruments. Concessional financing reduces annual debt service, first-loss capital protects senior lenders from downside risk, and the revenue guarantee stabilizes CFADS. Together, these measures increase DSCR by more than 0.30x, sufficient to meet lender requirements.

However, this improvement comes with tradeoffs. Blended finance structures are inherently complex. They involve multiple stakeholders with different objectives, require coordination across institutions, and typically extend the time required to reach financial close. In this case, transaction timelines may increase significantly (if reached at all) relative to a standard commercial structure. The cost of these instruments is also distributed differently. Concessional lenders accept below-market returns, while first-loss sponsors accept higher risk and lower expected returns.

Guarantees may involve fees or fiscal commitments. While these costs reduce overall returns, they are necessary to enable the project. From an investor perspective, the resulting IRR of 9.2% remains below typical commercial thresholds. However, this reflects the underlying risk of the project rather than inefficiency in the financing structure. Without these instruments,

the project would not proceed at all. The role of the blended structure is therefore enabling rather than optimizing returns.

This case illustrates a key principle. In high-risk environments, financial instruments do not simply improve performance; they fundamentally change the feasibility of the project. By redistributing risk across stakeholders with different risk appetites, they make investment possible where it would otherwise not occur.

6.6 From Financial Structuring to Risk Transfer

The instrument families covered in this chapter work primarily by allocating climate-related risk within the project's capital structure: between senior and subordinated lenders, between sponsors and third-party guarantors, and between the project and the public sector. They address residual risk by changing who bears the financial consequences of disruption when it occurs, and by ensuring sufficient liquidity to absorb temporary shortfalls. What they do not do is move risk outside the capital structure altogether.

That function belongs to risk-transfer instruments, principally insurance, parametric products, Cat bonds, and related capital-market mechanisms, which convert specific climate exposures into a premium paid to a third party willing to assume the loss. These instruments are particularly important for low-frequency, high-severity events that cannot be efficiently managed through reserves or subordinated capital, and for project types where lender requirements make insurability a precondition for financial close. The next chapter examines the insurance landscape available to infrastructure sponsors in LAC and sets out a framework for assembling a layered risk-transfer strategy that complements the financial structuring approach developed here.



07

Insurance Landscape *for Sponsors*

This chapter examines five risk-transfer options that sponsors can combine to build a strong, bankable insurance strategy. As climate hazards intensify across LAC, the ability to transfer climate risk effectively through insurance is becoming a core determinant of infrastructure bankability. Physical climate risks translate directly into higher deductibles, reduced limits, exclusions, and volatility in insurance pricing, with clear implications for debt service coverage, covenant compliance, and investor returns. While insurance markets in Chile, Brazil, and Mexico offer deep capacity and sophisticated catastrophe modeling, availability and affordability remain constrained in the Caribbean and parts of Central America, where high catastrophe exposure and limited local capacity drive elevated premiums and retentions.

To preserve financial resilience and maintain lender confidence, infrastructure sponsors must move beyond single-policy solutions and adopt a layered risk-transfer strategy. In deeper insurance markets, this may begin with standard project-level indemnity coverage for construction and operations, complemented by parametric insurance and larger-scale instruments such as Cat bonds, public risk pools, and resilience-linked structures. In more capacity-constrained markets, including parts of the Caribbean and Central America, the same strategic logic still applies, but the structure may rely more heavily on partial indemnity protection, higher retentions (i.e., deductibles), parametric products for rapid liquidity, sovereign or regional risk-pooling mechanisms, concessional or public support arrangements, and other forms of contingent financing. In this sense, a layered approach is not dependent on insurance availability; rather, it is a way of combining available market, public, and financial instruments to address protection gaps, liquidity needs, and affordability constraints. Importantly, well-designed risk-transfer programs can also reinforce Environmental, Social, and Governance (ESG) objectives by incentivizing adaptation, strengthening recovery capacity, and improving long-term asset resilience—factors increasingly recognized by lenders, insurers, and development finance institutions. By aligning insurance strategy with hazard profiles, project stage, and capital structure, sponsors can protect assets, satisfy lender requirements, and convert climate resilience into a measurable financial advantage.

The discussion that follows addresses not only how sponsors can optimize insurance in mature markets, but also how they can assemble workable risk-transfer structures where private insurance capacity is limited, costly, or uneven.

7.1 Selecting Risk-Transfer Options for Resilience

Risk-Transfer Options: Strengths, Weaknesses, and Smart Combinations

Infrastructure sponsors in LAC face a wide range of climate-driven hazards, insurance market conditions, and financing requirements that cannot be addressed through a single risk-transfer instrument. The section below provides a structured overview of the five principal risk-transfer options examined in this document, highlighting how each mechanism functions, the types of risks it addresses, and its relevance across project stages and regional contexts. Together, these instruments form the building blocks of a layered insurance strategy designed to protect asset value, preserve liquidity, and support long-term bankability.

To manage rising climate volatility, sponsors, lenders, and project sponsors should adopt a layered “risk stack” strategy that integrates multiple financial instruments and embeds adaptation measures directly into investment planning. This approach is intended to illustrate how different risk-transfer options can be combined into a coherent, complementary structure—each playing a distinct role in managing physical damage, cash flow disruption, and extreme loss volatility, particularly in markets where insurance capacity is constrained or climate exposure is acute. A well-constructed risk stack aligns protection with the asset’s risk profile, improves cash flow stability, and strengthens long-term resilience—ultimately minimizing liquidity gaps, protecting asset value, lowering long-term expected average annual losses (AAL), and improving bankability and project stability. The five risk-transfer options are illustrated in the graphic below.

Note on Case Studies

The case studies mentioned throughout this chapter are largely based on insurance policies held by public entities. This is due to the lack of real-world and publicly available private insurance structures in the relevant research and literature.

Figure 9. Overview of different risk-transfer options

	Traditional Indemnity Insurance	Parametric Insurance	Cat Bonds and ILS	Risk Pools & Public Insurance	Resilience-Linked and Public De-Risking Instruments
What it is	Covers physical damage & revenue losses; mandatory under financing agreements	Pays predefined amounts when hazard intensity (e.g., wind speed, earthquake magnitude) hits a set trigger; no loss adjustment required	Transfers low-frequency, high-severity climate risks to capital markets; relevant where traditional insurance capacity is limited	Aggregates risk across countries/sectors to improve affordability & access where standalone capacity is limited	Links insurance & financing terms to resilience KPIs; rewards adaptation with improved coverage or lower premiums
Pros	Lender-preferred; broad coverage; payout tied to actual damage	Fast, transparent payouts; fills gaps where indemnity deductibles are high; resilience measures can lower premiums & narrow basis risk	Multi-year price stability; broad investor base; transparent triggers; adaptation measures can improve pricing & investor confidence	Efficient pooled pricing; rapid payouts; regional hazard expertise; adaptation measures lower pooled losses & improve long-term solvency	Aligns incentives for resilience investment; pricing improves as risk reduces; can unlock concessional capital & guarantees
Cons	Slow payouts; coverage disputes; high deductibles; requires physical damage to trigger	Potential basis risk due to payouts based on hazard index, not actual loss; cannot fully replace indemnity insurance	Complex & costly to structure; minimum size thresholds; best suited to large portfolios or national programs	Not tailored to individual projects; modest payouts relative to total losses; vulnerable to political influence	Limited standardization in LAC; requires robust KPI verification; high structuring costs
Best use-case	Core risk layer; pair with parametric for faster liquidity	First-responder liquidity layer; pairs with indemnity to cover immediate post-event financial needs	Sovereign or portfolio-level risk transfer; delivers large, rapid capital injections after extreme events	Complement to indemnity & parametric coverage; best integrated into a layered risk-financing strategy	Long-term funding initiatives where resilience investments can be measured & demonstrably reduce future losses

Traditional Indemnity Insurance

Traditional indemnity insurance pricing is influenced in part by expected losses, typically expressed as Average Annual Loss (AAL) and derived from actuarial analysis and catastrophe modeling. A key metric in climate and insurance analysis is AAL, which represents the long-term average expected loss from hazards over time, based on the probability and severity of different events. In practical terms, AAL is a modeled estimate of the average amount an asset or portfolio is expected to lose each year from insured or insurable hazards. It is often used as a summary output of the broader risk value chain: hazard → exposure → vulnerability → loss → AAL. Because AAL condenses multiple possible loss scenarios into a single expected loss metric, it is widely used by insurers, reinsurers, lenders, and sponsors to assess risk, inform pricing, and evaluate the effect of resilience investments.



Case Study 1: Unipol

Italian insurer Unipol developed adaptation action plans for companies. By sharing loss prevention expertise and a risk assessment tool, Unipol enhanced extreme weather preparedness and enabled sustainable underwriting in a high-risk area. Twenty-eight firms completed adaptation action plans with over 565 adaptation actions (e.g., flood barriers, green roofs). This protected insurer capital while maintaining the availability of indemnity coverage.

Adaptation measures that reduce an asset's exposure or vulnerability, such as structural hardening, elevated construction, floodproofing, redundancy in critical systems, or defensible space in wildfire-prone areas, can improve the underlying risk profile and reduce modeled losses. However, these improvements do not always translate into proportional reductions in insurance premiums. Pricing is influenced not only by asset-level risk, but also by broader market dynamics such as reinsurance costs, portfolio concentration, recent catastrophe experience, and insurer capital requirements. In practice, adaptation often helps preserve insurability, stabilize pricing, support underwriting confidence, and maintain access to capacity in climate-exposed markets, even where premium reductions are modest.[487]

Effective risk mitigation, which is discussed earlier in this guide, can reduce loss severity, which is particularly important for high-cost lines such as property damage and business interruption, where large losses can materially affect underwriting results. For example, implementation of improved building codes and targeted retrofits can further enhance asset resilience by reducing the likelihood and scale of major claims, contributing to more stable long-term loss experience. Moreover, scaling up asset-level risk

adaptation efforts can also bring benefits to a larger region or community because implementing large-scale adaptation measures may be needed before insurers provide improved insurance availability or reduced premiums for risk-reduction measures. As physical risk is demonstrably reduced, insurers may respond with more favorable terms, which may include improved pricing, subject to market conditions, potentially lower deductibles, and broader coverage conditions. From the insurer's perspective, adaptation measures help protect capital and support sustainable underwriting capacity in climate-exposed markets, reinforcing the long-term availability of indemnity insurance where it is most needed.[488]



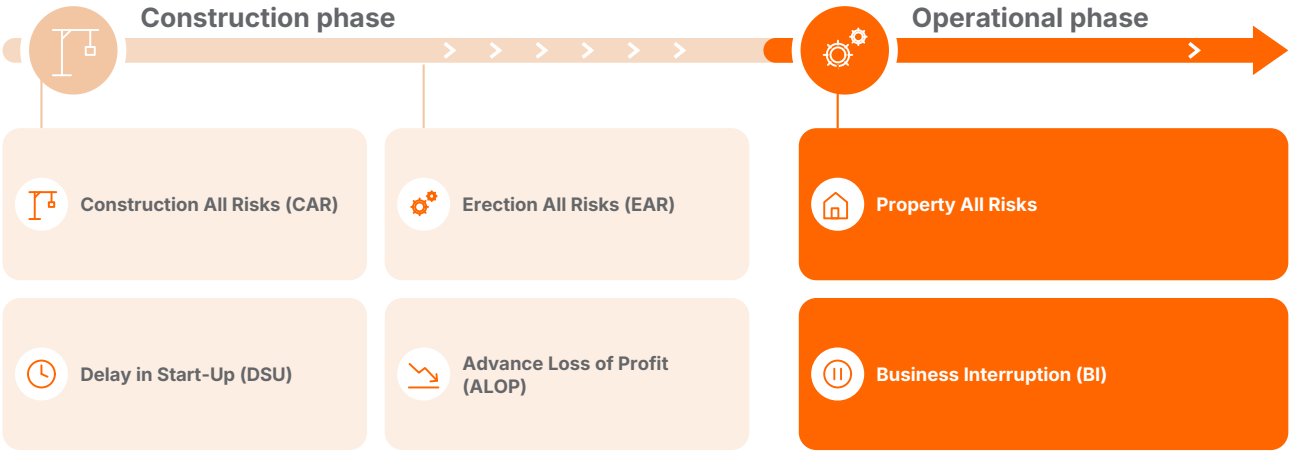
Case Study 2: Traditional Indemnity Insurance: The Urban Infrastructure Insurance Facility (UIIF)

UIIF is a facility designed to help cities in LAC assess climate and disaster risk and obtain insurance protection for infrastructure assets, so that post-event losses can be reimbursed and recovery can begin faster after a covered disaster. The UIIF works with cities such as Recife in Brazil, Mérida in Mexico, and Tegucigalpa in Honduras to integrate tailored climate insurance into their disaster risk management strategies to protect critical infrastructure from the impacts of climate change.489 Tofacilitate rapid access to funds after natural disasters, the program subsidizes premiums and covers up to 60% of the insurance cost in the first year of coverage.

Infrastructure sponsors rely on a core suite of insurance products to manage risk throughout the asset lifecycle. During construction, indemnity policies such as Construction All Risks (CAR) or Erection All Risks (EAR), often paired with Delay in Start-Up (DSU) or Advance Loss of Profit (ALOP), protect against physical damage and financial delays (see Figure 10). While CAR/EAR policies form the core indemnity coverage for construction risks, DSU/ALOP are typically structured as specialized endorsements or separate coverages requiring additional underwriting.

Once operational, Property All-Risks and Business Interruption (BI) coverage safeguard assets and revenue streams from damage-related disruptions. In most markets, BI is either embedded within or readily added to property indemnity policies, although specific terms, limits, and triggers vary by jurisdiction and insurer.

Figure 10. Indemnity policies for construction and operational phases of an asset's lifecycle



Traditional Indemnity Insurance for Core Asset Protection

Traditional indemnity insurance is typically mandatory under financing agreements and remains the primary mechanism for transferring day-to-day operational and catastrophe risk. Its strengths include:

- A direct correlation between the damage and the payout
- Strong bankability that makes it preferred by lenders
- Broad protection across many perils
- Coverage for income loss

However, indemnity policies can involve slower payouts due to loss adjustment processes, may be subject to coverage disputes, often carry high deductibles in risk-prone areas, and require physical damage to trigger payment. As a result, traditional indemnity is best used as a core foundational layer of risk management, ideally paired with parametric solutions to provide faster liquidity.

The use of traditional indemnity insurance for core asset protection (including Property, BI, Construction All-Risk, and DSU policies) is the backbone of coverage and offers several important advantages. It provides a direct link to physical damage, which strengthens its credibility and alignment with actual loss scenarios. It also supports bankability by meeting lender and investor expectations, delivers broad peril coverage across multiple hazard types, and protects income through established mechanisms such as BI and DSU.[490]

What Is a Trigger Mechanism?

A trigger mechanism defines the predefined conditions such as insured losses, industry-wide losses, or physical event measurements (e.g., rain level, wind speeds) that, if met, cause sponsors to lose part or all of their principal to pay the issuer for losses. Triggers ensure quick capital access for insurers and are essential for determining risk and returns.[491]

Although there are downsides to indemnity policies, this structure should still consistently be maintained as a core layer of risk transfer across regions and sectors. To address liquidity constraints and enhance financial responsiveness following an event, parametric solutions can be deployed as a complementary instrument designed to provide rapid access to funds. Lenders commonly require that sponsors secure indemnity protection for all financed assets to cover physical damage, revenue interruption, and construction risks.

The Role of an MDB in Insurance

MDBs play a critical role in project financing. Beyond traditional project lending, MDBs support limited or shallow insurance markets by helping governments manage disaster and climate risks through risk-transfer solutions, including Cat bonds. In this role, MDBs—such as the World Bank and regional development banks—act as arrangers, issuers, or providers of technical and financial support, enabling countries with weak domestic insurance and reinsurance capacity to access global capital markets and secure rapid post-disaster liquidity. By reducing barriers such as high costs, data limitations, and investor confidence gaps, MDBs help expand insurance coverage, stabilize public finances, and crowd in private capital where commercial insurance markets alone are insufficient.

Parametric Insurance

Parametric insurance provides rapid, predefined payouts based on hazard intensity rather than measured loss. It pays a predetermined amount when a defined hazard index—such as wind speed, rainfall level, or earthquake magnitude—meets or exceeds the agreed trigger.[492] Its strengths lie in the speed and transparency of payouts, providing rapid liquidity that can be especially valuable in situations where traditional deductibles are high or where indemnity policies leave gaps in coverage. Using parametric insurance is a proactive measure to recognize resilience investments upfront to protect and unlock capital. In fact, 71% of insurers are developing parametric insurance products to support climate-resilient construction and property.[493] Because payments are based on an index rather than the actual cost of repair, parametric products introduce basis risk and cannot fully replace traditional indemnity insurance.[494] Instead, they serve best as a first-responder liquidity layer, complementing indemnity coverage to help organizations bridge the immediate financial needs that arise after an event.

What Is Basis Risk?

Basis risk refers to the risk that an insurance payout doesn't fully match actual losses due to imperfect external triggers.

What Is an Imperfect Trigger?

An imperfect trigger is a situation that doesn't activate the insurance coverage because the agreed-upon terms have not been fulfilled. For example, if a hurricane's high wind speeds cause damage but don't meet the trigger's threshold, coverage is not activated.



Case Study 3: Parametric Insurance: Liberty Latin America

Liberty Latin America is one of the largest communications and entertainment service providers in LAC. Liberty was covered by parametric weather derivatives and received a $44 million payout after Hurricane Beryl activated the parametric triggers based on hurricane wind speed. The payout helped repair communications infrastructure and restore customer service without a lengthy claims assessment. Coverage from parametric insurance is generally important for critical communications companies because assessing the damage to each property can take a significant amount of time.[495]

While adaptation and resilience measures do not alter the frequency of large-scale hazards such as hurricanes or earthquakes, they meaningfully affect how parametric contracts are structured, particularly through the calibration of triggers and thresholds. Improved resilience can justify higher trigger thresholds, enable payout structures that better reflect reduced vulnerability, and support more granular geographic regions. Because adaptation lowers the likelihood that an event will generate losses, it reduces the expected payout frequency, improving premium adequacy (meaning that premiums cover expected losses and expenses without under- or over-pricing risk) and can ultimately reduce insurance costs. At the same time, decreasing underlying vulnerability helps reduce risk by aligning parametric payouts more closely with actual financial impacts. Stronger, more resilient infrastructure as described earlier in this guide can also expand the feasibility of parametric coverage, especially in sectors that are traditionally difficult to insure, including agriculture, coastal property, and public-sector assets. Moreover, demonstrated investment in adaptation can make risk portfolios more attractive to parametric insurers, often resulting in more competitive pricing due to the expectation of lower losses.

Catastrophe Bonds and Insurance-Linked Securities

Cat bonds are a type of risk-linked security that transfers specific disaster risks—such as hurricanes, earthquakes, or floods—from insurers or governments to capital-market sponsors. If a predefined catastrophic event occurs, sponsors may lose some or all of their principal, which is instead used to cover insured losses; if no event occurs, sponsors earn an above-market return. **Insurance-linked securities (ILS)** are the broader asset class that includes Cat bonds as well as other instruments (such as collateralized reinsurance or industry loss warranties) that allow insurance risks to be securitized and funded by capital markets rather than traditional insurers alone. Cat bonds are a type of ILS.

Overview of Catastrophe Models Used in Infrastructure Risk Assessment

- **Regional Peril Models:** These models simulate natural hazards such as hurricanes, storm surge, inland flooding, earthquakes, and severe storms across specific regions.

- **Standard Property Models:** Traditional Cat property models estimate damage to buildings based on construction type, height, occupancy, and location. These models are well suited to residential and commercial real estate but are often insufficient for infrastructure assets where damage is driven by equipment failure and operational disruption.

- **Industrial Facilities Models (IFM):** IFMs provide a more advanced framework for complex infrastructure assets such as power plants, water utilities, ports, airports, hospitals, and renewable energy facilities. IFMs evaluate risk at the component level, explicitly modeling damage to machinery, electrical systems, process equipment, and control systems, as well as associated downtime. This approach is particularly relevant in the Caribbean, where BI and service outages often exceed physical repair costs.

- **Financial and Insurance Structure Models:** Once physical losses are estimated, financial models apply insurance terms such as deductibles, limits, waiting periods, and coverage sublimits. These models translate technical losses into insured and uninsured financial impacts, supporting capital planning and insurance program design.

- **Scenario and Stress-Testing Models:** Scenario analyses examine the effects of plausible extreme events—such as a Category 4 or 5 hurricane impacting a single island or asset corridor—to test liquidity, debt service resilience, and recovery timelines under adverse conditions.

Why This Matters for Sponsors:

Using multiple Cat models—particularly those incorporating IFM—provides a more realistic understanding of how Caribbean infrastructure assets perform under extreme events. This multi-model approach supports better insurance structuring, targeted resilience investments, and more stable long-term returns.

Cat bonds, especially in LAC and developing countries, typically rely on public or semi-public funding, so case studies 4–6 focus on public funding sources rather than private ones.



Case Study 4: Cat Bonds: Impacts of Hurricane Melissa on Jamaica

Hurricane Melissa made catastrophic landfall in 2025 and caused widespread damage to infrastructure across Jamaica. After the storm, a full $150 million payout was triggered from Jamaica's Cat bond, arranged by the World Bank. Hurricane Melissa's central pressure and direct path met the required parametric conditions to mobilize a full payout quickly after the storm.[496] The parametric Cat bond enabled Jamaica to restore infrastructure and other assets effectively, and the government's strong financing framework provided critical resources to support relief efforts.[497]

Cat bonds and ILS transfer low-frequency, high-severity climate risks to capital markets, often at the sovereign, sub-sovereign, or portfolio level. Cat bonds are established when sponsors lend money to insurers; if a predefined catastrophe occurs, sponsors lose part or all of their principal, which pays claims. ILS include Cat bonds and transfer insurance risks directly to capital markets instead of traditional reinsurers. These instruments are particularly relevant in regions with repeated catastrophe exposure where traditional insurance capacity is limited or volatile. Their strengths include price stability over several years, access to a broad and diversified investor base, and transparent trigger mechanisms that make risk transfer clearer to both issuers and sponsors. However, these instruments require complex and often costly structuring, typically have minimum size thresholds, and are generally most practical for national programs or large aggregated portfolios.

When used effectively, Cat bonds and ILS can deliver large, rapid injections of capital after extreme events, helping to reduce economic disruption, stabilize public finances, and provide critical liquidity to a region.

Case Study 5: Cat Bonds: Mexico

In 2024, the World Bank issued $420 million in Cat bonds for Mexico, which provide four years of catastrophe insurance coverage. The payouts are triggered if a defined earthquake or named storm meets the parametric criteria set in the bond terms. Storms can affect Mexico's critical infrastructure systems, so these Cat bonds will allow the country to recover quickly in the event of a payout. Additionally, these bonds attracted 27 institutional sponsors, so risk was transferred into private capital markets as well.[498]

Cat bonds and other insurance-linked securities are priced using models that estimate the likelihood and potential severity of major disasters, such as hurricanes or earthquakes. These estimates are made at a regional or system level and are used to set investor returns and payout conditions, rather than being tied to losses at individual assets. Adaptation measures can contribute to lower modeled losses and reduce exposure or vulnerability—such as seawalls, strengthened building codes, or nature-based solutions—and can lower the modeled loss severity associated with catastrophic events, thereby improving bond pricing dynamics.

When adaptation reduces modeled tail risk (low-probability, high-impact risk), it directly affects the catastrophe model outputs used in ILS structuring, resulting in lower expected loss levels, more favorable risk spreads, and stronger investor confidence in the underlying modeling assumptions.

In parametric Cat bond structures, which use measurable parameters as triggers for investor principal loss rather than actual claims or modeled loss, adaptation can affect trigger thresholds, payout scales, and the definition of geographic exposure zones. Furthermore, sustained investment in resilience can support multi-year ILS transactions by demonstrating stable or improving risk profiles, which is a key consideration for long-term sponsors.



Case Study 6: Jamaica Cat Bond

The World Bank issued a Cat bond that provided Jamaica with $185 million of insurance cover against tropical cyclones for the 2021–2023 hurricane seasons. According to the World Bank case study, the bond complemented Jamaica's broader disaster risk financing portfolio, which already included a contingency fund, contingent credit, and catastrophe insurance through CCRIF, and was designed to help address financing gaps for severe cyclone events. This example illustrates how Cat bonds can complement other layers of sovereign and regional disaster risk financing.

Public Insurance and Risk Pools

Public insurance is a risk-transfer mechanism backed or administered by governments or public entities to absorb losses from specified hazards, particularly where private insurance capacity is limited. Their primary objectives are to improve affordability, expand access to coverage, and stabilize markets for households, businesses, and infrastructure systems exposed to systemic risk. These schemes are especially important in regions such as LAC, where disaster risk is highly correlated, and domestic insurance markets are often too small to diversify extreme losses on their own.

Case Study 7: Public Insurance/ Risk Pools

The Caribbean Catastrophe Risk Insurance Facility (CCRIF SPC) is a catastrophe risk insurance pool that serves the Caribbean and Central America. It was formed as an effort to protect the region from hurricanes and earthquakes. CCRIF offers government members insurance coverage for tropical cyclones, earthquakes, and excess rainfall. To support insurance-buying decisions, CCRIF builds individual risk profiles for member countries using hazard and exposure mapping and works with countries to customize coverage parameters to best suit their unique climate-related risks. For example, CCRIF allowed The Bahamas and Trinidad and Tobago to divide their excess rainfall policies into subnational units.[499]

Risk pools are arrangements in which multiple participants—such as countries, municipalities, utilities, or sectors—combine their exposure to similar hazards into a shared risk-financing mechanism, allowing losses to be spread across a broader base rather than individually. By aggregating risk, pools can achieve more affordable pricing, improve access to coverage in capacity-constrained markets, and enable faster payouts after disasters, particularly for large, correlated events. Public insurance schemes often rely on risk pools as a core structural component, using them to operationalize government-backed risk sharing at a national or regional scale. In this context, a public insurance scheme can provide a policy mandate, capital support, or guarantees, while a risk pool can serve as the technical mechanism that diversifies risk, manages premiums, and funds payouts. Importantly, risk pools can also exist outside formal public insurance schemes—such as mutual or sector-based pools—but when embedded within public frameworks, they play a central role in stabilizing markets and extending protection where private insurance alone is insufficient. Many regional risk pools also benefit from deep hazard and exposure expertise, allowing program design to reflect localized risk characteristics rather than relying solely on global market assumptions.

Risk pools do, however, have important structural limitations. They typically operate at a national or government-backed level and are not designed to cover losses at individual projects or facilities. Payouts are often modest relative to total reconstruction needs, reflecting their role as liquidity providers rather than full indemnification tools, and participation or product design may be influenced by political priorities alongside technical risk considerations. For these reasons, risk pools are most effective when used as part of a broader risk-financing strategy rather than as a standalone solution.

Adaptation investments can materially strengthen the performance and sustainability of risk pools. National, municipal, or sector-level measures—such as flood protection systems, wildfire mitigation programs, or resilient land-use planning—can lower pooled expected losses, improve risk equalization, and enhance long-term solvency. In parametric risk pool structures, resilience improvements may also support recalibration of triggers, such as rainfall or wind thresholds, to better reflect reduced vulnerability. Beyond technical risk metrics, a visible commitment to adaptation signals strong governance and risk management, helping pools attract reinsurance, donor support, and climate finance, and enabling more sophisticated layered structures that combine pooled retention, parametric coverage, and Cat bonds.

Caribbean Spotlight: Insurance Affordability, Capacity Constraints, and Risk-Transfer Solutions in the Caribbean

1 · Market constraints

The Caribbean presents one of the most challenging insurance environments in LAC. Small market size, high exposure to hurricanes, storm surge, flooding, and other climate-related hazards, as well as strong dependence on international reinsurance contribute to high premiums, elevated retentions, and limited underwriting capacity. In some markets, concentration among insurers and reinsurers can further constrain competition and reduce flexibility in coverage terms, particularly for public infrastructure, utilities, and smaller project sponsors.

2 · The role of adaptation

In this context, adaptation should not be viewed only as a mechanism for reducing expected losses. In the Caribbean, adaptation often plays an equally important role in preserving access to insurance, supporting underwriting confidence, and maintaining coverage availability over time. Measures such as stronger building standards, flood protection, resilient energy systems, backup power, redundancy in critical infrastructure, and improved O&M can help demonstrate a more stable risk profile even when market-wide premium pressures remain high.

3 · How to combine instruments

Because private insurance capacity can be constrained, Caribbean risk-transfer strategies often need to rely on layered structures. These may include core indemnity insurance for physical damage and BI, parametric products for rapid post-event liquidity, regional risk pools for sovereign or public-sector support, public support mechanisms or concessional structures to improve affordability, and capital-market instruments for peak catastrophe risk where sufficient scale exists. For sponsors, the implication is clear: in the Caribbean, insurance strategies often need to be approached as part of a broader resilience and financing framework rather than as a standalone procurement exercise.

Layered insurance structures are important for infrastructure investments in LAC, where multi-hazard exposure (e.g., extreme wind, extreme rain, and flooding simultaneously) creates risks that can overwhelm singular-policy strategies. For example, a Caribbean water utility facing hurricane winds, storm surge, and flooding requires Property All-Risks for physical damage repair, parametric cyclone cover for immediate post-event liquidity to restore essential service delivery, and BI to cover revenue losses during extended outages. This structure addresses high property deductibles and reinsurance dependency that characterize Caribbean insurance markets. Similarly, Central American transmission assets exposed to overlapping wind, flood, and seismic hazards benefit from combining indemnity coverage with targeted parametric triggers, ensuring both repair costs and cash flow stress are managed while claims adjustment proceeds.

In LAC, limited local underwriting capacity and catastrophe pricing concentrated across regional portfolios make layered structures critical for maintaining insurance availability and affordability. For instance, an Andean toll road vulnerable to rainfall-triggered landslides needs indemnity insurance for physical damage paired with parametric rainfall cover for rapid clearance and stabilization. In effect, layered insurance structures can enable LAC infrastructure sponsors to manage complex multi-hazard exposures and sustain or rebuild essential services in markets where single policies cannot address a region's unique climate-related risks. Layering policies can also materially improve recovery capacity, lender confidence, and financial resilience.

Takeaway

For sponsors, the implication is clear: in the Caribbean, insurance strategies often need to be approached as part of a broader resilience and financing framework rather than as a standalone procurement exercise.

Resilience-Linked and Public De-Risking Instruments

Resilience-linked and public de-risking instruments are an emerging class of solutions that connect insurance, finance, and climate adaptation outcomes. By recognizing investments in resilience and loss prevention, they can reduce premiums, improve coverage terms, and unlock concessional or blended capital. Public de-risking leverages partial credit guarantees and multilateral/DFI support to improve credit quality and attract capital at lower financing costs. Resilience-linked financing and insurance improve terms when borrowers or policyholders meet defined resilience KPIs, directly tying financial benefits to adaptation performance and, where applicable, using guarantees to absorb specific climate or hazard risks.



Case Study 8: Caribbean Livelihood Protection Policy (LPP)

The LPP is a parametric insurance product designed for the Caribbean that covers losses from high winds and heavy rainfall and provides rapid payouts within 14 days when triggers are met. The policy was developed so that a private insurer, Guardian Insurance, could offer an affordable product for vulnerable communities, with its development supported by a broader public-private insurance initiative. The LPP is ideal for Caribbean communities that face frequent risks from cyclones and extreme wind and rain.[500]

Resilience-linked financing operates through performance-based pricing: coupons or margins decrease when predefined resilience KPIs are achieved and may increase with underperformance. This structure monetizes adaptation by tying borrowing costs to measurable risk-reduction outcomes—rather than to spending alone—and complements traditional risk transfer. Stronger resilience lowers modeled losses (e.g., AAL and loss volatility), which can support better insurance pricing and more efficient risk-layering. Adaptation measures that reduce an asset's exposure or vulnerability (such as structural hardening, elevated construction, or defensible space in wildfire-prone areas) may lower AAL and, in turn, the technical premium required by insurers. As used in this chapter, AAL refers to the long-term average modeled annual loss associated with the asset or portfolio's hazard, exposure, and vulnerability profile.

Key Performance Indicator Design and Data

Effective KPIs are outcome-oriented and decision-relevant—for example, the share of assets meeting elevation and floodproofing standards, facilities compliant with wildfire hardening or wind-uplift requirements, or measurable reductions in operational downtime for critical services. Aligning KPIs with parametric thresholds (e.g., wind speed or rainfall levels at which assets remain functional) can strengthen coherence between financing and risk-transfer structures. In practice, a limited set of three to five KPIs—supported by clear baselines, interim targets, and independent verification—maintains analytical clarity and reduces greenwashing risk. Robust data systems embedded in design and operations (asset-level hazard mapping, CAPEX tracking by hazard type, post-event performance validation) improve market credibility and pricing efficiency while providing a multi-year roadmap that signals an improving risk profile to lenders and sponsors.

Despite their advantages, resilience-linked and public de-risking instruments remain relatively nascent in LAC, with limited standardization, a high bar for KPI verification, and structuring costs that can challenge smaller projects. Furthermore, the use of blended finance instruments and guarantees enables the absorption or redistribution of specific risks that might otherwise deter private investment, thereby improving overall project viability and capital mobilization. As a result, these tools are best suited to larger or long-tenor financings—or to programmatic/aggregated approaches—where resilience investments can be measured and where reduced losses justify the added complexity. When applied in these contexts, resilience-linked and public de-risking structures align incentives, translate adaptation into financial value, and strengthen overall project viability and capital mobilization.

Selecting Risk-Transfer Options for Resilience

Figure 11 shows the key steps involved in selecting risk-transfer options for infrastructure assets.

Figure 11. Steps for selecting appropriate insurance solutions for infrastructure assets



Step 1: Understanding the Project Stage

Determining which insurance solutions are most appropriate for an infrastructure asset begins with Step 1: understanding the project stage. During construction, sponsors must start with the essentials—CAR or paired with DSU coverage—to protect against physical damage and revenue delays before operations even begin. Once the project transitions into operation, the focus shifts to Property All-Risks and BI insurance, which safeguard both the asset's integrity and its cash flow. Across both phases, parametric products can serve as a valuable complement to other insurance structures such as indemnity policies, providing rapid liquidity when an event occurs and helping stabilize the project before more detailed loss assessments are complete. Early consideration of risk-transfer approaches can also help monetize adaptation investments and, over time, reduce the cost of capital.

Step 2: Evaluating the Hazard Landscape

With the project stage defined, Step 2 involves evaluating the hazard landscape. Regional context is critical at this stage. While larger markets such as Brazil, Mexico, and Chile may offer deeper capacity and more mature underwriting environments, sponsors in the Caribbean and parts of Central America often face higher premiums, more limited capacity, and greater reliance on layered public or regional risk-financing solutions. Flooding, excess rainfall, hurricanes, and windstorms, earthquakes, drought, and landslides all require tailored approaches. Indemnity-based products remain central, but parametric solutions add speed and flexibility when facing acute hazards—triggering payouts after predefined thresholds related to wind speed, rainfall, seismic magnitude, or soil moisture are exceeded. Sponsors can leverage long-standing structures such as CCRIF in the Caribbean for tropical cyclone and flood protection, sovereign Cat bond programs in countries like Mexico and Chile, or blended finance mechanisms that support coverage in higher-risk emerging markets. Matching hazard profiles with the right blend of indemnity and parametric protection ensures liquidity arrives when it is most needed.

Step 3: Tailoring Selections to the Relevant Sector

Different infrastructure sectors face distinct climate hazards, and each requires a tailored blend of risk-transfer tools and adaptation measures to maintain resilience and financial stability. The next layer of decision-making, Step 3, is sector specificity. Transportation, energy, water and sanitation, telecommunications, and social infrastructure each exhibit distinct vulnerabilities and operating profiles. Energy systems may require additional windstorm and equipment breakdown protection; water utilities often face dual exposure to flood and drought; transportation assets such as roads, ports, and airports are sensitive to both extreme rainfall and seismic activity.

Sector-tailored insurance strategies—combining mandatory baseline covers with recommended parametric and resilience-linked enhancements—help ensure that protection aligns with how each asset generates value and where it is most exposed. By matching hazard profiles with the right mix of indemnity, parametric, and capital-markets instruments, sponsors can strengthen liquidity, protect asset value, and improve long-term insurability. Importantly, each insurance approach becomes more effective, and often more affordable, when paired with targeted adaptation investments that measurably reduce exposure and vulnerability. Table 36 illustrates how combining

hazard-specific insurance strategies with practical resilience upgrades can enhance protection across key infrastructure sectors. Because the risk-transfer needs of infrastructure assets vary significantly across sectors, the table below groups the principal categories of projects and illustrates how hazard exposure, insurance strategy, and adaptation measures may differ across them.

Table 36. Risk-transfer considerations by sector

Sector	Illustrative Project Types	Typical Hazard Profile	Insurance Strategy Options	Illustrative Adaptation Link
Transportation	Roads, highways, bridges, tunnels, ports, airports, rail, logistics platforms	Flood, landslide, wind, seismic risk, storm surge	CAR/EAR, Property All Risks, BI, DSU, parametric rainfall or wind, public de-risking	Slope stabilization, scour protection, drainage, floodproofing, resilient design standards
Energy	Solar plants, wind farms, hydropower, substations, T&D lines, storage systems	Wind, flood, wildfire, drought, heat stress	Property All Risks, CAR/EAR, BI, parametric wind or rainfall, resilience-linked finance	Equipment elevation, wind hardening, drainage, redundancy, firebreaks
Water and sanitation	Water treatment plants, wastewater systems, pipelines, desalination, pumping stations	Drought, flood, power disruption, contamination events	Property All Risks, BI, parametric drought/flood, public support mechanisms	Dual intakes, backup power, flood barriers, storage, leakage reduction
Telecommunications	Data centers, telecom towers, fiber networks, digital backbone assets	Wind, flood, heat, power outage	Property All Risks, BI, parametric triggers for severe events, portfolio solutions	Backup power, redundancy, cooling resilience, tower hardening
Social infrastructure	Hospitals, schools, affordable housing, health facilities	Wind, flood, seismic risk, service interruption	Property All Risks, BI, parametric cover for rapid liquidity, public or concessional support	Floodproofing, roof hardening, backup power, protected access routes

Other Considerations

An important consideration when selecting the appropriate risk-financing option: the chosen legal and corporate structure drives investor financing decisions by establishing the degree to which project assets can be legally isolated, adequately insured, and shielded from broader financial exposure.

In capacity-constrained markets, it may be better to identify what level of indemnity protection is realistically available and then build outward using complementary liquidity, public, and financing instruments, rather than assembling a complete commercial insurance package immediately.

In addition to project stage, hazard profile, and sector exposure, sponsors should also consider the **financing structure** through which the asset is being developed or operated. Risk-transfer needs often differ materially between project-finance structures and corporate-balance-sheet structures. In project finance, risk is typically housed in a ring-fenced SPV, and lender requirements generally place greater emphasis on mandatory asset protection, BI coverage, liquidity support, and covenant protection. In corporate structures, sponsors may have greater flexibility to retain selected risks, pool exposures across assets, access portfolio-level insurance or reinsurance solutions, and combine insurance decisions with broader treasury and capital-management strategies.

Documenting and Quantifying Resilience

Lastly, regardless of stage, hazard, or sector, sponsors strengthen their insurance and financing outcomes when they can **document and quantify resilience**. Demonstrating reductions in AAL, providing engineering reports, and showing evidence of upgraded design standards can materially influence underwriting decisions, resulting in improved premiums, expanded capacity, or better terms. For lenders and sponsors, this documentation can serve as evidence that climate adaptation is reducing both expected physical loss and the probability of financial stress, thereby supporting a more favorable view of project credit quality. As discussed in earlier chapters, these same measures can also support broader reductions in credit risk by improving operating continuity, protecting cash flows, strengthening debt service resilience, and reinforcing lender confidence in the asset's long-term performance. In this sense, quantified resilience is not only an insurance input; it is also part of the broader financial case for project bankability.

Project type also influences the design and effectiveness of the risk-transfer strategy. Assets with highly visible and immediate service-interruption consequences—such as hospitals, airports, ports, water systems, and transmission infrastructure—may place a greater premium on rapid post-event liquidity and continuity support, making parametric layers or contingent financing particularly valuable. By contrast, projects with more diversified corporate support or more flexible revenue structures may be better positioned to absorb selected risks through retentions, captives, or portfolio-level arrangements. Similarly, greenfield construction projects may prioritize CAR/EAR and DSU protection, while mature operating assets may focus more on property damage, BI, and resilience-linked refinements to long-term financing and insurance structures.

The following modeled scenarios shown in Table 37 and Table 38 demonstrate how sponsors may stack insurance options to support effective risk management for energy and transportation infrastructure assets in LAC. These are hypothetical examples that are not based on real-world scenarios and offer an illustrative glimpse into how insurance options may be stacked to build resilience.

Table 37. Scenario 1: Transmission grid in Brazil

Transmission Grid in Brazil

Objective

Enhance grid reliability across large geographic areas exposed to high wind speeds.

Risk Stack

Base Layer: Comprehensive Property and BI coverage for substations, towers, switching facilities, and associated equipment, recognizing that terms and pricing are likely to depend on the extent of hardening, redundancy, maintenance quality, and exposure concentration across the network.

Parametric Layer: Wind or other event-based triggers to provide rapid funding for emergency response, tower stabilization, debris removal, temporary network reconfiguration, and accelerated restoration after severe weather events.

Macro Layer: Participation in national catastrophe programs, portfolio-level risk management structures, or other broader financing mechanisms to help absorb high-severity events that affect multiple assets or regions at once.

Resilience-Linked Finance: Financing terms tied to KPIs such as reduced outage hours, hardened towers, improved vegetation management, elevated or flood-protected substations, and increased system redundancy.

Adaptation Measures: Tower hardening, substation elevation, flood protection, vegetation management, network redundancy, equipment replacement cycles, and improved restoration planning can reduce expected losses, shorten outage duration, and strengthen the insurability profile of the system. For larger sponsors, these measures can also support portfolio-level underwriting, resilience-linked financing, and more efficient access to insurance or reinsurance capacity.

Investor Benefit

Lower system downtime, improved performance metrics for regulated assets, and stronger long-term risk-adjusted returns.

Table 38. Scenario 2: Andean mountain highway

Andean Mountain Highway

Objective

Maintain construction timelines and reduce landslide disruptions across high-altitude, climate-sensitive terrain.

Risk Stack

Base Layer: CAR/EAR + DSU for construction phase CAPEX and schedule protection, recognizing that for high-exposure transport concessions, pricing and availability may depend heavily on the treatment of geotechnical, hydrological, and access risks in the original design. Where landslide or washout exposure is poorly mitigated, sponsors may face higher premiums, tighter exclusions, larger deductibles, or more limited DSU availability.

Operational Layer: Property and BI cover for tunnels, tolling stations, plazas, retaining structures, and other critical assets, recognizing that coverage quality may vary depending on how slope stability, drainage, and network redundancy are addressed in the underlying project design.

Parametric Layer: Rainfall index coverage to release emergency funds for slope stabilization, landslide clearance, temporary rerouting, and emergency traffic management—particularly valuable where indemnity claims may take time to adjust.

Public De-Risking: Partial credit guarantees or multilateral/DFI backing to enhance creditworthiness and reduce financing costs, particularly where climate and terrain risks remain material despite resilience measures.

Adaptation Measures: Route optimization, slope stabilization, improved drainage, retaining structures, scour-resistant foundations, erosion control, and strengthened inspection and maintenance protocols can materially reduce expected loss and improve traffic continuity. These measures may not eliminate insurance constraints, but they can improve underwriting confidence, support access to more workable terms, and reduce the severity of interruptions that affect revenues and debt service.

Investor Benefit

Reduced financing risk, stabilized concession revenues, and improved resilience of critical transport corridors.

Accessing Reinsurance and Alternative Risk-Transfer Options

In addition to traditional insurance and public risk-pooling mechanisms, large infrastructure sponsors and sovereign entities may access risk transfer directly through reinsurance markets or capital-market instruments. This can be achieved through structures such as captive insurance companies, which retain and manage risk internally while purchasing reinsurance for excess layers; SPVs, which facilitate the issuance of Cat bonds or other insurance-linked securities; or direct participation in reinsurance placements.

These approaches can offer greater flexibility in structuring coverage, improved pricing efficiency at scale, and access to deeper global capital pools, particularly for low-frequency, high-severity risks that exceed the capacity of domestic insurance markets. However, they also require more advanced risk analytics, governance, and financial management capabilities. In practice, direct access to reinsurance is often used in combination with traditional insurance and risk pooling, forming part of a layered risk-financing strategy that balances risk retention, transfer, and capital efficiency.

7.2 Key Recommendations

1. ***Start with mandatory indemnity insurance as the foundation***
   Traditional indemnity insurance should be treated as the essential base for project bankability. During construction, secure CAR/EAR and DSU/ALOP. During operations, ensure Property All Risks and BI coverage. These protections satisfy lender requirements and safeguard core asset value before layering in complementary risk-transfer instruments.

2. ***Use a layered approach to risk transfer, not a single product, when market conditions allow***
   Climate-exposed infrastructure should not rely on indemnity insurance alone. Indemnity coverage should be combined with parametric insurance to provide rapid access to liquidity after extreme events. Where feasible, portfolio-level or public instruments—such as Cat bonds, regional risk pools, or government-supported de-risking programs—should be added to address high-severity risks, market capacity constraints, and affordability challenges.

3. ***Use parametric insurance to manage liquidity needs, not to replace indemnity***
   Parametric products are most effective as a complement to indemnity insurance, particularly for hurricanes, floods, earthquakes, and drought. Their primary value lies in delivering fast, predictable payouts immediately after an event, helping projects cover emergency costs, stabilize cash flow, and maintain debt service while indemnity claims are assessed. As assets become more resilient, parametric triggers and limits should be recalibrated to reflect reduced vulnerability, while avoiding deliberate pursuit of positive basis risk. Although positive basis risk can provide useful liquidity when damage is limited, it should be treated as a by-product rather than an objective, consistent with insurers' need to preserve alignment with indemnity principles.

4. ***Consider the following measures when insurance constraints exist***
   In some markets—particularly in parts of the Caribbean—core indemnity coverage may



be unavailable, incomplete, or prohibitively expensive. In these cases, sponsors should not assume that the solution is simply to accept higher premiums or thinner coverage at a later stage. Instead, they should address insurability early by integrating adaptation and resilient design into project preparation, strengthening the asset's underlying risk profile, and structuring a layered response around whatever level of indemnity protection is realistically available. This may include combining partial indemnity cover with parametric products for rapid liquidity, public or regional risk-financing mechanisms, contractual contingency planning, and financing instruments that help absorb residual risk. For concession- and PPP-based projects, these resilience measures often need to be built upstream into site selection, technical standards, drainage and elevation requirements, redundancy provisions, maintenance obligations, and risk-allocation frameworks, since many of the factors that influence insurance availability and affordability are effectively determined before financial close. In privately developed projects, the same principle applies at the sponsor and design stage: resilient siting, engineering, asset configuration, and continuity planning should be incorporated early enough to influence underwriting outcomes, financing terms, and the long-term insurability of the project.

5. *Match insurance choices to the project stage, hazard profile, and sector*

Insurance structures should reflect the project lifecycle, dominant climate hazards, and sector-specific vulnerabilities. Risk-transfer strategies should be aligned not only with hazard and sector exposure, but also with the financing structure of the asset,

recognizing that project-finance transactions and corporate-balance-sheet structures often require different combinations of insurance, liquidity support, and risk retention. For example, transport assets exposed to flooding or landslides benefit from rainfall-based parametric coverage alongside indemnity insurance. Power and telecommunications assets exposed to wind and flood risk are better served by pairing Property All Risks with parametric wind or storm surge products. Sector-specific tailoring improves both protection and cost efficiency.

6. *Quantify and document resilience measures to improve insurance terms*

Adaptation investments should be explicitly linked to insurance strategy not only because they can reduce expected losses, but also because they can help preserve insurability, stabilize pricing, and sustain access to coverage in markets where premium reductions may be limited by broader market conditions. Modeling expected losses before and after resilience upgrades—and demonstrating reductions in AAL as used in this chapter (the long-term average modeled annual loss associated with the asset or portfolio's hazard, exposure, and vulnerability profile)—is critical to showing that the asset's risk profile has materially improved. Measures such as elevated substations, improved drainage, structural reinforcement, or redundant systems should be supported by engineering designs, as-built certifications, and O&M plans.

7. *Monetize resilience through insurance design, finance, and public de-risking*

More resilient assets can justify adjustments in parametric structures—such as higher triggers or lower limits—to reflect reduced damage severity and improve pricing efficiency. In parallel, resilience-linked loans and bonds can reduce borrowing costs when adaptation-related KPIs are met, translating physical risk reduction into financial benefits. Public de-risking mechanisms, including guarantees, concessional capital, Cat bond programs, and participation in regional risk pools (e.g., CCRIF or sovereign Cat bond platforms), can further lower insurance and financing costs while expanding insurer and investor participation in high-risk or capacity-constrained markets.

8. *Link insurance strategy to financing and long-term cost of capital*

Insurance decisions should be integrated into the project's broader financing strategy. By aligning indemnity coverage, parametric solutions, resilience investments, and public risk-transfer tools, sponsors can stabilize long-term insurance costs, capture the financial value of adaptation, and ultimately reduce the cost of capital. Where core coverage is limited or unaffordable, sponsors should respond early by improving the project's insurability through design-stage adaptation, stronger technical standards, and a layered mix of partial indemnity protection, liquidity instruments, and broader risk-financing support. In concession and PPP contexts, these actions often need to begin upstream with the public authorities structuring the project; in privately sponsored projects, they should be integrated into the project design and development process from the outset.

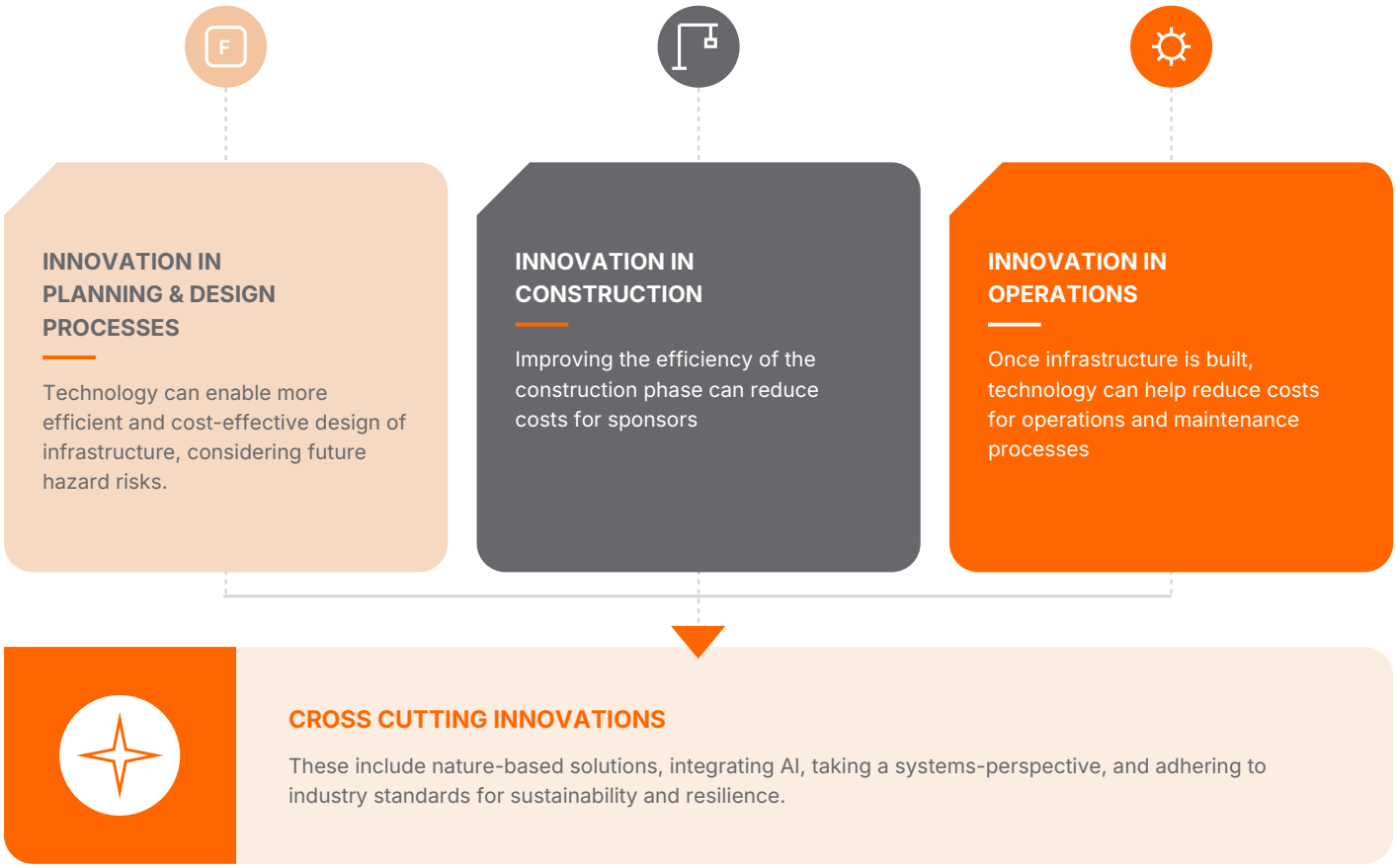
Technological Innovations *in Resilient Infrastructure*

This chapter provides an overview of innovative approaches to increasing infrastructure resilience throughout the project development process. The increasing intensity and frequency of climate change impacts worldwide have driven renewed research and development efforts across universities, private sector laboratories, and public institutions to advance technologies that enhance the resilience of infrastructure. Innovative solutions emerge from cutting-edge research, experience-based breakthroughs, the reemergence of traditional knowledge (particularly for natural infrastructure), or combinations of these approaches. Innovation involves introducing new or improved products, services, processes, or business models that improve performance, competitiveness, or efficiency. While many solutions are developed for site-specific conditions, there is significant potential to translate successful projects and approaches across geographies and contexts in LAC. Private sponsors are particularly well positioned to serve as early adopters of new technologies. They often have greater flexibility, can act quickly, and will respond nimbly to a rapidly evolving technology landscape.

8.1 When Does Innovation Happen in the Project Development Process?

Innovation can occur at every stage of the infrastructure development lifecycle (see Figure 12).

Figure 12. Key steps in an innovative project development process



During planning and design, innovation emerges by explicitly accounting for climate change hazards early in the process and embedding resilient design standards, materials, and systems that reduce long-term risk and avoid costly retrofits. During this phase, private companies and public authorities tendering concessions should consider how innovations can advance climate resilience. During construction, climate hazards are already reshaping how infrastructure is built, driving innovation in construction sequencing, materials selection, worker safety protocols, and site management to reduce exposure to extreme heat, flooding, and weather-related disruptions. During operations, digital technologies, remote sensing, and AI-enabled monitoring systems are transforming asset management by improving real-time performance tracking, predictive maintenance, and reducing the need for intensive manual oversight. Finally, innovation also occurs in financing, where new

financial instruments, risk-sharing mechanisms, and climate-aligned investment structures help allocate risk more effectively and mobilize capital for resilient infrastructure across its full lifecycle. The subsequent sections provide further details on details about innovations across this lifecycle. However, this chapter is not meant to be an exhaustive list of innovative ideas for infrastructure development.

8.2 Innovation in Project Planning and Design: Building Resilience Into Infrastructure

Innovation in project design occurs when climate risk considerations are embedded early and systematically into how infrastructure assets and systems are conceived, sited, and specified. Rather than treating climate resilience as a retrofit or add-on, innovative climate-smart design integrates forward-looking hazard information into decisions about asset location, elevation, materials, system configuration, and performance standards. This early integration enables planners and engineers to evaluate tradeoffs holistically, align infrastructure functionality with projected climate conditions, and avoid lock-in to designs that may become unsafe, uninsurable, or financially stranded over time. Design-stage innovation also includes the integration of advanced materials and components that improve durability under extreme conditions, the incorporation of nature-based solutions that provide protective and co-benefits, and systems-level approaches that improve redundancy and adaptive capacity across networks rather than only at the asset level. By embedding resilience into design from the outset, innovative projects can reduce lifecycle costs, protect long-term asset value, and improve the reliability of essential services for communities and sponsors alike.

- **Considering Climate Early and Often:** Incorporating climate considerations early in the design process, rather than retrofitting solutions after the fact, is far more cost-effective and leads to more resilient outcomes. Infrastructure built today will operate for decades, meaning assets designed without accounting for shifting precipitation patterns, rising sea levels, more frequent extreme heat events, or intensifying storms risk becoming stranded, damaged, or obsolete well before the end of their intended lifespan. Early integration also allows engineers and planners to evaluate tradeoffs holistically (e.g., costs associated with designing to different flood protection levels), embedding adaptive capacity and NBS from the ground up rather than as expensive add-ons. Ultimately, climate-smart design protects both the investment itself and the communities that depend on it, turning a potential vulnerability into a foundation for long-term sustainability and safety.

- **Siting and Alignment:** By aligning the location and elevation of critical assets such as transport corridors, electrical substations, and data centers with probabilistic hazard overlays, planners can systematically avoid or minimize exposure to the full spectrum of climate-driven risks, including flooding, debris flows, and wildfire. Some hazards (like extreme heat) may be more difficult to move away from due to their non-site-specific character, in which case other adaptation measures should be considered. Unlike reactive measures applied after a site has already been chosen, climate-smart siting embeds resilience at the earliest and most consequential decision point in the project lifecycle, reducing the need for expensive protective infrastructure down

the line and lowering long-term operational risk. Considering the larger system may make siting and alignment decisions easier. For example, the Brazil Pro-Roads project adopted an innovative, climate-smart siting approach by using a flood risk analysis early in planning to identify roadway segments most vulnerable to flooding and determine where elevation or alternate alignments were required from the outset. This analysis considered the entire road network, and by integrating climate risk information into initial alignment and elevation decisions, the project reduced long-term exposure to flood damage and avoided costly retrofits later in the asset lifecycle.[501]

- **Systems:** A systems approach is innovative in infrastructure design because it fundamentally redefines how resilience is conceived, planned, and delivered. Rather than treating infrastructure as a collection of discrete assets to be designed and optimized in isolation, a systems approach introduces a new design paradigm centered on the performance of interconnected systems and the services they provide. This approach innovates by explicitly addressing interdependencies, cascading failures, and critical system bottlenecks that traditional asset-level design systematically overlooks but that often determine real-world outcomes under climate stress. By shifting design priorities toward sustaining service functionality across networks, a systems approach enables more strategic, high-leverage investments that can strengthen multiple assets simultaneously. It also advances adaptive and cost-effective infrastructure design by embedding flexibility, sequencing decisions over time, and accounting for deep uncertainty at the system scale rather than through costly over-engineering of individual assets. Critically, this represents both a technical and institutional innovation, breaking down sectoral silos in planning, financing, and implementation to align infrastructure investments with how complex systems actually behave. A systems approach enables resilience to be achieved at scale, not just project by project.

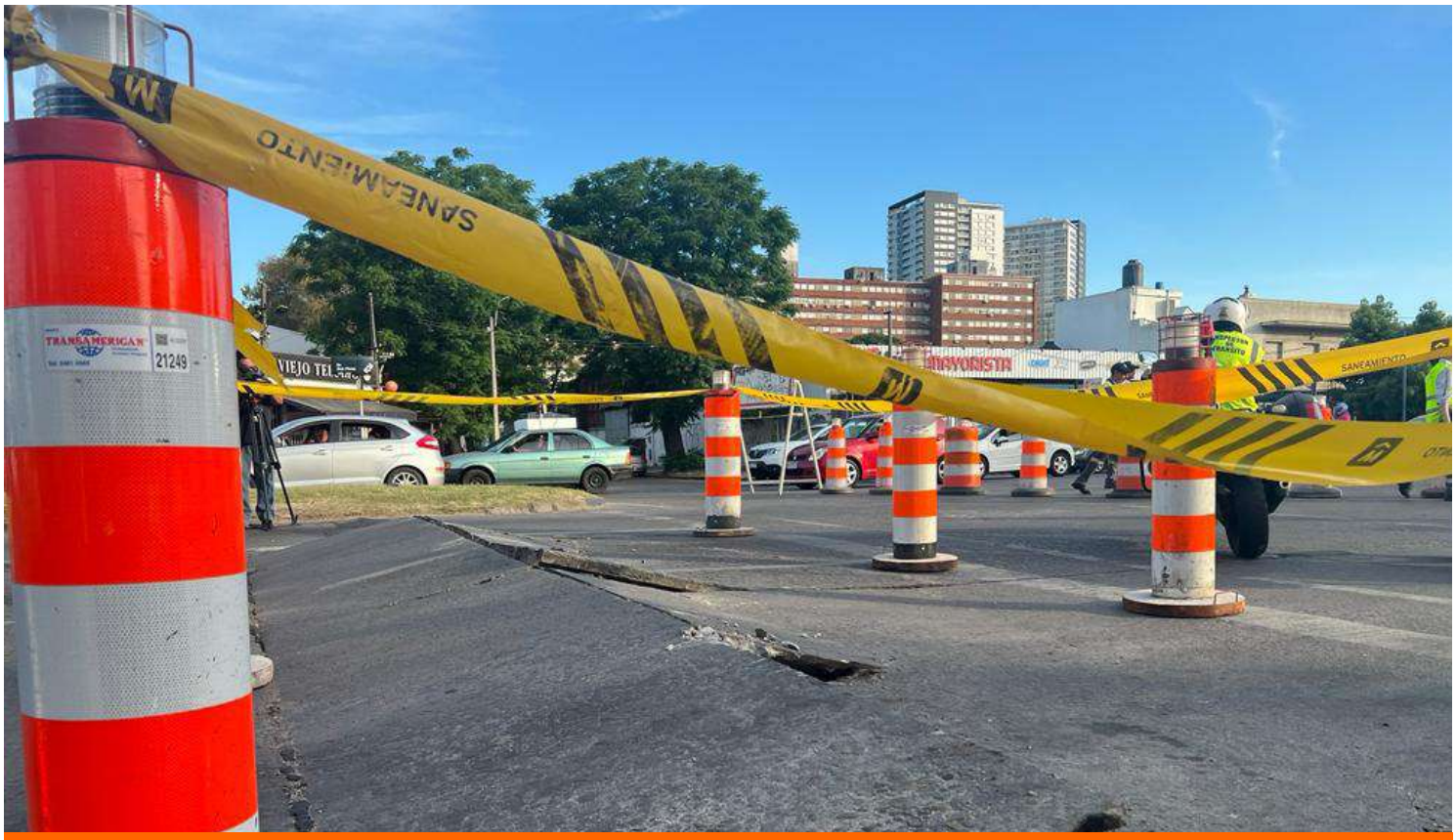
- **Materials & Components:** Selecting appropriate materials significantly enhances the long-term durability and climate resilience of infrastructure. Advanced materials (such as fiber-reinforced polymers, corrosion-resistant alloys, and high-reflectance, low-emissivity surfaces) reduce degradation from extreme heat and heavy precipitation events, extending asset lifespans and lowering maintenance costs. In addition to these engineered solutions, nature-based defenses such as mangrove buffers, riparian vegetation corridors, and green roofs can be woven directly into project designs to provide shoreline protection, urban cooling, and stormwater management benefits. Some innovative materials have positive impacts during the design and construction or the operational phase. Permeable pavements and cool pavement technologies help mitigate the urban heat effect that makes working conditions more dangerous and accelerates asset degradation. Choosing these materials and methods from the outset reflects a broader commitment to construction practices that are not only more sustainable, but better suited to the hotter, more variable conditions that project teams increasingly face.



Figure 13. The Afobaka Dam was completed in 1965 and generates about 50% of the total electricity consumed in Suriname (source: Staatsolie)

Climate Adaptation Case Study: *Afobaka Floating PV Plant*

This floating solar investment is innovative because it takes a systems view of electricity supply, integrating new solar generation in a way that strengthens overall system resilience rather than adding a standalone asset. By pairing floating solar with the existing Afobaka hydropower plant, the project complements hydropower output during periods of hydrologic variability (droughts) while leveraging existing transmission and grid interconnections. There are many unique innovations in the design of the installation itself, too. The floating PV installation reduces evaporation losses from the reservoir, improves solar panel efficiency through water-based cooling, and avoids land-use conflicts, all while diversifying the generation mix. Its modular design enables phased capital investment and creates opportunities to add hybrid storage over time to further stabilize output. This multi-benefit approach demonstrates how taking a systems approach to ensure electricity generation reliability can yield innovative investments like this coordinated solar-hydro system.[502] See Appendix A for more information on this case study.



Extreme Heat Case Study: Montevideo, Uruguay

The vulnerability of urban road infrastructure to extreme heat was illustrated in Montevideo, Uruguay, during a heatwave in December 2022. On General Flores Avenue, a sudden "blow-up" caused the asphalt to expand and rupture, creating an immediate safety hazard, disrupting traffic, and requiring urgent repairs. This incident underscores a broader regional challenge: many urban road systems are not designed to withstand the increasing frequency and intensity of extreme heat events, and road construction practices often fail to incorporate heat-resistant materials. Elevated temperatures also accelerate pavement deterioration, driving up maintenance costs. Research suggests that a temperature increase of just 1.8°C could reduce the average lifespan of pavement by 75% over a century—cutting durability from 16 years to only four. Similar impacts were observed in Santa Quitéria, Brazil, in August 2023, when a newly resurfaced section of the CE-257 highway melted shortly after completion as extreme heat liquefied the asphalt binder. Combined with construction deficiencies, the incident caused significant road damage and posed serious risks to both pedestrians and drivers, highlighting the urgent need for heat-resilient materials, design standards, and construction practices. The need for innovative materials that are resilient to extreme heat and standards that promote their use can prevent these disruptions across road networks. [503]

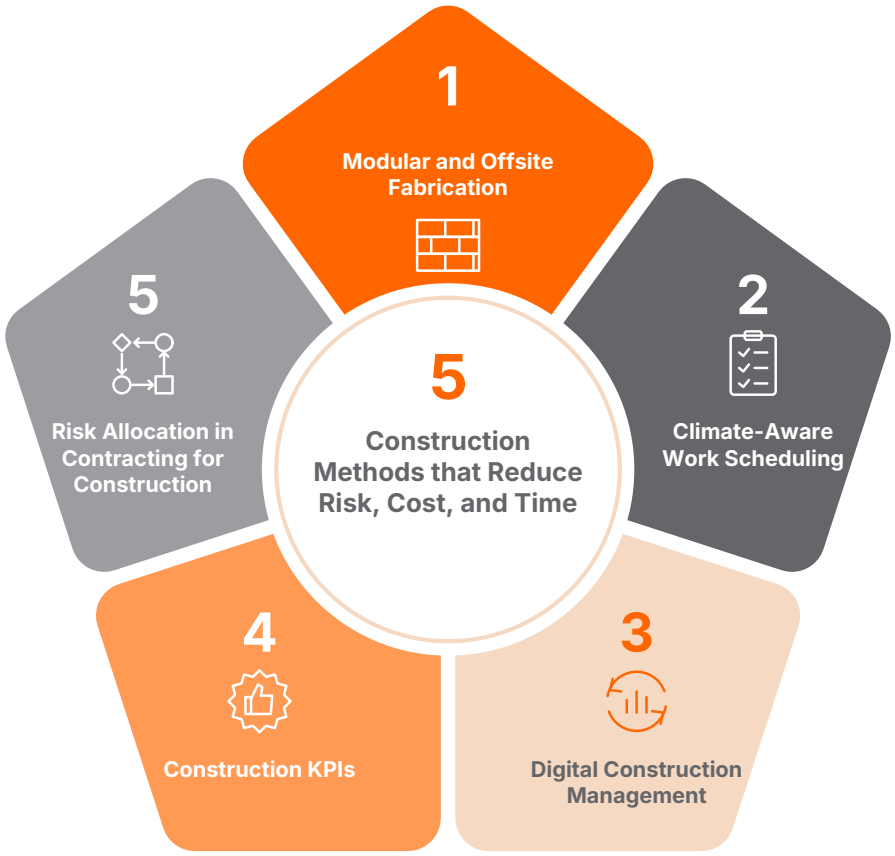
- **Digital First Design Process:** A digital-first design process improves the efficiency and effectiveness of infrastructure planning by embedding automation and advanced computation. Tools such as digital twins, parametric design, and AI-enabled modeling allow engineers and developers to rapidly generate, test, and refine thousands of design alternatives, reducing the length of design cycles while making cost-risk tradeoffs more transparent and tractable. Rather than relying on a limited set of static assumptions, these platforms enable systematic optimization across multiple objectives, including capital cost, operating performance, emissions, safety, constructability, and resilience. Machine learning models further enhance this process by translating probabilistic climate and hazard data into actionable design inputs, allowing risks to be priced, mitigated, or accepted with greater confidence. Underpinning these capabilities is a commitment to open standards and interoperable data architectures, ensuring that assets designed today can seamlessly integrate emerging technologies, such as sensors, distributed energy resources, and microgrids, over their full lifecycle.

- **Certifications and Standards:** During the project design phase, certification frameworks play a critical role in catalyzing innovation by translating complex technical, environmental, and governance considerations into clear, investable indicators of project quality. Frameworks such as FAST-Infra, Envision, LEED, and IFC's EDGE embed innovation upfront by shaping design decisions related to resilience, energy and resource efficiency, lifecycle cost optimization, and transparency. By influencing standards early (before decisions are locked in), these systems help ensure that climate, operational, and social risks are systematically identified and addressed while design flexibility is still high and the costs of change are lowest. For private sponsors, design-stage certification reduces future due-diligence burdens, improves comparability across projects, and strengthens confidence in underlying assumptions related to performance, costs, and risk management. Projects that integrate these standards early are more likely to demonstrate bankable efficiency gains (e.g., lower energy and water demand), which improve operating margins and enhance long-term financial performance. Innovation at the governance and ESG design level (such as strengthened safeguards, decision-making protocols, and risk management frameworks) represents low-cost, high-impact interventions that reduce execution and integrity risks. For institutions such as IDB Invest and its private-sector partners, mainstreaming these practices during project preparation provides a scalable, cost-effective pathway to improve development outcomes while crowding in private capital. Collectively, design-stage standards and certifications function as market-aligned innovations that lower transaction costs, reduce risk, and strengthen the investment case for climate-resilient infrastructure across LAC and beyond.

Financial impact of using innovation in project planning and design: Embedding climate resilience into project planning and design improves **CAPEX efficiency and long-term asset performance** by reducing the risk of maladaptive investments, costly retrofits, and premature asset degradation. By lowering exposure to physical risks and strengthening system reliability from the outset, **it supports more stable long-term cash flows and protects asset value** over the lifecycle. This upfront risk reduction can also improve **insurability and financing conditions**, particularly for long-lived or climate-exposed infrastructure.

8.3 Innovation in Construction: Methods That Reduce Risk, Cost, and Time

Figure 14. Five construction methods that reduce risk, cost, and time.



Innovations in climate-resilient construction reduce exposure to weather-related disruptions while accelerating build times and improving quality control. By shortening on-site construction windows, minimizing rework, and standardizing components, many approaches strengthen resilience to climate hazards while delivering improvements in cost efficiency, productivity, and worker safety.

1. ***Modular and Offsite Fabrication:*** Modular and offsite fabrication can reduce construction exposure to climate-related hazards. By completing a greater portion of work in controlled factory environments, project teams can shorten on-site schedules and limit the window during which workers and materials are exposed to climate-related hazards such as flooding, extreme

heat, or severe storms. This innovation has the potential to improve the efficiency of construction and reduce cost and schedule overruns.

2. ***Climate-Aware Work Scheduling:*** Effective construction management in a changing climate requires moving beyond fixed schedules to promote flexible approaches informed by real-time observations and seasonal projections. By monitoring rainfall, temperature, and storm outlooks, project teams can schedule tasks to prioritize weather-sensitive activities during periods of relative stability, protecting both productivity and worker safety. This strategy is particularly conducive to avoiding risks associated with extreme heat. For example, scheduling construction to occur earlier in the morning or later in the evening to avoid the hottest hours of the day can protect workers from exposure to dangerous heat conditions. This innovation has the potential to improve the productivity and safety of workers by limiting their outdoor work during high-heat events when they are less efficient and more prone to errors.

3. ***Digital Construction Management:*** Digital tools are redefining how construction sites are managed, monitored, and coordinated. Building Information Modeling provides a single, authoritative source of truth in the field, replacing printed drawings and static documents with a live, integrated model that keeps all teams aligned. Drones and Light Detection and Ranging (LiDAR) surveys enable continuous quality assurance and progress tracking, while computer vision can detect defects before they lead to costly repairs. Layered on top of these tools, data-driven forecasting that integrates weather signals into project planning helps teams anticipate disruptions rather than simply react to them, and centralized communication platforms ensure that site teams, subcontractors, and suppliers remain coordinated even as conditions change. Digital Construction Management can improve the efficiency of projects, reducing delays and cost overruns.

Spotlight on Work Planning and Worker Protection Tools

A growing number of technology providers offer work-planning and worker-protection tools that help construction managers anticipate and adapt to extreme heat. For example, platforms such as Perry Weather, AEM, and WeatherBuild integrate hyper-local forecasting, heat-stress (wet bulb temperature) monitoring, and automated alerts to support proactive schedule adjustments, including shifting labor-intensive activities to cooler nighttime or early-morning hours. These tools address a critical productivity challenge: in labor-intensive sectors like construction, heat stress is associated with productivity losses of roughly 29%–41% depending on task type, contributing to schedule overruns and significant economic losses. This underscores the importance of innovative scheduling and heat-management solutions to limit productivity and financial risks for sponsors.[504]

4. ***Construction KPIs:*** Quantifying resilience during the construction phase requires KPIs that go beyond traditional cost and schedule metrics. Tracking schedule adherence during identified hazard periods can demonstrate the success of adaptive planning in practice. Monitoring rework rates and safety incidents on high-heat days can show the success of resilient site management practices. Variance in contingency drawdown due to hazard delays or disruptions can provide an early signal of whether climate risks are being adequately anticipated and budgeted, giving sponsors and project managers a more complete picture of performance under real-world conditions. KPIs can help reduce the use of contingency funds by adequately tracking performance during construction.

5. ***Risk Allocation in Contracting for Construction:*** Resilience requirements should be embedded in construction contracts, ensuring that resilience is a contractual obligation rather than an abstract goal. In construction contracts and public-private partnerships, performance-based milestones and incentives can be tied to the delivery of climate-resilient features—such as flood-tolerant foundations, heat-resilient materials, or adaptive site drainage—aligning contractor behavior with long-term asset performance under climate stress. Standardized parametric addenda (provisions that trigger predefined responses when specific hazard thresholds are crossed, such as extensions of time, predefined cost adjustments, or activation of alternative construction methods) reduce disputes and delays when climate events occur during construction, creating more predictable delivery and clearer risk allocation for all parties. Including specific risk-allocation provisions in contracts can reduce sponsors´ exposure to risk and transfer responsibilities to contractors.

6. ***Financial impact of using innovation in construction:*** Innovative construction methods can improve **CAPEX predictability and schedule adherence** by reducing exposure to climate-related disruptions and minimizing rework. This lowers the risk of cost overruns and contingency drawdowns, supporting more stable project delivery and protecting expected returns. In turn, more reliable execution profiles can enhance **investor confidence and financing conditions**, particularly for large or hazard-exposed projects.



8.4 Innovation in Operations: Data, Finance, and Active Risk Management

Utilizing innovative digital tools and analytics can strengthen O&M for infrastructure while protecting cash flows under increasing climate variability. By integrating real-time data, advanced analytics, and proactive risk management, infrastructure operators can anticipate disruptions, optimize performance, and reduce unplanned outages that hinder financial stability. The approaches highlighted in this section demonstrate how sensing technologies, AI, hazard forecasting, and digital twins are shifting resilience from a one-time design exercise to an ongoing, financially grounded operational strategy.

Sensing and Drones: Sensing networks provide continuous visibility into the condition and performance of infrastructure assets, allowing asset managers to make informed decisions about operations and avoid damage and disruptions. Internet of Things (IoT) sensors (network-connected devices that transmit data) equipped with edge analytics can detect early warning signs of damage before they escalate to asset-level failures. Drones and LiDAR technology are transforming the speed and accuracy of inspections for linear assets like pipelines that traditionally have been costly and time-consuming to assess. Robotics and remote inspection tools are reducing the need for workers in hazardous environments altogether, lowering workers´ exposure to climate-related hazards. AI systems can use data collected through these methods to optimize performance in real time. For example, this data may be used to balance energy loads across a grid during an extreme heat event when demand patterns shift rapidly and unpredictably.

AI for Predictive Maintenance and Asset Management: By analyzing sensor readings, inspection records, and operational histories in combination, AI-driven predictive maintenance and asset management platforms can forecast component failures before they occur. These predictions allow maintenance teams to intervene proactively rather than respond to forced outages.

AI in Action

AI capabilities are already delivering measurable results across the water sector. AI-powered leak detection platforms are identifying subsurface losses that conventional methods miss, and intelligent demand forecasting tools are helping utilities anticipate consumption peaks with far greater accuracy. The impact can be substantial — one water utility deploying AI-driven analytics across its network achieved water savings of up to 37% in key pipeline sections, illustrating the scale of operational gains that predictive, data-driven management can unlock.[506]

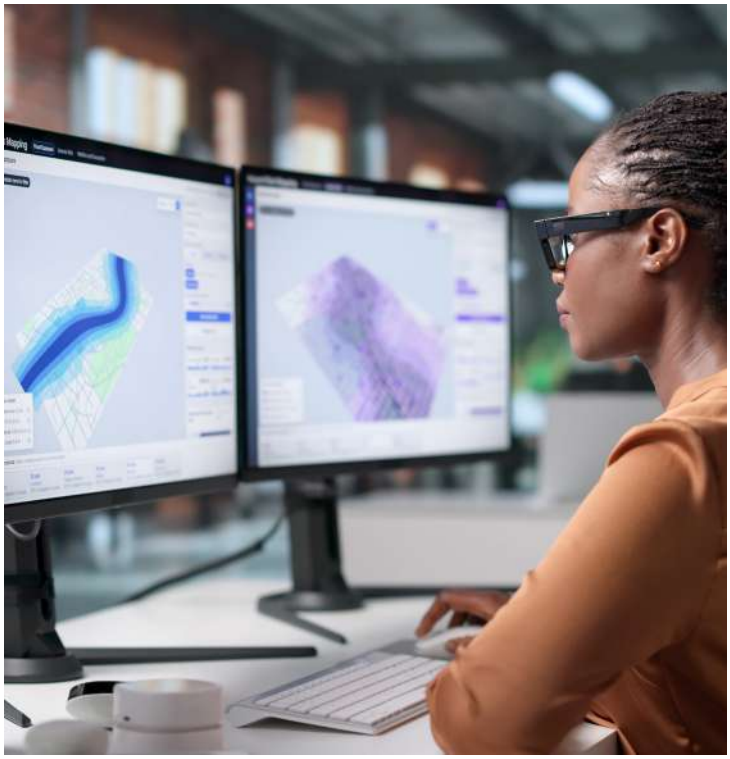
Hazard Forecasting and Workforce Protection: Protecting workers who operate and maintain infrastructure is a critical dimension of climate-resilient operations. Many operators deploy third-party workforce safety tools that combine employee location tracking with real-time environmental monitoring and issue automated alerts to supervisors and field workers when temperatures exceed a certain temperature threshold, for example. Advanced work planning tools allow infrastructure managers to model and prepare for extreme weather events. For example, rescheduling outdoor maintenance to early morning hours on days when dangerous heat is expected can reduce worker exposure to extreme

temperatures. Taking this measure to protect workers' safety can have significant impacts on productivity as well. A 2024 study similarly found that 60% of construction workers exposed to wet bulb temperatures above 28°C or air temperatures above 35°C demonstrate measurable reductions in output.[505] Left unmanaged, these losses translate directly into longer project timelines, cost overruns, and compounding economic impacts.

Digital Twin: Not Just for Design: Beyond their role in design, digital twins are emerging as operational decision-support tools. A digital twin allows managers to simulate and stress-test responses to a wide range of disruptive events, from pipe breaks and power outages to wildfires and flood gate activations, giving teams the opportunity to strengthen preparedness before hazards occur. Operators can use digital twins to explore intervention options, evaluate cascading risks, and coordinate responses. As climate change increases both the frequency and severity of climate-related hazards, digital twins offer meaningful opportunities to improve operational resilience.

Financial impact of innovating operations: Data-driven operations improve **OPEX efficiency and cash flow stability** by reducing unplanned outages and enabling proactive asset management. Tools such as sensing networks, predictive maintenance, and digital twins help operators avoid costly disruptions and maintain service reliability under climate stress. This strengthens **Earnings Before Interest, Taxes, Depreciation, and Amortization (EBITDA) stability and debt service capacity**, particularly for assets with exposure to extreme weather variability.

8.5 Innovation in Finance



Technology plays a central role in innovative financing for infrastructure, especially when the goal is to mobilize private sector capital, manage risk, and improve project bankability. This section presents an overview of how technology is being used in innovative ways, with a focus on mechanisms and value that are most important for private sponsors, developers, and financiers.

Use technology to demonstrate climate resilience as a credit enhancer, not a cost center: It is innovative to shift how climate adaptation is treated in financing decisions: resilient investments are explicitly linked to lower residual risk and improved access to capital. Sponsors care deeply about cash flow predictability and downside risks. Climate change has the potential to disrupt this predictability and increase risks, but technology helps by making these risks more transparent and quantifiable, so sponsors can be better prepared. Geospatial data, remote sensing, and climate

models are used to assess exposure to floods, heat, sea level rise, and other shocks, reducing the uncertainty surrounding long-term asset performance. Artificial intelligence and machine learning-based scenario analysis can allow lenders to test revenue, demand, and operational assumptions under multiple economic or climate futures. Digital twins simulate how assets perform over time, helping financiers price risk more accurately. By explicitly allocating climate risk across capital layers, these structures improve risk-adjusted returns for sponsors.

Projects are structured based on post-adaptation risk profiles, allowing well-adapted assets to rely more heavily on conventional commercial financing, while reserving concessional capital and guarantees for genuinely high-risk exposures. For sponsors, this reframes adaptation spending as a tool that protects cash flows, stabilizes debt service, and supports longer tenors and tighter pricing, rather than as an unproductive add-on.

Better risk quantification lowers perceived risk premiums, improves creditworthiness, and can unlock commercial debt or equity that otherwise would not participate.

Pre-arranged disaster liquidity to protect returns through climate shocks: Rather than relying on ad hoc post-disaster borrowing, there is a growing role for ex-ante liquidity instruments. These innovations include contingent credit facilities, Cat DDOs, parametric insurance, and extended liquidity reserves, which can be used to manage climate-driven revenue disruption and fiscal stress. These instruments are designed to deploy immediately after extreme events, helping projects and public counterparties avoid technical defaults, preserve credit quality, and maintain operational continuity. For sponsors, this approach reduces tail-risk volatility and supports more predictable performance across the investment lifecycle.

Case Study: Rainfall as an Indicator

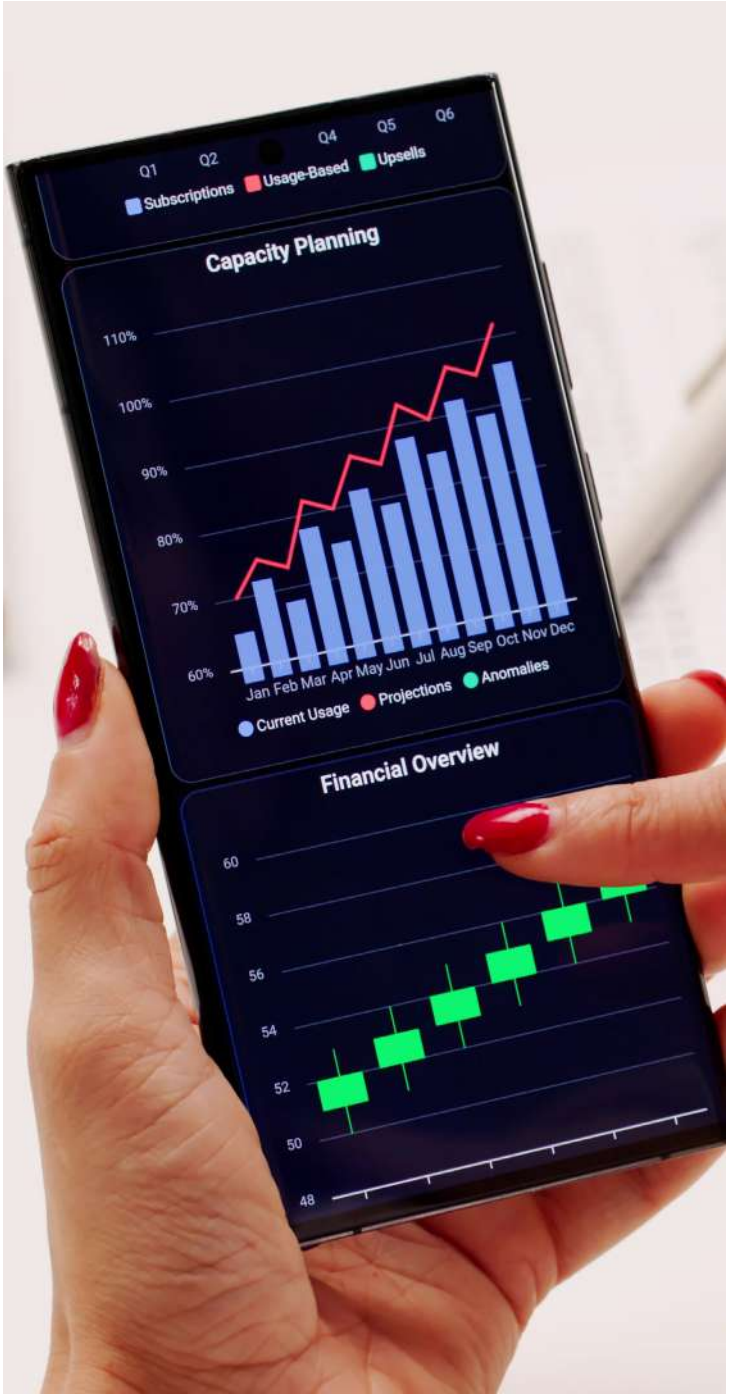
Parametric insurance for hydropower operations in Africa is increasingly attractive to sponsors because it directly stabilizes cash flows against climate volatility, specifically drought and unpredictable rainfall. This scheme eliminates the delays and disputes of traditional loss-based claims. Major reinsurers such as Swiss Re and Munich Re already underwrite and structure these products: Swiss Re's index- triggered "lack of water" cover for hydropower links payouts to independently verified hydrological or rainfall indices, explicitly designed to protect revenues, maintain credit ratings, and support project finance in water- stressed regions, while Munich Re offers parametric weather and hydrology solutions across the energy sector to rapidly transfer risks that are otherwise hard or uneconomic to insure, improving bankability and resilience.[507, 508] For sponsors, the appeal lies in predictable, fast liquidity, lower basis and transaction costs, and scalability across portfolios and geographies, which can reduce the cost of capital for hydropower assets and crowd in private finance alongside DFIs. This advantage is widely noted for renewable energy and climate adaptation investments in emerging markets.

Parametric insurance can help reduce insurance costs and supply gaps for utility-scale renewable energy, smallholder farming, and NBS for climate adaptation.[509, 510] Structuring essentials: index selection and basis risk management; layering with traditional indemnity coverage; coupling with CAPEX for resilience upgrades.

Layered and blended capital structures that crowd in private investment at scale: Sponsors can innovate by layering financing structures combining concessional loans, first-loss capital, guarantees, and commercial debt. These instruments are increasingly used together to mobilize private capital into climate-exposed sectors such as water, transport, and coastal infrastructure. Technology can be used to improve how these structures are designed and governed. Portfolio-level analysis can help sponsors aggregate project-level data across sectors and geographies, enabling portfolio diversification strategies that spread risk across a wide variety of investments and sponsors. Digital monitoring, reporting, and verification platforms track outputs and outcomes, and smart, data-driven platforms enable results-based financing, where private sponsors are repaid based on verified performance. For institutional sponsors, this represents a scalable pathway to access climate-resilient infrastructure assets that would otherwise remain outside the bounds of commercial investment ability.

Mobilize capital through fintech and capital markets innovations: Infrastructure assets or revenue streams (such as tolls or power purchase agreements) can be tokenized, allowing fractional ownership, lowering minimum investment sizes, and increasing liquidity. This is important for attracting non-traditional private sponsors. Digital platforms can also facilitate green bonds, SLBs, and resilience bonds with embedded impact metrics. Automated disclosure and compliance systems reduce issuance costs and reporting burdens. By increasing liquidity, scalability, and automated transparency, infrastructure investments are more comparable to other investable asset classes.

Financial impact of innovation in finance: Technology-enabled risk quantification and financial structuring improve access to capital and reduce the cost of financing by making climate risks more transparent and manageable. Instruments such as parametric insurance, contingent credit, and blended finance reduce downside risk and stabilize cash flows during climate shocks. This allows projects to achieve **longer tenors, tighter pricing, and stronger risk-adjusted returns**, particularly in climate-exposed markets.



Case Study: IDB Contingent Credit Facility (CCF): De-Risking Climate Exposure for Private Capital

IDB's CCF is an innovative climate and disaster risk finance instrument designed to strengthen fiscal resilience in climate-vulnerable countries while crowding in private capital by reducing sovereign risk and improving investment conditions. The CCF provides pre-arranged, rapid-disbursement financing that is triggered following the declaration of a natural disaster or public emergency, enabling governments to respond quickly without disrupting macro-fiscal stability.

From a private-sector investor perspective, the CCF's core value proposition lies in its ability to mitigate downside risk and stabilize sovereign balance sheets in the aftermath of climate shocks. By ensuring immediate access to liquidity, the CCF reduces the likelihood that governments will resort to distortionary fiscal measures, emergency borrowing at punitive rates, or payment delays to contractors and service providers. This enhances creditworthiness, predictability of cash flows, and overall investment confidence in disaster-prone markets.

The CCF is structured as a contingent credit line with clearly defined triggers, offering certainty to markets about when and how funds will be released. This design limits ambiguity around post-disaster financing and complements risk-transfer instruments such as insurance and Cat bonds. For private sponsors, the CCF functions as a public-sector risk buffer that lowers sovereign and project-level exposure to climate volatility, thereby improving the risk-return profile of investments in infrastructure, utilities, and other climate-sensitive sectors.

Critically, the CCF is embedded within IDB's broader Climate and Disaster Risk Finance framework, which promotes proactive risk management and policy reform. Countries accessing the CCF are incentivized to strengthen disaster risk governance and fiscal planning, further reinforcing the enabling environment for long-term private investment. As climate risks intensify across LAC, the CCF demonstrates how multilateral development banks can use contingent public finance to unlock and safeguard private capital, accelerating resilience while preserving fiscal and market stability.



8.6 Cross-Cutting Innovations to Promote Resilience

Figure 15. Five cross-cutting innovations to promote resilience



Integration of Technology and Artificial Intelligence: Across every phase of the infrastructure lifecycle, from design and construction to long-term O&M, AI and machine learning are becoming useful tools for enhancing the resilience of infrastructure assets and systems. For example, AI enables infrastructure owners and asset managers to break down silos that have historically kept valuable datasets separate and underutilized, synthesizing satellite imagery, LiDAR surveys, IoT sensor feeds, climate models, and socioeconomic data into a unified analysis that can be used to better predict risks and deploy solutions during design and planning, construction, and operations. AI is also becoming incorporated into other technological systems, such as digital twins and sensor networks, allowing managers to better anticipate and prepare for challenges and disruptions.

Use technology to take a Systems Approach to Resilience: Taking a systems perspective when it comes to building resilience calls for a portfolio approach that looks beyond individual assets to assess risk across the entire system. By identifying the most vulnerable points within that system, decision-makers can prioritize interventions where they will have the greatest impact, as strengthening one vulnerable asset can build resilience across the whole system. A systems approach can mean leveraging adaptation measures such as dual sourcing for critical components and implementing

climate risk due diligence for suppliers. Climate risk analysis across a system can be used to better size strategic reserves of critical materials, spare parts, or consumables. If these needs are determined across the whole system based on quantified need instead of a historical average, efficiencies can be gained. Supply chain resilience is a co-benefit of applying this framework to infrastructure investments. For example, upgrading a port to better withstand future sea level rise and storm surge may protect that asset, but if the connecting service roads are not also considered, one flooded road can undermine the entire supply of goods to and from the port.

Standards, Certifications, and Safeguards: Forward-looking standards, certifications, and safeguards represent a critical cross-cutting innovation for mobilizing private investment in climate-resilient infrastructure. Rather than relying on untested approaches, private sponsors increasingly favor proven, leading-edge standards that embed climate risk considerations into infrastructure design, construction, and operation, which reduces uncertainty while improving long-term asset performance. Updated international and national standards (e.g., ISO, NIST, ASCE) that explicitly incorporate emerging data on climate hazards such as flooding, extreme heat, and wind loads help standardize resilience expectations across markets and sectors, and can bring efficiency to a private-sector portfolio across the region. While uptake varies across LAC, these standards are increasingly referenced in public procurement, multilaterally financed projects, and insurance underwriting, making them directly relevant and adaptable to regional contexts.

A good example of market alignment is the use of resilience-oriented design standards recognized by the insurance industry, such as the FORTIFIED standards developed in the United States.[511] These standards demonstrate how technical design requirements can translate directly into financial incentives, including reduced insurance premiums or improved coverage terms when assets are designed to higher resilience thresholds. For private developers and financiers, this linkage effectively monetizes resilience by lowering operational costs and protecting asset value. This approach could be replicated or localized in LAC markets where climate risk and insurance affordability are growing constraints.

Nature-Based Solutions: NBS are increasingly recognized as an innovative investment for private developers and sponsors seeking to manage climate risk while enhancing long-term asset value. Unlike large, capital-intensive engineered defenses, NBS are typically place-based, modular, and closely aligned with specific hazards, allowing them to be targeted where risk reduction delivers the greatest financial return. Investments such as wetlands for

Example:

Dominican Republic's Blue Spot analysis[513] evaluated the entire country's road system to determine the most critical and vulnerable components of the network. This allowed planners to deploy solutions that tackle the most at-risk infrastructure components for the entire network's performance, even if, individually, these assets were not the most vulnerable. By taking a systems approach, DR has the ability to maintain adequate levels of service across the country's roads.

flood attenuation, mangroves for coastal protection, or green infrastructure for heat and stormwater management directly reduce physical climate risks that threaten revenues, insurability, and asset lifespans. For private capital, this spatial and functional specificity translates into clearer value propositions: reduced exposure to losses, improved operational reliability, and stronger alignment with lender, insurer, and ESG requirements. NBS therefore function not only as environmental interventions, but as risk-mitigation assets embedded within development and infrastructure portfolios.

NBS are also innovative because they reframe resilience as a value-added feature rather than a sunk or recurring cost. Well-designed NBS investments tend to appreciate over time as ecosystems mature, delivering increasing protective benefits and co-benefits that can support multiple revenue and financing pathways, including performance-based contracts, insurance premium reductions, and blended finance structures. This durability aligns well with the long investment horizons of infrastructure asset investments. By integrating NBS into projects, developers can internalize resilience into core asset design, improving long-term returns while meeting growing expectations from regulators, sponsors, and communities. In this way, NBS represent a shift in how private markets innovate around climate resilience: leveraging natural systems to enhance asset performance, manage downside risk, and unlock sustainable value creation. Hydropower operators in Colombia and Costa Rica are integrating upstream nature-based solutions, such as forest restoration and watershed management, to stabilize water flows, reduce sedimentation, and protect generation reliability amid increasing climate variability, strengthening long-term asset performance and energy security without relying solely on new gray infrastructure.[512]

Technology plays a critical enabling role in making NBS more effective, measurable, and investable. Advanced geospatial analytics, remote sensing, and climate models allow NBS to be sited and designed with precision, ensuring interventions are deployed where they deliver the greatest risk-reduction benefit relative to cost. Once implemented, digital monitoring tools like sensors, satellite imagery, and analytics platforms can provide ongoing visibility into ecosystem performance, enabling adaptive management and quantification of avoided losses under real-world climate conditions. In this way, technology makes NBS appealing to markets, transforming them from qualitative sustainability features into scalable, risk-mitigation assets embedded within infrastructure portfolios.

Risk Allocation Across the Project Lifecycle (Planning, Construction, and Operations): Effective risk allocation should span the full project lifecycle (planning and design, construction, and long-term operations) by embedding climate resilience requirements as enforceable contractual obligations rather than aspirational objectives. During planning and design, contracts and tender documents should clearly allocate responsibility for identifying climate vulnerabilities and integrating resilience into technical standards, performance specifications, and capital cost assumptions. In construction and PPP delivery models, performance-based milestones and incentives can be linked to the delivery of climate-resilient features, aligning contractor and concessionaire behavior with long-term asset performance. Across construction and into operations, standardized parametric contract provisions (e.g., trigger-based extensions of time, predefined cost adjustments, or activation of adaptive operating protocols when hazard thresholds are exceeded) can reduce disputes and provide predictable responses to climate shocks. Clear, lifecycle-wide risk allocation reduces investor uncertainty, improves bankability, and ensures that responsibilities sit with the parties

best positioned to manage climate risks over the asset's full operating life.

Financial impact of using cross-cutting innovations to promote resilience: Standards, certifications, and nature-based solutions reduce **lifecycle risk and operating cost pressure** by embedding resilience into asset performance and governance. These approaches improve comparability, reduce due diligence uncertainty, and strengthen alignment with lender, insurer, and ESG requirements. As a result, they support **more stable long-term cash flows and improved bankability**, particularly for institutional sponsors.

8.7 Conclusion

For private infrastructure sponsors, innovation is no longer defined by isolated technologies or one-off design choices, but by how effectively data, digital tools, and advanced analytics are integrated to inform better decisions over time. The adoption of AI, sensing technologies, digital twin models, and climate analytics enables infrastructure stakeholders to move from reactive risk management to proactive, system-wide resilience. Uncertainty is better quantified, trade-offs are made transparently, and resilient investments are prioritized for maximum impact. When embedded into planning, construction, operations, and financing, these innovative technologies transform resilience from an added cost into a value-enhancing strategy that protects cash flows, strengthens asset performance, and improves bankability. For the private sector in particular, technology serves as the connective tissue linking climate risk information to design standards, operational decisions, and financial structures, enabling resilient infrastructure to be delivered at scale. As climate risks intensify across LAC, accelerating the adoption of these digital and systems-based approaches will be critical to building resilience into infrastructure for the future.



For Private Infrastructure Sponsors and Financiers

For sponsors, innovation should be approached as a risk-management and value-protection strategy, not an experimental add-on.

Key Recommendations:

Adopt "digital-first" due diligence. Use climate analytics, geospatial data, and scenario modeling to quantify physical climate risk, test revenue and cost assumptions, and differentiate well-adapted assets from those likely to become stranded across the system.

Price and allocate climate risk explicitly. Incorporate innovative tools into financial structuring to stabilize cash flows, protect debt service, and reduce tail-risk volatility (e.g., digital twins, predictive maintenance platforms, parametric insurance, and pre-arranged liquidity).

Favor projects that embed resilience across the lifecycle. Prioritize systems and assets that integrate innovation from design through construction and operations (e.g., climate-smart materials, modular construction, AI-enabled O&M), as these characteristics are associated with stronger long-term performance and bankability.

Leverage standards and certification to reduce transaction costs. Use recognized resilience, sustainability, and governance standards to streamline due diligence, improve comparability across assets, and access expanded pools of capital, including green and sustainability-linked financing.





For Infrastructure Owners, Developers, and Operators

Owners and operators play the critical role of turning innovation into day-to-day operational resilience.

Key Recommendations:

Embed innovation at project inception, not after construction. Integrate climate risk, systems thinking, and digital tools during planning and design to avoid costly retrofits and operational constraints later.

Treat operations as an active risk-management function. Deploy sensors, drones, AI-driven predictive maintenance, and workforce protection tools to anticipate failures, reduce outages, and protect staff under increasingly extreme conditions.

Use digital tools to support adaptive decision-making. Apply digital twins and real-time data platforms to stress-test operations, prepare for compound shocks, and coordinate responses across interconnected systems.

Align internal incentives with long-term performance. Track resilience-focused KPIs (e.g., avoided downtime, maintenance efficiency during hazard events, contingency drawdown) so innovation directly informs budgeting, asset management, and capital planning.

Appendix A: *Adaptation Case Studies*

In this section, case studies highlight the wide range of available adaptation strategies and the incremental costs tied to these investments, while describing the significant resilience benefits they deliver. Sponsors operating across diverse geographies, economies, and financial instruments increasingly need to understand the rationale and financial implications of investing in climate adaptation. To support sponsors' informed decision-making, this section presents a set of case studies that exemplify the range of adaptation activities relevant to infrastructure investments. Adaptation strategies span a wide spectrum in terms of type and scale, and the associated costs also vary considerably. The financial requirements for sponsors to implement these strategies can differ significantly depending on the nature and scope of the strategy. The case studies represent one or more categories of adaptation options, each representing a different relationship between climate resilience, costs, and project objectives.

Type 1 – Activities That Are Adapted:

These projects integrate climate risk management measures to safeguard the project's core objectives. Adjustments are made to ensure performance under current and future climate conditions; adaptation is not the primary goal. These types of investments are common in infrastructure and energy sectors where climate risks are material to operational success. Adaptation measures may include: **soft or hard improvements** (e.g., adjusting maintenance and infrastructure tracking schedules or upsizing the design of culverts to cope with increased risk of extreme rainfall), **gray or green infrastructure** (e.g., a seawall or vegetated dunes to reduce impacts of sea level rise), and **upfront or long-term costs** (e.g., capital investment in new built infrastructure or long-term adaptive management of assets over time).

Type 2 – Activities With Shared Resilience and Investment Objectives:

These initiatives are designed to directly reduce climate risks while simultaneously advancing additional investor goals. They are grounded in a robust understanding of the climate vulnerabilities of the systems in which they operate. Adaptation is a co-equal objective, often embedded in economic development, water resource management, or urban planning efforts. For example, diversifying the water sources of a private water utility can meet the increased demand of a growing population and simultaneously reduce risks to the water supply reliability due to increasing severity of droughts. Similarly, an energy company operating only hydroelectric plants may seek to diversify its generation sources by adding solar installations to reservoirs behind its hydroelectric facilities. The use of diverse technologies ensures reliable generation capacity that is more resilient to droughts.

Type 3 – Activities That Enable Resilience:

These investments target the systemic drivers of climate vulnerability, aiming to create enabling conditions for broader resilience. They may involve large-scale infrastructure construction, policy reform, capacity building, technological innovation, or ecosystem restoration. Building resilience through adaptation is the primary objective, and these activities often yield long-term resilience dividends beyond their immediate scope to varying degrees depending on the type of intervention. For example, although a levee may be a significant expense for a community, the protection it would provide may avoid millions of dollars in future damages across multiple assets by preventing floodwaters from inundating structures and facilities in the town. The costs of the levee, when spread out across a number of assets, could represent a small percentage of the value of each asset. An early warning system in the same town could be installed at a much lower cost. The system can warn citizens of impending flood risks and limit public health and safety impacts. A warning system can also warn dam managers about impending flooding, giving them time to implement managed water releases. This type of investment could protect human health and protect buildings or infrastructure without other actions by facility managers.

By protecting and strengthening the broader value chain for economic activities, these measures enhance the long-term viability and competitiveness of an investor's entire portfolio. While these investments are generally led by the public sector, private sector partners often add considerable value to these efforts by bringing technological innovation, project management expertise, and cost discipline. Private sector participation, such as in deploying smart infrastructure and technology-driven solutions, enhances efficiency, enables scalability, and

ultimately drives down the long-term costs of building resilience. A single well-targeted investment can yield positive economic returns across multiple facets of an investor's portfolio while simultaneously advancing regional climate resilience. See Section 4.2: Infrastructure Vulnerabilities and Adaptation Costs and Benefits Across Key Sectors for more information.

Type 1 investments are typically focused on specific assets, or on investments that address associated risks and vulnerabilities to which a project may be exposed and cause financial underperformance. Type 2 and 3 investments address wider climate risks and vulnerabilities that have broad socioeconomic implications and risks to the larger value chain. Together, these types of

Climate-Resilient Roadways Reduce Recovery Costs for Sponsors and Users

Elevating roadway flyovers above flood-prone river crossings is a strategic investment. This type of infrastructure upgrade not only reduces the frequency and duration of roadway closures during extreme weather; it also delivers wider societal and economic benefits.

For the **public**, it ensures safer, more reliable transportation routes, supports emergency response, and minimizes disruptions to daily commutes and commerce.
From an **investor's perspective**, this adaptation measure can yield direct and indirect returns. Raised flyovers minimize repair costs needed to restore infrastructure after flood events. If the investor holds stakes in adjacent or dependent assets, such as industrial parks, logistics hubs, or manufacturing facilities, reliable access to the road network ensures continuous operations, thus reducing downtime and ensuring more stable revenue.



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investments in resilience achieve differing levels of protection and have different associated costs and benefits. Adaptations for climate resilience typically represent a small portion of the overall project scope for Type 1 and 2 projects. In contrast, Type 3 projects' primary objective is resilience, and the cost of adaptation measures can encompass the entire project cost. The case studies illustrate these different approaches to resilience, demonstrating how adaptation can be integrated, co-prioritized, or directly targeted by investment strategies. They also offer practical insights into how adaptation costs and benefits can be tracked in different circumstances, helping private sponsors align their portfolios with their climate resilience goals. The table below shows the case studies and adaptation type(s).

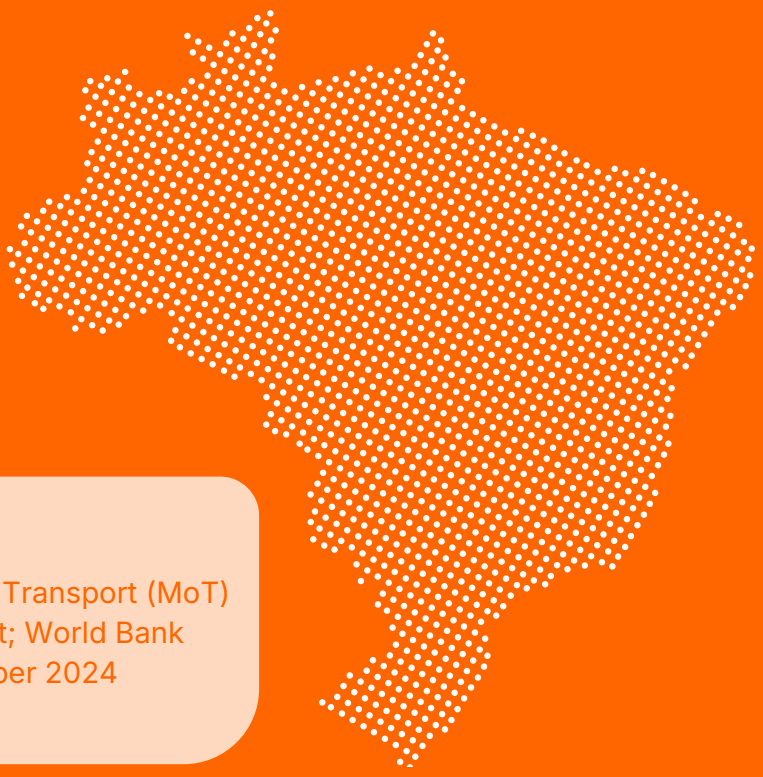
Case studies and adaptation type(s)

Case Study	Type 1 Activities That Are Adapted	Type 2 Activities With Shared Resilience and Investment Objectives	Type 3 Activities That Enable Resilience
Brazil Pro-Roads Project	✓	✓	•
Metro São Paulo Line 4 Phase III Extension	✓	•	•
Xochi, Flower Road	✓	•	•
Corsan: Solutions for Reducing Water Loss	•	✓	•
Ceará Port and Industrial Green Hydrogen Hub	✓	•	•
Floating Solar-Hydro Hybrid at Afobaka Dam	•	✓	•
Remote Area Rural Electrification Program	✓	•	•

✓ Applies • Does not apply

Brazil Pro-Roads Project

Brazil Pro-Roads: *Proactive, Safe, and Resilient Road Asset Management Program*



Country: Brazil
Owner/Project: Ministry of Transport (MoT)
Status: Under development; World Bank financing closed in November 2024

Project Cost:

$200M

Financiers:

$150M
World Bank

$12.5M
Private capital Mobilization

$37.5M
Brazil Government

Climate Risk(s) Addressed:

Floods

Landslides

Sea Level Rise

Extreme Weather

Extreme Heat



Performance-Based Contracts (PBCs) Support High-Quality Construction and Maintenance

Traditional contracts are paid based on inputs (i.e., quantities of work performed), whereas PBCs are paid based on *outputs* (i.e., road quality).

PBCs provide significant savings for all sponsors through reduced operating and maintenance costs over the lifespan of the project: an analysis of PBCs compared to traditional methods for a five-year period found that the **PBC approach saved 20% compared to traditional contracts and resulted in better road conditions.**

PBCs are known in Brazil as *Contratos de Reabilitação e Manutenção,* or CREMA.

Background

This project aims to improve the long-term resilience of the state of Bahia's public road network with financing from the World Bank, the state government, and private capital investments. The project has several components to address climate risks. These include: **targeted safety and resilience improvements for road infrastructure** to reduce damage and improve transport access and reliability; and **proactive maintenance** to address roads that are in poor condition and require rehabilitation, and roads that lack long-term maintenance contracts or require improvements to withstand climate hazards. Investments in proactive maintenance and climate-resilient designs enhance the reliability of the road network, allowing economic activities to continue uninterrupted.

The project leverages multi-year performance-based contracts (PBCs) (see textbox) for design, build, and maintenance functions (CREMA-DBM) and public-private partnerships (CREMA-PPP), which provide significant financial benefits for

sponsors and allow for more efficient use of funds. The project includes clear intermediate KPIs for components related to climate resilience, including the number of hazardous spots for climate resilience that are improved and the implementation of other climate resilience studies and adaptation actions. Road revenues do not include tolls; rather, these contracts are set up to delegate to the private sector the management responsibility of the road infrastructure, with regular payments for road performance based on surface quality. A total of $12.5 million in private capital mobilization is expected for CREMA-DBM. The World Bank estimates that in Bahia, $200 million of private capital for additional investments across the state is expected to be enabled through this program.[514]

This project will ensure high-quality roads across the state of Bahia, with positive cascading benefits for businesses and sponsors throughout the value chain. Improved road asset management through long-term PBCs under the responsibility of the private sector for climate resilience and road safety improvements will ensure better quality roads and fewer road network disruptions. This case study demonstrates how a major network transportation infrastructure project has effectively addressed climate risk by incorporating adaptations that improve resilience and ensure long-term financial benefits for private sponsors through unique PBC contract arrangements.

Climate Risks

Climate change is already impacting Bahia State's road network. Extreme rain events cause severe flooding and landslides, making roadways impassable and disrupting access to critical destinations especially along the coast. Heavy rain can weaken and damage roadway pavement, erode road foundations and embankments, and in extreme cases, wash out bridges and roads. By 2040, intense rainfall events are projected to increase by at least 20% compared to the 1970–1999 average, and 51% of the main road network will face increased precipitation exposure.[515] Nearly 80% of the route segments currently at risk will also see increased risk from intense precipitation in the future. Overall, only 12.5% of Brazil's roads are paved, exacerbating the network's vulnerability to climate events. Extreme high temperatures can also cause pavement deformation and cracking. Sea level rise is expected to make some roads impassable in the coming decades. Road improvements in Phase 1 will focus on the Baixo Sul region, which has one of the highest levels of precipitation in the country and is at high risk of sea level rise, floods, and landslides.

Adaptation Strategies and Benefits

The project incorporates a wide range of physical adaptation strategies to ensure road improvements are designed, constructed, and maintained to withstand future climate hazards. These strategies can significantly decrease or eliminate the need for unplanned infrastructure repair costs, in addition to increasing economic activity by providing reliable transport access year-round.

- **Proactive Maintenance:** The current condition of Brazil's road infrastructure has resulted in a reactive, costly maintenance cycle, where failures are only addressed *after* they occur. This project uses long-term maintenance contracts that explicitly consider climate risks, helping the country transition to a proactive maintenance approach. The CREMA contract includes long-term maintenance and climate resilience measures, such as reinforcing culverts, upgrading longitudinal drainage, enhancing slope protection, and using heat-resistant pavement. Proactive maintenance helps prevent failures, reducing disruptions to transport, extending the lifespan of critical infrastructure, and minimizing costly repairs

due to climate events. The overall net cost-effectiveness of using CREMA for proactive maintenance is approximately 24% across the region; CREMA rehabilitation work unit costs in Brazil are 25–35% lower than traditional rehabilitation costs signed during the same period. Maintenance costs for roads in Brazil are 34% lower than conventional maintenance costs. CREMA final unit costs over a full 5-year rehabilitation and maintenance cycle have been 19% lower than the rehabilitation and maintenance cumulative costs for 13 federal roads which benefited from separate contracts for rehabilitation works and maintenance services after construction.[516, 517]

- **Climate-Resilient Design:** Brazil's road network drainage systems cannot withstand current heavy rainfall events, and these events are expected to worsen. The project incorporates future precipitation projections into hydraulic designs to ensure drainage systems have sufficient capacity for higher water volumes, limiting washouts and impacts to movement on the road network. The CREMA contract includes designs for improvements of climate-vulnerable roadway segments that account for the intensification of weather events. The higher short-term costs of improved drainage structures and maintenance are estimated to be 2.5% of total rehabilitation costs.[518] This relatively modest investment will decrease repair costs by reducing the impact of flooding events on road infrastructure. Where possible, road improvements will also use climate-resilient building materials, such as heat-resistant pavement to reduce damage from future extreme heat.

- **Flood and Landslide Protection Measures:** Both gray engineering and bioengineering solutions will be incorporated in road improvements to strengthen and protect road infrastructure and reduce disruptions to transport. For example, construction of flood bypasses and high road crossings in flood-prone areas will allow traffic to move above flooded areas during heavy rain events. Gray and green infrastructure solutions, such as gabions, riprap, vegetated swales, and bio-engineered slopes, will be used to stabilize slopes and reduce flooding and landslide risks. Wooden bridges will be replaced with standard concrete bridges, which can withstand more severe weather events. Although infrastructure improvements have additional near-term costs, they will reduce costs in the long term by avoiding costly repairs associated with extreme weather events.



Costs and Financial Returns

In Bahia, $200 million of additional private capital is expected to be enabled throughout the value chain as a result of this program and more reliable and resilient transportation in the state. The costs associated with specific adaptation measures for the road network in Bahia are summarized in *Table 39*.

Table 39. Adaptation measures and associated costs[519]

Scope	Adaptation Measures	Cost ($)
Proactive maintenance (including road rehabilitation and spot improvements)		
1,000 km vulnerable state roads: • 650 km: full rehabilitation • 350 km: maintenance and spot improvements	• Erosion protection measures and bioengineering for slope stabilization: retaining walls, gabions, riprap, use of natural materials (vetiver, bamboo) • Drainage improvements: upsizing culverts, deeper foundations, longitudinal drains • Heat-resistant materials: modified bitumen to avoid deformation/cracking	**$121.5 million** total **$121,500** per km
Long-term (20-year) proactive maintenance for safe and resilient state roads		
800 km of roads	• Proactive maintenance: cleaning drainage infrastructure, sealing pavement cracks • Drainage improvements: reinforcing culverts, drainage upgrades • Slope protection measures • Heat-resistant pavements	**$5 million**
Geospatial tool for climate resilience adaptation		
Climate Risk and Resilience Assessment Tool	• Critical tool for understanding climate risks and deciding on interventions to strengthen climate resilience of the network, with additional interventions adequate to the maintenance strategy—with climate focus—of the state • Supports cost-effective adaptive management of road assets, enabling managers to focus on the most vulnerable areas of the network	**$400,000** for tool development

Scope	Adaptation Measures	Cost ($)
Strategic Conservation and Maintenance Plan for Roads		
Develop a Strategic Conservation and Maintenance Plan including models and methodologies for tackling climate vulnerabilities	• Implement climate resilience design standards in the strategy, aimed at improving climate resilience of the road network • Assess and quantify risks related to road infrastructure and identify potential threats • Identify critical and vulnerable road infrastructure that is susceptible to flooding and landslides • Adaptation and investment strategies offer possible ways to anticipate changes to road transport and invest accordingly • The activity will focus exclusively on climate resilience and no other natural hazards and disaster risk management such as flooding / landslides • This type of investment would be applied on an ongoing basis to deploy asset-level adaptations	**$150,000** for strategic plan development
Construction of three flood bypasses along state road corridors		
• Design and construction of three bypasses around cities	• Flood bypasses • Slope protection • Bridge construction/upgrades to withstand future extreme rainfall events (future 100-year return period flood event) • Climate-resilient hydraulic design	**$10 million** per bypass
Spot improvements in the road network to provide all-season transport access		
• 600 spots with high climate vulnerability • Focus on state and non-paved roads	• Construction of high road crossings in flood-prone areas • Bridge construction, upgrades, and repairs, including replacement of wooden bridges with standardized concrete bridges • Culvert and drainage improvements, removal of quagmires • Leveling of slopes	**$20.9 million** **$34,792** per location

A BCA was conducted for Phase 1 of the project, indicating a **NPV of $294.5 million and an IRR of 39.4%**. This exceeds the estimated opportunity cost of capital (12%). A sensitivity analysis also showed that these results are robust to the risks associated with project implementation, variations in the discount rate, and reductions in time savings. Table 40 summarizes the project benefits, and many of these benefits have indirect implications for private sponsors in the State.

Table 40. Summary of Phase 1 project benefits

Project Benefits	NPV ($ million)
Time savings and vehicle operation cost reduction on the improved roads	$192.5
Time savings from construction of bypasses in Baixo Sul	$18.5
Time savings and other benefits from improved accessibility in rural roads	$18.5
Road safety benefits resulting from a reduction in road traffic fatalities	$56.9
Gains from reduced CO_2 emissions	$8.1

Key Findings and Replicability

This project highlights the importance of investing in long-term maintenance and ensuring funds are used efficiently through PBCs. The benefits outlined above have meaningful implications for private sponsors, particularly those with diversified exposure across the value chain and who rely on functioning transportation and logistics infrastructure. Time savings and reduced operating costs with an NPV of $192.5 million can enhance supply chain efficiency and lower operating expenses for businesses reliant on road transport. Improvements in rural accessibility and bypass construction have a combined NPV of $37 million and can unlock new markets and facilitate more efficient movement of goods and labor; this is especially valuable for sponsors with exposure to manufacturing, agri-business, and retail distribution. Road safety enhancements with an NPV of $56.9 million can reduce the risk and liability for fleet operators and private insurers, while gains from reducing CO_2 emissions align with ESG investment strategies and regulatory compliance. Together, these benefits contribute to a more resilient and cost-effective infrastructure ecosystem which enhances road network reliability and indirectly boosts returns while reducing risk for private sponsors in Bahia State.

Metro São Paulo Line 4 Phase III Extension

***Private Delivered Metro São Paulo** Line 4 Phase III Extension*



Country: Brazil
Owner/Project: State of São Paulo / ViaQuatro)
Status: Active implementation. World Bank funding closed July 2025

Project Cost:

$847M

Financiers:

The World Bank and private capital

Climate Risk(s) Addressed:

Flooding

Heat

Extreme Weather



Background

This major public-private partnership project will develop a 3.3-km extension of the São Paulo Metro from Vila Sônia to Taboão da Serra, including two stations and necessary supporting infrastructure. The project includes design, engineering, procurement, and construction components. The expansion route is situated in a region highly vulnerable to climate impacts—particularly flooding and extreme heat. Therefore, the project incorporates a suite of resilience-enhancing features to mitigate climate risks and support uninterrupted operations of the Metro Line 4 extension. The project design also incorporates several service improvements, including universal accessibility features, seamless bus-metro integration, and the reduction of road crossings to create a more pedestrian-friendly environment.

Climate Risks

The major climate risks for the project **are increasing temperatures, fluctuating water levels, and increasingly frequent and intense extreme weather events.**[520] Services to São Paulo's estimated population of 12 million residents are impacted by seasonal flooding, which damages infrastructure and impacts Metro operations across the area.[521] Extreme weather events, such as heavy rain and hailstorms, have the potential to disrupt operations, cause service delays, and damage equipment. In fact, these impacts are already challenging the reliability of services. Historical records from São Paulo's Civil Defense Agency document numerous flood events within the project area, especially near the drainage zones of the Pirajuçara and Charque Grande streams, which intersect the planned Metro Line 4 extension. Operational data from SP Metro over the past decade further reveal repeated climate-related service disruptions, particularly due to heavy rainfall and hail events. As climate risks mount, system managers realize that these disruptions highlight the urgent need for a resilient design for the extension that includes protections and system redundancies to safeguard against shutdowns and ensure continuous service. In addition, rising temperatures impact the efficiency of electricity infrastructure and reduce the service life of building materials. A warmer future, particularly extremely hot days, is expected to drive increased demand for electricity to support cooling. Fluctuating water

levels—especially groundwater—increase the need for pumps, flood management infrastructure, and water conveyance systems. These climate-related impacts are exacerbated by the rapid urbanization underway. Intense development has significantly altered the natural hydrology of the area; canalized streams, obstructed waterways, and constrained floodplains are reducing drainage capacity and further intensifying the frequency and severity of flood events.[522]

Adaptation Strategies and Benefits

To address infrastructure vulnerability, the design incorporates a range of adaptation measures:

1. **Flood Protection:** Installation of drainage systems designed to withstand future precipitation events, elevation of entrances, stations, and other critical infrastructure above projected flood levels, installation of pervious pavement to absorb rainwater and reduce runoff, and deployment of dry floodproofing measures—such as protective walls and sealed gates—to safeguard stations and tunnels from inundation.

2. **Durable Materials:** Use of waterproof concrete and coatings engineered to withstand high temperatures and humidity, ensuring long-term structural integrity under warmer climate conditions projected in the future.

3. **Thermal Management:** Enhancement of ventilation systems, including raising infrastructure and equipment out of flood-prone areas, application of reflective coatings, and installation of thermal insulation on roofs and walls to reduce heat absorption. Special attention is given to minimizing the use of glass roofing to mitigate internal temperature rise.

4. **Resilient Energy:** Deployment of solar panels and other renewable energy sources to reduce dependence on external power grids and ensure reliable electricity service during climate-related disruptions. Redundant power supplies, surge protection, waterproof cabling, and redundant communication systems all ensure continuous operation during power grid disruptions.

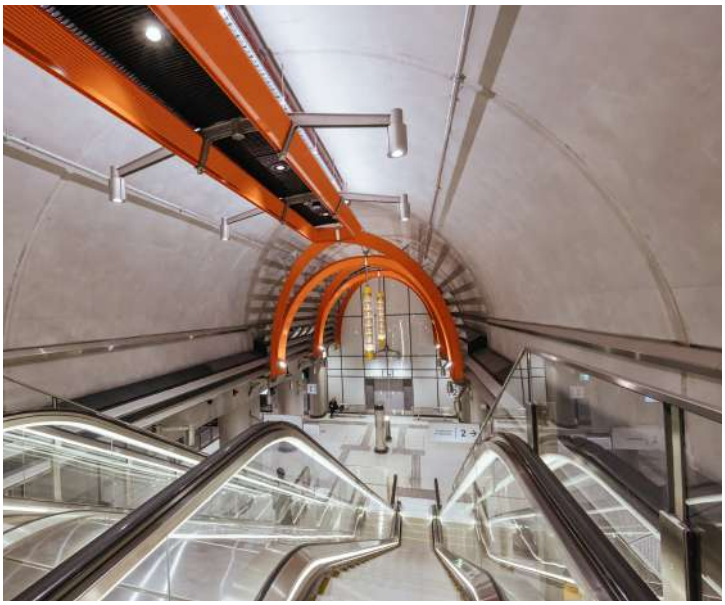
5. **Monitoring Technology:** Installation of sensors and advanced technologies for real-time monitoring of environmental conditions, enabling data-driven adjustments to optimize O&M.

Costs and Financial Returns

The total cost of the project is $847 million. Of this, the Government will contribute approximately 80% ($686 million). Of this, $400 million will be financed by the World Bank, with the remainder covered by public funds. ViaQuatro, the private concessionaire, will mobilize the remaining 20% (around $169 million), which will be recovered through the existing PPP Contract through increased ridership, incremental fare increases, and contract extension[xxiii]

Key infrastructure components associated with this project demonstrate the modest incremental costs of strengthening the resilience of the design to manage climate risks. The World Bank estimates that $33 million in adaptation financing contributes to civil works systems, representing an incremental cost of 4.13% of the total infrastructure cost.

xxiii An extension of the concession period from June 2040 to November 2041



This cost includes the advanced drainage systems, waterproof tunnel linings, elevated entrances, heat-resistant materials, and permeable surfaces around stations to absorb rainwater.

A future climate-related service disruption on the Line 4 extension could have significant direct financial impacts for sponsors and the operator; further, this type of interruption can have wide-ranging economic impacts on businesses and consumers. Each disruption would result in lost productivity, business revenue losses, and increased costs for alternative services. Line 4 ridership is approximately 800,000 passengers per day, and by 2040, Line 4 is expected to transport one million passengers daily.[523] At R$5.20 per trip, a one-day outage equates to over $760,000 per day in lost revenue from fares alone and $960,000 per day by 2040, a significant impact on ViaQuatro's overall revenue.[xxiv]

Assessment of financial risks for different climate-related disruptions demonstrates the financial value of investing in resilience upfront. For example, in a hypothetical scenario without adaptation investment and projecting an average of two outages per year over the course of the 30-year planning horizon, the financial losses would total $45 to $58 million.

Proximity to transit service can boost local economic activity, leading to increased constructed areas and commercial property development, shifting land use that supports denser and more mixed-use development, and stronger investor and developer confidence. The reliability of this transit service is key to this dynamic of catalytic investment. While a single outage may not persuade people to find new jobs and/or alternative transportation options, or deter developers from investments linked to transit locations, continued service disruptions can be expected to erode consumer confidence and depress ridership over the long term. As climate change hazards increase in frequency and intensity, resilient design ensures that the development benefits of transit investment are realized.

Key Findings and Replicability

This project demonstrates the benefits of integrating climate-resilient design into new transportation infrastructure. Benefits are realized by both the private sector owner/operator and by the broader economy. By drawing on both historic observations of weather events and on modeled climate projections, transit stations and rail lines can be designed to withstand more intense flooding, storm events, and extreme heat. For owner/operators, the relatively modest incremental costs of more resilient design are offset by the direct benefits of reduced service disruptions, more reliable revenues, and predictable operational costs. These direct benefits are further supported by the economic development that is spurred by enhanced mobility and access to services for the surrounding community.

xxiv Exchange rate 5.38 Brazilian Real to 1 United States Dollar (as of 21 October 2025).

Xochi, Flower Road

***Xochi** Flower Road*

Country: Guatemala
Owner/Project: Fondo BPS S.A.
Status: In implementation

Project Cost:

$55M

Financiers:

IDB Invest

Climate Risk(s) Addressed:

Landslides

Flooding

Wind

Wildfire



Figure 16. Digitally rendered image of the finished project. Source: IDB Invest.

Background

This project includes the construction, operation, and maintenance of a 30.5 km bypass road to alleviate traffic issues and congestion on the CA-2 highway and boost connectivity in the departments of Suchitepéquez and Retalhuleu in Guatemala. **The project was designed to account for future climate conditions and will ensure reliable transportation access along a critical highway in Guatemala, serving over 22,000 daily travelers and reducing travel time from over three hours to just 25 minutes.** The project is entirely private and consists of a term loan to Fondo BPS S.A., a special purpose vehicle (SPV) established in Panama, and its shareholder, BPS General Partner Corp. IDB Invest will use blended finance funds for the project. The syndicated amount for the project is $10 million, and the total financing amount is $55 million.

Xochi Road will ultimately positively benefit businesses and sponsors in the region by reducing travel time and ensuring continuous, reliable transportation access, even during extreme weather events. This case study demonstrates the value of conducting a BCA for climate adaptation measures before designing a project, as adaptations can provide significant long-term financial benefits by reducing service disruptions and repair costs.

Climate Risks

A climate risk assessment was conducted to inform the selection of adaptation measures early in the project design process, considering both historic conditions and modeled projections of future climate. Guatemala is especially vulnerable to extreme weather events such as hurricanes and tropical storms due to its location between the Pacific and Atlantic Oceans. The climate risk assessment identified extreme heat, flooding, landslides, cyclonic winds, humidity, and wildfires as significant risks to the project's design and

operation. Maximum temperatures are projected to increase by up to 2.4°C by the end of the century, heat waves are projected to become longer and more frequent, and extreme storms are projected to intensify. Heat waves can accelerate pavement deterioration and damage the pavement substructure, increasing maintenance costs over time. Additionally, extreme precipitation events can flood roadways and cause landslides, leading to service disruptions and significant repair costs.

Adaptation Strategies and Benefits

The project will incorporate a diverse range of adaptation measures, with a focus on flooding, erosion, and extreme heat. These adaptation measures can significantly reduce long-term costs associated with maintenance and repair following extreme weather events, in addition to reducing service disruptions and bolstering economic activity in the region.

- **Heat Resilience Measures for Pavement:** Multiple measures will be incorporated to increase pavement resilience to extreme heat events. For example, performance-grade and polymer-modified asphalt mixes will be used, which are more resistant to aging and weathering and have greater elasticity, reducing the risk of cracking under extreme high temperatures. These asphalt mixes are also more resistant to deformation and rutting from heavy traffic loads, increasing their lifespan. The project will also use light-colored asphalt pavement, which can help lower air temperatures by reflecting more sunlight and reducing the urban heat island effect. Light-colored asphalt pavement is also more durable and can improve visibility and road safety.

- **Slope Stabilization Measures:** A significant concern for both roadways and bridges in the project area is erosion from extreme rain events. Both gray infrastructure and nature-based adaptation measures will be used in the project to stabilize slopes and reduce erosion risk from projected future storm events. For example, slope linings will be used along riverbanks and roadway embankments to reinforce soils. Slope linings can be constructed from riprap (using blocks and stones), gabions (wire-mesh baskets filled with stones), and concrete slabs depending on the level of reinforcement required. Log protection barriers and high-strength anti-erosion mesh will be used for slope stabilization and vegetation growth.

- **Flood Protection Measures:** Multiple strategies will be incorporated in the project to mitigate scour of bridge structures and better convey stormwater runoff during extreme rain events to reduce flooding in the future. For example, guide dikes will be constructed to channel water to the bridge approach and reduce scour next to the bridge abutments. The project will also use vegetated swales to capture and treat stormwater runoff, reducing the risk of inundation of roadways.

Costs and Financial Returns

A detailed BCA was conducted to evaluate the financial viability of each of the proposed adaptation measures for the project, and all but one of the measures were found to be viable and were included in the project (see Table 41). Lower maintenance costs, indirect cost savings, and avoided repair costs drive the financial viability of

the proposed adaptation measures. The NPV of each adaptation measure varies significantly. For example, the NPV for speed buffers is just over $5,000, while the NPV for light-colored asphalt pavement and guide dikes is over $10 million. The IRR for the viable adaptation measures ranges from approximately 10% to nearly 40%.

Table 41. Summary of the BCA results for the project

Measure	Initial Incremental CAPEX[xxv]	OPEX NPV[xxvi]	NPV[xxvii]	IRR[xxviii]	Viability
Use of a Performance Grade asphalt mix	$(6,801,380)	$3,705,544	**$4,177,713**	10.87%	Viable
Use of a polymer-modified asphalt mix	$(7,439,009)	$4,976,841	**$6,610,496**	13.07%	Viable
Use of a light-colored asphalt pavement	$(637,629)	$3,899,884	**$10,191,467**	27.57%	Viable
Use of a capillary breaker box	$(14,574,384)	$2,587,743	**$(18,339,387)**		Not viable
Slope lining	$(15,965)	$24,137	**$8,172**	12.25%	Viable
Speed buffers	$(6,898)	$12,159	**$5,261**	13.67%	Viable
Replacement of embankments with causeways	$(1,593,243)	$116,914	**$947,837**	12.60%	Viable
Protective barriers with logs	$(78,471)	$431,084	**$354,472**	31.99%	Viable
Guide dikes	$(2,040,862)	$2,003,506	**$10,417,883**	37.36%	Viable
Gabion	$(1,307,790)	$1,904,019	**$629,443**	11.83%	Viable
StratumEco system	$(275,958)	$48,699	**$161,487**	12.10%	Viable
Capillary breaker layer	$(71,383)	$449,234	**$378,126**	37.96%	Viable
High-strength anti-erosion mesh	$(168,902)	$10,584	**$50,933**	10.28%	Viable
Vegetated ditches	$(583,374)	$(311,028)	**$2,334,733**	28.23%	Viable

Key Findings and Replicability

This project highlights the value of conducting a detailed climate risk assessment and BCA during the project design stage. Identifying the greatest climate risks to the project area can help guide the identification and development of adaptation measures, and the BCA can ensure those measures are financially viable. In addition to reducing congestion and travel time for a key state highway in the region, the Xochi Road project will provide reliable transportation access in the face of worsening climate conditions.

xxv **Initial Incremental Capital Expenditures (CAPEX):** This is the sum of the initial investment in the first two years with a measure minus the sum of the initial investment without a measure. That is, it is the initial cost of implementing the measure.
xxvi **Operating Expenditures (OPEX) NPV:** Shows the net present value, i.e., discounted, of the sum of the expected or predictable maintenance cost of the measured scenario minus the unmeasured scenario.
xxvii **NPV:** The sum of the discounted cash flows (including CAPEX and OPEX) of each measure.
xxviii **IRR:** The discount rate that equates the present value of a project's future cash flows to the initial investment cost.

Corsan: Solutions for Reducing Water Loss

Corsan Project: *Solutions for Reducing Water Loss in Rio Grande do Sul*



Country: Brazil
Owner/Project: Companhia Riograndense de Saneamento (Corsan)
Status: Approved

Project Cost:

R$8,368,780,000 (CAPEX)[xxix]

Financiers:

$155M
IDB Invest

$55M
Operational cash generation by Corsan Previous

Climate Risk(s) Addressed:

Flooding

Droughts

Heavy Storms

xxix Based on exchange rate of R$1.00 = USD$0.19 on 4/1/2026 https://www.xe.com/en-ca/currencyconverter/convert/?Amount=1&From=BRL&To=USD



Background

Companhia Riograndense de Saneamento (Corsan), a sanitation and water company, aims to strengthen water and sanitation infrastructure in the state of Rio Grande do Sul, Brazil, through a program to reduce treated water losses and expand sewage coverage. The program is designed to meet ambitious targets: **reducing water loss rates from 42.4% to 30% by 2033.** The IDB Invest loan of $155 million builds on Corsan's existing loan from IFC and aims to expand efficiency in its network which serves approximately 7.3 million people in 317 municipalities. Proceeds will finance a structured Non-Revenue Water (NRW) reduction program including network modernization, metering upgrades, automation, and real-time monitoring.

The region faces an increasing number of climate impacts, including increasing occurrence of storms, floods, and droughts. Without intervention, climate risks will exacerbate water loss and undermine universal access, but by integrating climate adaptation strategies into operations, Corsan will ensure continuity of essential services during extreme events, reducing vulnerability while achieving universal access, improving public health, and safeguarding revenue.

Climate Risks

The state of Rio Grande do Sul faces increasing exposure to climate events. The region experienced five strong storms and two severe droughts since 2023, including floods in May 2024 caused by El Niño affecting 475 cities and over 2.3 million people.[524] These events disrupted Corsan's operations by flooding water and WWTPs, cutting power to pumps and motors, obstructing water capture systems with debris, and forcing the evacuation of administrative headquarters, ultimately disrupting supply. These disruptions have significant cost implications for Corsan, leading to service disruptions, deferred billing, and higher unplanned O&M costs for equipment cleaning, electrical replacement, and disinfection.

Projected climate trends indicate that floods, heatwaves, and fire risks will continue to increase across Corsan's service region. These hazards threaten the continuity of Corsan's essential services and economic stability in the region.



Specific vulnerabilities include:

- Flooding of critical assets.
- Energy supply disruptions.
- Stress on supply systems caused by droughts.
- Damage to water capture systems.
- Operational shutdowns of data centers and commercial systems.

Adaptation Strategies and Benefits

Corsan has planned to implement a comprehensive set of measures designed to strengthen climate resilience across its water and sanitation infrastructure systems. The strategies target both drought resilience and flood preparedness, aiming to improve operational efficiency, maintain customer access, and reduce water loss.

- **Enhanced structural design:** By upgrading aging treatment plants and pumping stations, Corsan is reinforcing critical water and sanitation infrastructure to withstand future floods and storms, reducing vulnerability to asset flooding and service disruptions. The plan also invests in reservoirs and dredging wells to secure water availability during prolonged droughts, while implementing dam safety plans for 35 identified high-risk dams to prevent catastrophic failures during extreme flood events.
- **Improved operations and management:** Corsan is enhancing climate resilience by deploying remote sensors for leak detection and managing water loss through implementing hydraulic modeling and pressure control. These measures not only improve reliability during climate shocks but also minimize stress on aging infrastructure, helping maintain service continuity during droughts and floods.
- **Emergency response and crisis management:** Additionally, Corsan has strengthened its capacity to respond to extreme climate events by deploying over 200 generators to restore power to key infrastructure assets during grid outages, ensuring access to water trucks to supply affected populations, and installing provisional pumps to reestablish service after floods. The plan also includes emergency action plans, chlorine leak scenarios, and is designed to strengthen response teams for rapid repair and recovery of critical assets.

- **Planning and governance:** Corsan also plans to develop a climate change risk and impact management program aligned with the Paris Agreement to integrate climate considerations into future investments and operational planning. Integrating climate adaptation strategies benefits Corsan financially and ensures that there is higher service reliability during extreme events.

Costs and Financial Returns

A key component of increasing climate resilience and adapting to climate change is reducing NRW loss from Corsan's current rate of 42.5% to 30%. This is especially important as more frequent and severe droughts are expected to further decrease water availability. Based on Corsan's 2024 water production of 625 million m^3, this reduction would save approximately 77.5 million m^3 annually. At Corsan's average water tariff per m^3 of water (BRL$6.60–BRL$8.52 or $1.24 to $1.60), this reduction translates to **between R$511–R$660 million in annual savings ($102M–$132M) with NRW improvements.**[525] The reduction of physical water losses will also lower energy consumption for pumping and treatment, reducing unnecessary electricity use. These savings represent a strong business case to invest in climate resilience. By reducing water loss and ensuring universal access, Corsan not only increases production and distribution revenue but also improves financial stability, strengthens its ability to service debt, and enhances its attractiveness to green financing. The financial benefits extend beyond direct cost savings to include avoided emergency repair expenses, reduced operational disruptions, and improved investor confidence.

Key Findings and Replicability

The project demonstrates how Corsan is integrating climate resilience into core operations and investments rather than treating them as an add-on. Recent droughts and floods in Rio Grande do Sul, which caused over $15 billion in damages statewide, underscore the financial and operational risks utilities like Corsan face when climate hazards disrupt services.[526] Reducing NRW loss is not only an efficiency goal but also a resilience strategy, as technologies can reduce stress on infrastructure during climate shocks and help maintain continuity of essential services for vulnerable populations.

For sponsors, the incentives to address climate risks are clear: resilient investments reduce financial volatility and protect revenue streams from climate-driven disruptions. Achieving the water loss target of 30% could enable more efficient use of water resources and save more than R$500 million annually, strengthening Corsan's ability to service debt and attract green financing. These benefits translate into direct gains through avoided water losses and emergency repair costs, as well as indirect gains such as universal access leading to improved public health, reduced service disruptions, improved consumer confidence, and enhanced industry reputation.

Corsan's approach is highly replicable in other areas. Technical measures like remote sensors, automation, and emergency preparedness plans can be scaled across South America's water utilities, while stakeholder engagement models can be adapted to other infrastructure sectors. Linking resilience outcomes to financial instruments such as green bonds and sustainable loans creates a scalable model for climate-smart infrastructure investment.

Ceará Port and Industrial Green Hydrogen Hub

Ceará Green
Hydrogen Hub



Country: Brazil
Owner/Project: Complexo Industrial Portuario de Pecém (CIPP)
Status: Implementation

Project Cost:

$175M [527]

Financiers:

The World Bank + Climate Investment Fund

Climate Risk(s) Addressed:

Drought

Sea Level Rise

Background

The project aims to enable clean hydrogen production in the Complex of Pecém in Brazil, a large port and industrial complex. This site is an ideal location for a clean energy hub as it is connected to the high-voltage national electricity grid, has an abundance of onshore wind and solar generation, and is an industrial export free zone that provides attractive tax incentives for businesses. The project will finance the necessary shared infrastructure to establish the Pecém Green Hydrogen Hub, including the construction of a utility corridor and access infrastructure to the export processing zone, the expansion of the Port of Pecém Multiple Utilities Terminal, and the expansion of Pier 2 in the Port of Pecém This case study demonstrates how considering resilience in shared infrastructure arrangements helps reduce production costs, increase competitiveness, and send positive signals to sponsors. The Pecém Green Hydrogen Hub project will ultimately help advance clean hydrogen production in Brazil. This project also demonstrates sponsors' favorable views of infrastructure projects that consider climate risks in their design, construction, and operation.

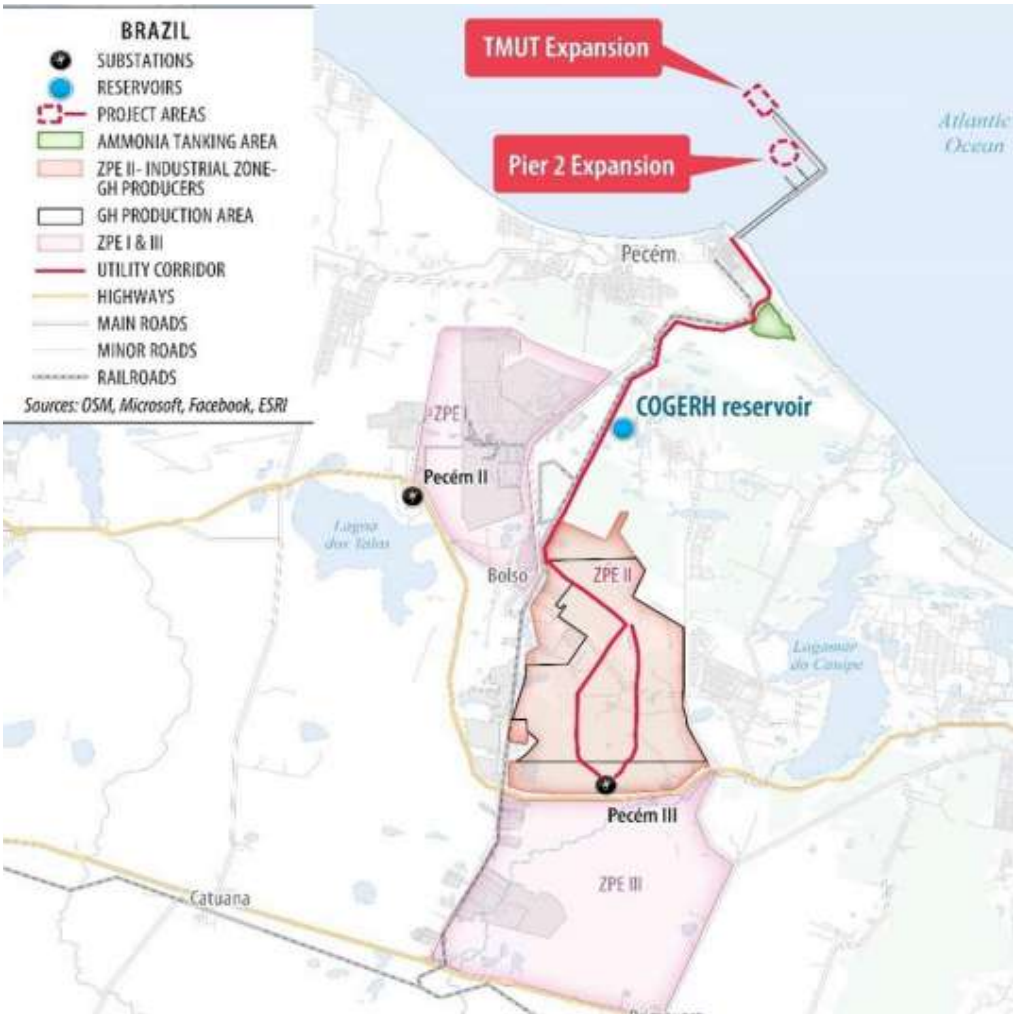


Figure 17. Map of the project area (Source: World Bank)

Climate Risks

The project area is vulnerable to multiple climate risks, particularly droughts. Ceará is a semi-arid region that is prone to prolonged droughts due to rising temperatures and decreasing precipitation. Droughts are a significant concern for hydrogen production as the electrolysis process is extremely water intensive. Additionally, sea level rise, coastal storms, and flooding are a concern in the region and are projected to worsen under future climate change. These hazards can directly damage port infrastructure in addition to disrupting operations.

Adaptation Strategies and Benefits

The project will be designed to account for climate risks in the region, ensuring that the hydrogen hub is able to withstand extreme weather events and reduce operational disruptions. Specific adaptation measures in the project include:

- **Recycled Water Usage:** Given concerns around drought and water requirements for the hydrogen hub, the state of Ceará is adopting measures to utilize recycled sewage water from the city of Fortaleza. Additionally, the state is conducting an assessment to determine the total water demand of the Hub and explore alternatives, including desalination. The World Bank is also supporting this technical assistance initiative, which will determine the feasibility of various water supply options. These measures will help address drought risk and ensure droughts do not disrupt operations at the hub.

- **Climate-Resilient Design:** The project will leverage climate-resilient engineering techniques to reduce risks to port infrastructure from sea level rise, coastal storms, and flooding. Potential engineering techniques include breakwaters, or permanent structures built in coastal areas to protect infrastructure from tides, waves, and storm surges. The project will consider other adaptation needs to ensure the hub and supporting infrastructure are designed to withstand extreme weather events and reduce operational disruptions.

Costs and Financial Returns

The project will consist of an Investment Project Financing (IPF) International Bank for Reconstruction and Development (IBRD) loan for $90 million, an IBRD grant for $9 million, a CIF-REI loan of $33.5 million, a grant of $1.5 million to the CIPP, and co-financing of $41 million from the CIPP over a five-year period, of which $10 million are guaranteed by the Government of Brazil. **$9 million of the total project funds will be used for climate adaptation.**[528] Table 42 shows the breakdown of the project costs by component.

Table 42. Breakdown of project costs by component

Project Component	Cost
1 Utility Corridor	$30 million
2 Expansion of Multiple Utilities Terminal	$106 million
3 Expansion of Pier 2	$39 million
Total	**$175 million**

A BCA was completed to evaluate the economic feasibility of the project under different scenarios with varying future gas prices and production capacities. The project is economically viable, even in an extreme stress scenario with an IRR of 19%, higher than the 15% cost of capital. In a scenario where natural gas prices are high, the project looks even better: the IRR jumps to 44.5%. The project's NPV is about $2.5 billion in that high-price scenario. Another scenario was modeled assuming green ammonia sales and cargo handling are 50% lower than projected, investment costs increase by 10%, and all projects are delayed by one year. This could be the result of an event like a flood or drought that disrupts production or damages infrastructure. Even under these conditions, the project remains financially viable for sponsors, with an expected financial IRR of 16.9% and an NPV of $40 million at a 12% discount rate ($18 million at 15%).

To date, as part of the creation of the hub, the CIPP has six pre-contracts for land leases within the industrial zone, which could lead to $10 billion in private capital for investments in clean hydrogen production over the next decade.

Key Findings and Replicability

This project demonstrates how clean energy projects can consider climate risks in their design and construction to ensure long-term resilience and help maintain operations. Additionally, the Green Hydrogen Hub will provide significant economic benefits and incentives to help advance clean hydrogen development in Brazil. The Hub will provide multiple benefits throughout the value chain, including creating additional jobs, fostering a circular economy for utilities, and incentivizing the construction of additional renewable energy generation.



Floating Solar-Hydro Hybrid at Afobaka Dam

***Afobaka Floating** Solar-Hydro Project*

Country: Suriname
Owner/Project: Staatsolie Power Company Suriname (SPCS)
Status: Under development

Feasibility study cost:

$200,000 [529]

Financiers:

IDB Invest

Climate Risk(s) Addressed:



Drought



Figure 18. The Afobaka Dam was completed in 1965 and generates about 50% of total electricity consumed in Suriname (source: Staatsolie)

Background

The Afobaka Floating Solar-Hydro project seeks to strengthen Suriname's energy system and climate resilience by integrating floating solar PV technology with the existing Afobaka hydropower dam. As part of the development process, a comprehensive feasibility study is being conducted to assess climate vulnerabilities, design efficient operating processes, and reduce financial risk for sponsors. Early in the scoping process, this foundational study will evaluate technical requirements, disaster risk considerations, and financial viability for deploying 25–75 MW of floating solar PV capacity on the Afobaka reservoir. By combining solar and hydropower resources, the project aims to enhance energy security and build resilience against future droughts.
Hydropower has long been a cornerstone of Suriname's electricity supply, but this innovative project is among the first in the region to pursue large-scale floating solar PV on a hydropower reservoir. This case study demonstrates how diversification of energy supply can build long-term climate resilience and boost economic activity by reducing power supply disruptions, and investing in the feasibility study upfront ensures that the project is resilient for the future.

Climate Risks

Suriname regularly experiences extreme weather events such as hurricanes, floods, and droughts. Increasing seasonal variability and changing rainfall patterns threaten the reliability of hydropower in Suriname. Drought rates have been rising over time; the 2024 drought in Suriname left the country without rainfall for over eight months.[530] Floating solar PV provides many benefits, including increasing the resilience of Suriname's energy supply to droughts. Suriname's electricity demand peaks during dry, hot periods—when solar generation is highest, and hydropower generation is limited.

Adaptation Strategies and Benefits

The project improves the resilience of electricity generation through hybrid operations that enable more flexible water management and ensure reliability during dry and hot periods. Seasonal variability in electricity generation can be smoothed. During the dry, sunny season, solar PV generation is maximized, while in the wet season, the hydropower system is utilized more heavily. This complementary approach optimizes resources year-round and enhances overall system stability.

Floating solar PV offers many advantages over land-based systems, including improved energy yield. The cooling effects of the water, combined with the decreased presence of dust and reduction of shading, can lead to a 5%–15% improvement in energy yield for floating solar PV.[531] Additionally, floating solar PV reduces water evaporation by 30%–50% over covered areas, is easy to install, and reduces land use conflicts. Floating solar PV also leverages existing energy grid assets, reducing CAPEX and OPEX.

Costs and Financial Returns

This feasibility study will further evaluate the costs and benefits associated with the system; however, floating solar PV systems can provide significant cost savings by leveraging existing bodies of water and therefore reducing land and maintenance costs. Additionally, the natural cooling of the water surface improves the efficiency of solar panels and increases energy output, increasing long-term cash flows from power sales. Floating solar installations can be especially cost-effective when installed on existing hydro reservoirs, where the PV system can share infrastructure like grid connections.

In Latin America, floating solar is becoming a viable option for sponsors, with costs only about 10% higher than traditional ground-mounted solar. This small difference suggests that high-value locations can approach parity with land-based solar installations. In Brazil, for example, floating PV costs around $65/MWh compared to $60/MWh for land PV.[532] The World Bank estimates that turnkey floating solar installations in LAC will cost between $0.8 million–$1.2 million per MW. Thus, the capital required to develop Afobaka would be estimated to be $20–$90 million depending on final sizing. In this context, this feasibility study that characterizes climate risks is less than 1.2% of total capital costs.

Key Findings and Replicability

This project leverages floating solar PV, an innovative technology that can increase Suriname's resilience to energy disruptions during extreme weather events, seasonal changes in rainfall, and long-term trends. Large hydropower reservoirs across LAC offer significant opportunities for floating solar expansion. Successful deployment of floating solar PV demonstrates an innovative model for other hydro-rich countries in the region. This project offers stable, long-term cash flows from power sales by ensuring steady production despite fluctuations in future hydroelectricity generation due to shifting climate conditions. Additionally, floating solar PV could potentially allow for premium pricing under renewable energy incentives and carbon credits, further boosting financial incentives for sponsors.

Remote Area Rural Electrification Program

Remote Area Rural
Electrification Program

Country: Honduras
Owner/Project: National Electric Power Company (ENEE)
Status: Closed

Project Cost:

$6,670,000 [533]

$6,420,000
IDB Invest

$250,000
Country counterpart

Financiers:

IDB Invest

Climate Risk(s) Addressed:

Floods

Landslides

Sea Level Rise

Extreme Weather

Extreme Heat



Background

This program aims to increase electricity access and reduce electricity costs in Honduras through decentralized and microgrid renewable energy generation projects. Rural, isolated areas of the country have limited electricity coverage, especially compared to urban areas. This project includes the design and construction of four rural electrification projects: two renewable energy generation systems with microgrids in the municipalities of Isla Guanaja and Brus Laguna; and two residential solar PV projects in the municipalities of El Corpus and Concepción de María. These rural municipalities were chosen based on electricity access, energy costs, and socioeconomic measures, including poverty levels. Each project consists of electrical infrastructure and will be designed and constructed to be resilient to climate risks, such as flooding and storm events. The project also includes institutional capacity building to support future design, construction, operation, and maintenance of renewable energy projects.

Each project consists of electrical infrastructure and will be designed and constructed to be resilient to climate risks, such as flooding and storm events. The types of climate risks associated with these projects, such as exposure to high winds, flooding, and extreme precipitation, are similar to those faced by other large-scale electrical infrastructure investments, including telecommunications towers, power transmission lines, and substation sites. These assets share vulnerabilities due to their reliance on aboveground structures, remote locations, and critical service delivery, making climate resilience measures essential for long-term reliability and safety.

Climate Risks

The project areas are characterized by tropical, rainy climates, with heavy rainfall events, flooding, and hurricanes and tropical storms presenting the greatest risks to the projects. Other climate hazards of concern are sea level rise and erosion. Flooding and sea level rise are especially concerning for solar projects on the coast. Additionally, exposure to high humidity levels, rainfall, and severe storms can all significantly damage infrastructure and equipment. Hurricanes and tropical storms are a known risk in the region with documented historical impacts. For example, Hurricane Mitch destroyed mangroves in Guanaja and caused landslides across the country, impacting built infrastructure.[534]

Adaptation Strategies and Benefits

Each of the rural electrification projects will be designed and constructed to prevent adverse impacts from climate hazards in the project areas. These strategies will help reduce operational disruptions and ensure the reliability of electricity in the project areas during extreme weather events. Specific adaptation measures in the projects include:

- **Climate-Resilient Design:** The site selection process and design of each project will incorporate climate considerations. For example, flood-prone areas and geologically unstable areas will be avoided during the site selection process. Project design will leverage durable materials, such as corrosion-resistant and wind-resistant materials, to prevent damage during flooding and extreme weather events. Additionally, drainage and erosion control measures will be incorporated to manage rainfall and altered drainage needs in the future.
- **Contingency Planning:** Each project requires a contingency plan for extreme weather events, including training, drills, and emergency protocols. Contingency planning can help ensure operators can quickly and efficiently respond when extreme weather events do occur, reducing operational disruptions and downtime.

Costs and Financial Returns

The program will be financed through an investment grant, funded by the Scaling Up Renewable Energy in Low Income Countries Program from the Strategic Climate Fund. The total project cost is $6.42 million. Table 43 provides a breakdown of the project costs by component.



Table 43. Breakdown of total project costs by component

Component	Cost ($)	Percent of Total [xxx]
1 Development of electricity generation systems in rural locations cut off from the interconnected grid	5,730,000	89.2%
• Brus Laguna microgrid (0.60 MW)	2,750,000	42.8%
• Isla Guanaja microgrid (0.75 MW)	2,550,000	39.7%
• Residential PV systems (0.07 MW c/u) in El Corpus and Concepción de María	430,000	6.7%
2 Strengthening of management capacities	430,000	6.7%
3 Administration and evaluation	260,000	4.0%
Total	6,420,000	

A BCA was conducted to select potential solutions for each component. For Component 1, PV microgrids were compared to a diesel-based solution, and the microgrid solution was found to be more cost effective. The analysis conducted for the microgrid systems calculated the net cash flow of the investment, operation, and maintenance costs against expected revenue from energy sales over a 25-year period. This yielded an IRR of 14.25% for Isla Guanaja and 14.75% for Brus Laguna. With a discount rate of 12%, the NPVs of $448,119 and $491,468 were obtained for Isla Guanaja and Brus Laguna, respectively.

A sensitivity analysis was conducted to assess the effects of variations in construction costs, electricity prices, and key financial flow variables, such as increases in operating and maintenance expenses, on overall financial performance. Across all scenarios, the investment's financial viability remained robust. The analysis indicates that construction costs would need to increase by approximately 32% before the solution would no longer be cost-effective. Although detailed cost estimates for the climate resilience measures are not available, comparable projects typically experience cost increases in the range of 5–10%. Therefore, it is reasonable to conclude that the projects would remain financially viable even with the incorporation of additional resilience measures.

Key Findings and Replicability

This case study demonstrates how renewable energy projects are financially feasible and how key financial metrics can accommodate climate adaptation and mitigation components that increase overall construction costs. Benefits include reducing energy costs and boosting economic activity and productivity. This program will make electricity significantly more accessible and affordable in the project areas. Additionally, the projects will incorporate climate-resilient design to ensure reliability, even during extreme weather events. For areas like Guanaja, where tourism is a major sector, lower energy costs and more reliable electricity supply will significantly boost economic activity.

xxx Total may not add to 100% due to rounding

Appendix B: *Overview of Benefit-Cost Analysis Methodologies*

There are several methodologies available to understand the benefits and costs of adaptation measures. Alternative methodologies to BCAs include **life cycle cost analysis, cost-effectiveness, economic impact analysis, and internal rate of return (IRR) analysis.** Many of the methodologies discussed below capture a combination of benefits to infrastructure owners, users, and non-users, as well as broad social benefits. Typically, these methodologies focus strictly on maintaining existing benefits or avoiding future losses and exclude transfer payments (such as changes in sales or employment), which can represent changes.[xxxi] The timing of costs and benefits is also critical and must be consistent, either by presenting dollar concepts consistently (e.g., clearly acknowledging fixed, constant, or Year of Expenditure) or placing dollar concepts in present value.

xxxi Transfer payments do not preserve or create new benefits. Adaptation investment may preserve benefits, and certain Type III adaptations can create new benefits.



Life Cycle Cost Analysis

Life cycle cost analysis (LCCA) is similar to a BCA, but only focuses on the upfront capital costs and long-term O&M costs (see Table 44). The LCCA provides the investor with a clear indication of the overall costs over time and enables scenario analysis to optimize maintenance schedules and activities over the course of the useful life of the investment.

Table 44. LCCA definition

Lifecycle Cost Analysis	Definition
Definition	Evaluates upfront capital costs and long-term O&M expenditures.
Applicability	Commonly used for analyzing the optimal O&M schedule to minimize costs while preserving infrastructure during useful life.
Strengths	Analyzes the full cost of investment.
Weaknesses	Does not estimate benefits of investments.

Cost Effectiveness Analysis

Cost-effectiveness analysis compares the costs and outcomes of different projects or scenarios against a set of goals to determine better value (see Table 45). This approach is more often used in health care, and in many cases a BCA is preferred for infrastructure projects given the ability to compare multiple project types across different time spans and investment levels.

Table 45. Cost effectiveness analysis definition

Cost Effectiveness Analysis	Description
Definition	Compares outcomes of multiple projects or scenarios.
Applicability	Commonly used to advance or select projects to meet goals.
Strengths	Captures fully realized costs of a project.
Weaknesses	Focuses on outcomes and less so on overall benefits or mix of benefits.

Economic Impact Analysis

Economic impact analysis provides estimates of changes in economic activity in terms of changes in jobs, business output (sales), GDP, and income (see Table 46). For private sponsors, these data could be used to estimate labor force needs and the size of supporting industries. Economic impacts are estimated using an economic impact model that uses spending data by industry sector to estimate the changes to the economy. Often, economic impacts are reported as a total change which is composed of the following impact categories: direct (prescribed change in spending), indirect (supply chain effect), and induced (income effect). While many economic models account for the local market's ability to supply the labor and capital requirements and import the remaining needed services, these models estimate the outcomes of spending, and therefore the projects or investments that spend the most will have the largest economic impact regardless of other benefits. In many cases, economic impacts can be distilled down to a ratio of jobs created per million dollars spent in a specific industry or project type.

Table 46. Economic impact analysis definition

Economic Impact Analysis	Description
Definition	Estimates the direct, supplier, and spending effects of an investment in terms of jobs, industry sales, income, and GDP.
Applicability	Commonly used to highlight the spending impacts on the local economy.
Strengths	Provides sales data by industry type, and estimates trade flows (e.g., locally supplied labor and services versus imported).
Weaknesses	Does not capture opportunity costs of investments. Larger investments show a larger result.

Internal Rate of Return

IRR is a financial metric that estimates the potential rate of return on an investment (see Table 47). Similar to the other methods, cash flows are converted to present value, and the discount rate at which the NPV is zero is the IRR. When applied to public infrastructure, the IRR incorporates other social benefits like emissions or safety and costs, which may include public subsidies. IRR is more often applied to private real estate and financial investments as opposed to public projects.

Table 47. IRR definition

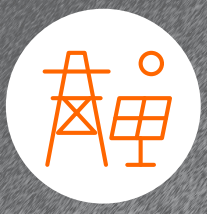
Internal Rate of Return	Description
Definition	Provides an estimate of the potential ROI based on cash flow and estimated future benefits.
Applicability	Most commonly used to evaluate financial investments and real estate.
Strengths	Allows for comparison across different projects and shows the project's break-even point.
Weaknesses	Does not account for project size.

Appendix C: *Hypothetical Adaptation Project Methodology*

This appendix outlines the methodologies used to quantify incremental costs and BCRs for hypothetical adaptation projects in Section 4.2. These quantitative analyses were only performed for a subset of asset types based on data availability and quality. Hypothetical projects were developed for the following asset types:



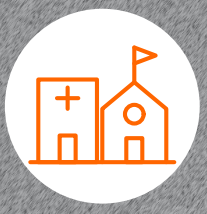
Transportation:
Roads



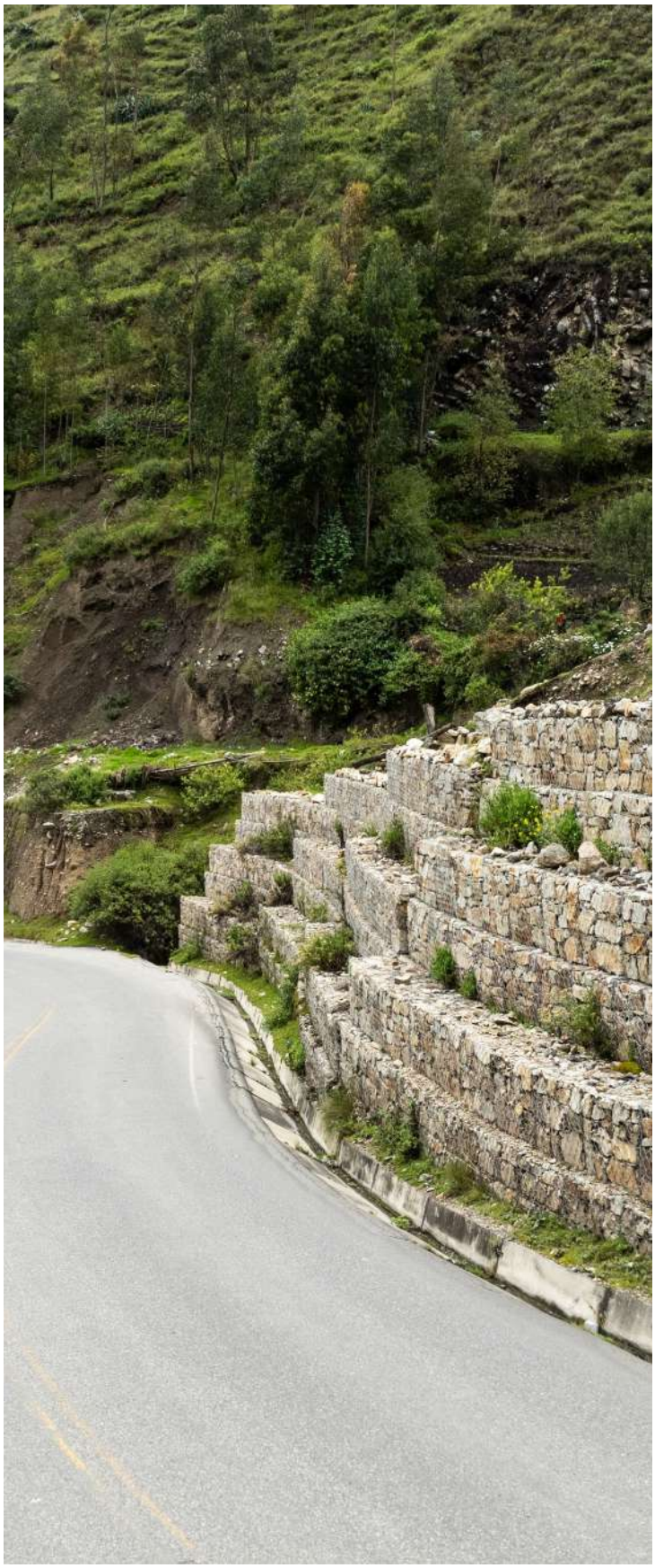
Energy:
Substations, solar farms



Water & Sanitation:
Pump stations, desalination plants, lift stations, WWTPs



Social Infrastructure:
Hospitals, schools



The BCR results for each asset type likely represent the upper limits of the project benefits. This is because the research team assumed that the adaptation measures would be implemented for assets that have high exposure, and that the adaptation measures would be very successful in protecting the asset once implemented. Additionally, the BCR is highly dependent on the asset and site characteristics. The BCRs would not be as high if the measures were implemented in a scenario in which assets were not exposed, or a scenario in which the measure was unsuccessful. For example, a flood barrier installed in the desert would have almost no benefits and very high costs, yielding a low or negative BCR.

It is assumed that each adaptation measure is implemented as a component of a new construction project. In most cases, it is not cost-effective to implement climate adaptation measures as retrofits to existing assets. It is important to note that many resilient investments provide additional co-benefits, including social and environmental benefits to the surrounding community, which are more difficult to quantify and not at the center of this analysis for private sponsors.

The following sections provide more details on the methods and assumptions used to quantify incremental costs and BCRs for each hypothetical project. The costs of infrastructure projects and associated adaptation measures vary widely across the LAC region. **All cost values are in 2025 US dollars but adjusted for the purchasing environment of Brazil.** They do not account for permitting, availability of qualified labor, and other factors that can impact the costs of adaptation measures across countries. There are many resources available to translate costs across time and space.[535]

Transportation: Roads

The research team used publicly available literature on transportation resilience projects, as well as in-house tools and resources, to develop and quantify unit costs and BCRs for adaptation measures for roads. In general, there is more information available in the literature for roads and bridges than for freight assets (such as ports and rail systems), which tend to be privately owned.



We identified two hypothetical roadway projects to which the road adaptation measures were applied:

1. A small road project, defined as an 8-km, 2-lane, non-interstate road project. The total cost for a new construction project in Brazil is $3,168,000.

2. A large road project, defined as a 16-km-long, 2-lane, interstate road project. The total cost for a new construction project in Brazil is $9,680,000.

The research team used publicly available literature with example projects and case studies to calculate unit-level costs for each adaptation measure and road project. Using the per-unit costs, the total illustrative project costs, and the scale of the adaptation measure, the research team estimated the percentage of the total cost associated with the adaptation measure.



Having illustrated the role of project scale in road resilience investments, we did not repeat this for the port and rail measures that we analyzed.

To calculate BCRs for general adaptation measures, the research team used its in-house BCA tool. The tool uses a standard BCA methodology for the transportation sector that considers inputs such as asset

size, level of risk to the asset, asset lifespan, detour length, and traffic volumes to determine owner cost savings from investing in resilience. These inputs are listed in Table 48 below.

Table 48. Hypothetical road project features

Feature	Small Road Project	Large Road Project
Level of risk to the asset before adaptation	High	High
Detour length	16 km	32 km
Assumed length of disruption if road is blocked or closed	5 hours	5 hours
Lifespan of the road	15 years	18 years
Average annual daily traffic	300 vehicles/day	12,000 vehicles/day
Percentage of vehicles that are cars	80%	50%
Percentage of vehicles that are trucks	20%	50%

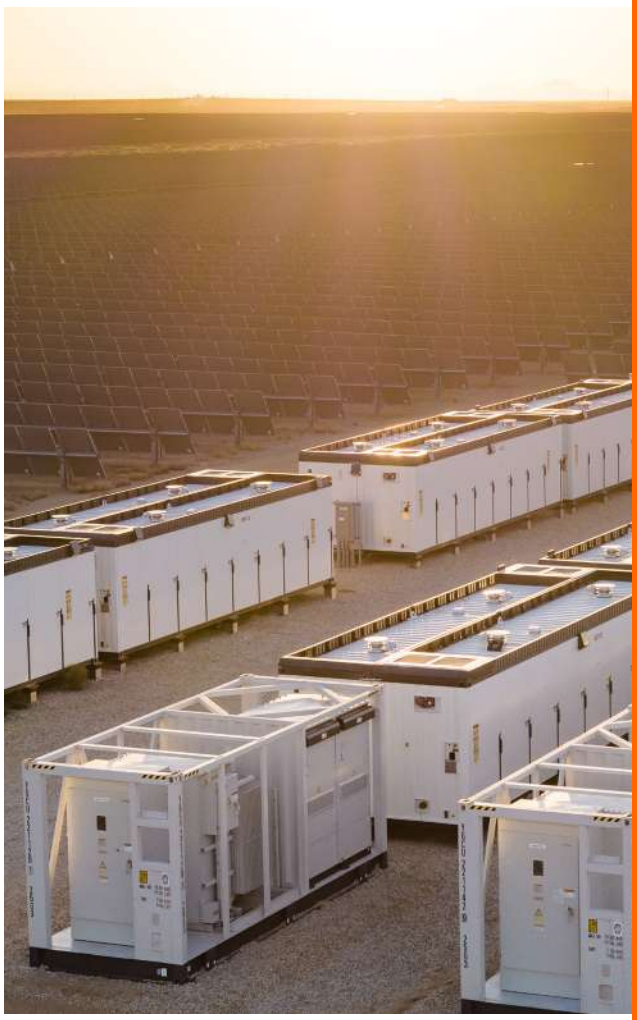
Additionally, the research team made assumptions regarding the scale of each adaptation measure (i.e., the length and height of flood barriers needed to protect the roadway). The assumptions for each climate adaptation measure applied to the hypothetical road projects are listed in Table 49 below.

Table 49. Hypothetical road project assumptions for each climate adaptation measure

Adaptation Measure	Small Road Project Assumptions	Large Road Project Assumptions
Drainage structures and pump stations with larger capacities	Assuming 8 km of pipe	Assuming 16 km of pipe
Early warning technology	Assumed to cover the entire roadway network, rather than an individual road asset. Therefore, the cost of the technology is the same for both small and large roads.	
Retention or detention ponds	Assuming a detention pond with ~6,700 cubic meter volume	Assuming a detention pond with ~19,200 cubic meter volume
Nature-based shoreline protection	Assuming 8 km of reef and 8 km of beach nourishment	Assuming 16 km of reef and 16 km of beach nourishment
Permanent flood barriers	Assuming 8 km length for seawalls, flood walls, and breakwaters. Assuming 1.5 meters for flood wall height	Assuming 16 km length for seawalls, flood walls, and breakwaters. Assuming 1.5 meters for flood wall height
Asset elevation	Assuming raising new and retrofitted roads by ~0.6 m, assuming 8 km of road	Assuming raising new and retrofitted roads by ~0.6 m, assuming 16 km of road
Landscape restoration for flood storage (wetland, streams, floodplains)	Assuming 8 km for stream restoration, 19 hectares for inland and coastal wetlands	Assuming 16 km for stream restoration, 55 hectares for inland and coastal wetlands
Heat-, fire-, and water-resistant materials	Assuming 8 km of road, 10 m wide	Assuming 16 km of road, 20 m wide
Shade trees	Assuming 800 trees	Assuming 1,100 trees
Slope stabilization and other erosion prevention measures	Assuming 224,000 m^2 of geosynthetic reinforcement and 22,000 tons of riprap	Assuming 576,000 m^2 of geosynthetic reinforcement and 266,000 tons of riprap

Energy: Substations and Solar Farms

The research team used the US Federal Emergency Management Agency (FEMA) Benefit-Cost Analysis (BCA) Toolkit and publicly available literature on energy resilience projects to quantify incremental project costs and BCRs for substations and solar farms. We identified **two hypothetical substation projects and two hypothetical solar farm projects** to which the energy adaptation measures were applied:



1. A **small substation project,** defined as a 400 sq. ft. compact kiosk or indoor distribution substation. The estimated total cost for a new construction project in Brazil is approximately $186,000.

2. A **large substation project,** defined as a 30,000 sq. ft. full urban primary distribution substation. The estimated total cost for a new construction project in Brazil is approximately $18 million.

3. A **small solar farm project,** defined as a 50 MW PV plant spanning 1 million sq. ft. The estimated total cost for a new construction project in Brazil is approximately $37,400,000.

4. A **large solar farm project,** defined as a 300 MW PV plant spanning 6 million sq. ft. The estimated total cost for a new construction project in Brazil is approximately $197,600,000.



The research team used publicly available literature with example projects and case studies to calculate unit-level costs for each adaptation measure and energy project. Using the per-unit costs, the total illustrative project costs, and the scale of the adaptation measure, the research team estimated the percentage of the total cost associated with the adaptation measure.

The FEMA BCA Tool uses inputs such as the total project cost, number of customers served, asset lifespan, and level of damage reduction to determine the BCR for the project. The tool inputs for the hypothetical substation and solar farm projects are listed in Table 50 and Table 51, respectively.

Table 50. Hypothetical substation project features

Feature	Small Substation Project	Large Substation Project
Square footage	400 sq. ft.	30,000 sq. ft.
Number of customers served	40,000	300,000
Building replacement value	$500 /sq. ft.	$400/sq. ft.

Table 51. Hypothetical solar farm project features

Feature	Small Solar Farm Project	Large Solar Farm Project
Square footage	1 million sq. ft.	6 million sq. ft.
Number of customers served	175,000	1,050,000
Building replacement value	$42 / sq. ft.	$58 / sq. ft.

For flooding adaptation measures, the depth damage function shown in Table 52 was used to estimate the level of damage to each asset (in dollars) based on the flood depth. For each flood depth, the building damage percentage is multiplied by the building replacement value to estimate the level of damage to the asset.

Table 52. Depth damage function used for flooding adaptation measures

Flood Depth	Building Damage %
0 ft	0.00%
0.5 ft	5.20%
2 ft	16.80%
3 ft	20.90%

In the FEMA BCA Tool, the daily value of the utility service ($/day) is automatically calculated based on the type of utility (i.e., electricity, potable water, wastewater) and the total annual number of customers. The daily service value increases rapidly as the total number of customers increases. The daily service value and the number of repair days pre- versus post-mitigation are the main drivers of the benefits quantification in the FEMA BCA Tool. Based on the configuration of the tool, daily service value and repair days are captured for flooding adaptation measures, but not for hazards like hurricanes and wildfires. Therefore, the BCRs for hurricane safe rooms and defensible space projects are likely higher than the BCRs provided in Chapter 4.

Additionally, the research team made assumptions regarding the scale of each adaptation measure (i.e., the size of the detention pond needed for flood storage). The assumptions for each climate adaptation measure applied to the hypothetical substation and solar farm projects are listed in Table 53 and Table 54, respectively.

Table 53. Hypothetical substation project assumptions for each climate adaptation measure

Adaptation Measure	Small Substation Project Assumptions	Large Substation Project Assumptions
Asset elevation	Assume elevation by 2.5 ft. is part of a new construction project for a substation and the full sq. footage of the substation is elevated.	
	Pre-Mitigation Flood Risk: 100-year flood event causes **3 ft. of flooding** and requires **15 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **5 repair days**.	**Pre-Mitigation Flood Risk:** 100-year flood event causes **3 ft. of flooding** and requires **45 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **10 days to repair**.
Dry floodproofing	Assume the amount of floodproofing needed covers the full sq. footage of the substation.	
	Pre-Mitigation Flood Risk: 100-year flood event causes **2 ft. of flooding** and requires **10 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **5 repair days**.	**Pre-Mitigation Flood Risk:** 100-year flood event causes **2 ft. of flooding** and requires **30 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **10 days to repair**.
Detention ponds for floodwater diversion and storage	Assume the flood storage volume needed is the sq. footage of the substation multiplied by 3 ft. (to capture 3 ft. worth of flooding across the substation). The same pre- and post-mitigation flood risk assumptions for asset elevation are assumed here.	
Flood wall (5 feet tall)	Assume the flood wall surrounds the entire substation. The same pre- and post-mitigation flood risk assumptions for asset elevation are assumed here.	
	Flood wall length is 80 linear ft.	Flood wall length is 770 linear ft.
Hurricane safe room	Assume the project is in a hurricane-prone region like Florida in the US. Assume a minimum depth of 2 ft. 6 in. Assume the safe room is designed for wind speeds of 160 mph. Assume the substation is reinforced.	
	8 ft. by 8 ft. safe room designed to fit 10 people	14 ft. by 14 ft. safe room designed to fit 20 people
Defensible space and hazardous fuels reduction for wildfires	Assume a 100-foot perimeter of defensible space around the asset. Assume the project is located in a fire-prone area, specifically California, US. Project activities include clearing lightly forested areas (tree thinning, brush removal), adding fire-resistant plantings, hardscaping (gravel paths, rock mulch zones), and 3" of pea gravel. Each activity only covers part of the project area based on the CAL FIRE Zones. Assume clearing lightly forested areas covers 60% of the project area, fire-resistant plantings cover 25% of the project area, hardscaping covers 10% of the project area, and pea gravel covers 5% of the project area. Add 15–25% to total costs for design and permitting.	
	• Value of infrastructure vulnerable to fire: $400,000 • Fire suppression costs of one typical fire within proposed project area: $100,000 • Other costs mitigated by proposed project: $500,000	• Value of infrastructure vulnerable to fire: $15 million • Fire suppression costs of one typical fire within proposed project area: $750,000 • Other costs mitigated by proposed project: $5 million

Table 54. Hypothetical solar farm project assumptions for each climate adaptation measure

Adaptation Measure	Small Solar Farm Project Assumptions	Large Solar Farm Project Assumptions
Asset elevation	Assume elevation by 2.5 ft. is part of a new construction project for a substation, and the full sq. footage of the substation is elevated.	
	Pre-Mitigation Flood Risk: 100-year flood event causes **3 ft. of flooding** and requires **25 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **5 repair days**.	**Pre-Mitigation Flood Risk:** 100-year flood event causes **3 ft. of flooding** and requires **60 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **10 days to repair**.
Dry floodproofing	Assume floodproofing includes marine-grade steel fasteners, rivet lock bolts, and through bolts for solar panels.	
	Pre-Mitigation Flood Risk: 100-year flood event causes **2 ft. of flooding** and requires **15 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **5 repair days**.	**Pre-Mitigation Flood Risk:** 100-year flood event causes **2 ft. of flooding** and requires **45 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **10 days to repair**.
Detention ponds for floodwater diversion and storage	Assume the flood storage volume needed is the sq. footage of the substation multiplied by 3 ft. (to capture 3 ft. worth of flooding across the substation). The same pre- and post-mitigation flood risk assumptions used for asset elevation are used here.	
Defensible space and hazardous fuels reduction for wildfires	The same defensible space assumptions used for substations are used here.	
	• Value of infrastructure vulnerable to fire: $38.5 million • Fire suppression costs of one typical fire within proposed project area: $500,000 • Other costs mitigated by proposed project: $2 million	• Value of infrastructure vulnerable to fire: $230 million • Fire suppression costs of one typical fire within proposed project area: $1 million • Other costs mitigated by proposed project: $5 million

Social Infrastructure: Hospitals and Schools

The research team used the same approach used for energy assets described above for social infrastructure, leveraging the US FEMA BCA Toolkit and available public literature on social infrastructure resilience projects. We identified **two hypothetical hospital projects and two hypothetical school projects** to which the adaptation measures were applied:



1. A **small, rural hospital** that is 22,600 sq. ft. and serves 3,000 customers per year. The estimated total cost for a new construction project in Brazil is approximately $2.6 million.

2. A **large, urban hospital** that is 600,000 sq. ft. and serves 450,000 customers per year. The estimated total cost for a new construction project in Brazil is approximately $70 million.

3. A **small, rural elementary school** that is 50,000 sq. ft. and serves 300 students. The estimated total cost for a new construction project in Brazil is approximately $2.15 million.

4. A **large, urban high school or college** that is 400,000 sq. ft. and serves 2,000 students. The estimated total cost for a new construction project in Brazil is approximately $17 million.



The tool inputs for the hypothetical hospital and school projects are listed in Table 55 and Table 56, respectively.

Table 55. Hypothetical hospital project features

Feature	Small Hospital Project	Large Hospital Project
Square footage	22,600 sq. ft.	600,000 sq. ft.
Number of customers served	3,000	450,000
Distance to closest alternate hospital	25 miles	3 miles
Number of customers served by alternate hospital	15,000	250,000
Building replacement value	$350 /sq. ft.	$500/sq. ft.

Table 56. Hypothetical school project features

Feature	Small School Project	Large School Project
Square footage	50,000 sq. ft.	400,000 sq. ft.
Number of students	300	2,000
Building replacement value	$350 / sq. ft.	$450 / sq. ft.
Annual operating budget	$6 million	$45 million

For flooding adaptation measures, the same depth damage function used for energy assets was used (see Table 52). Additionally, the research team made assumptions regarding the scale of each adaptation measure (i.e., the size of the detention pond needed for flood storage). The assumptions for each climate adaptation measure applied to the hypothetical hospital and school projects are listed in Table 57 and Table 58, respectively.



Table 57. Hypothetical hospital project assumptions for each climate adaptation measure

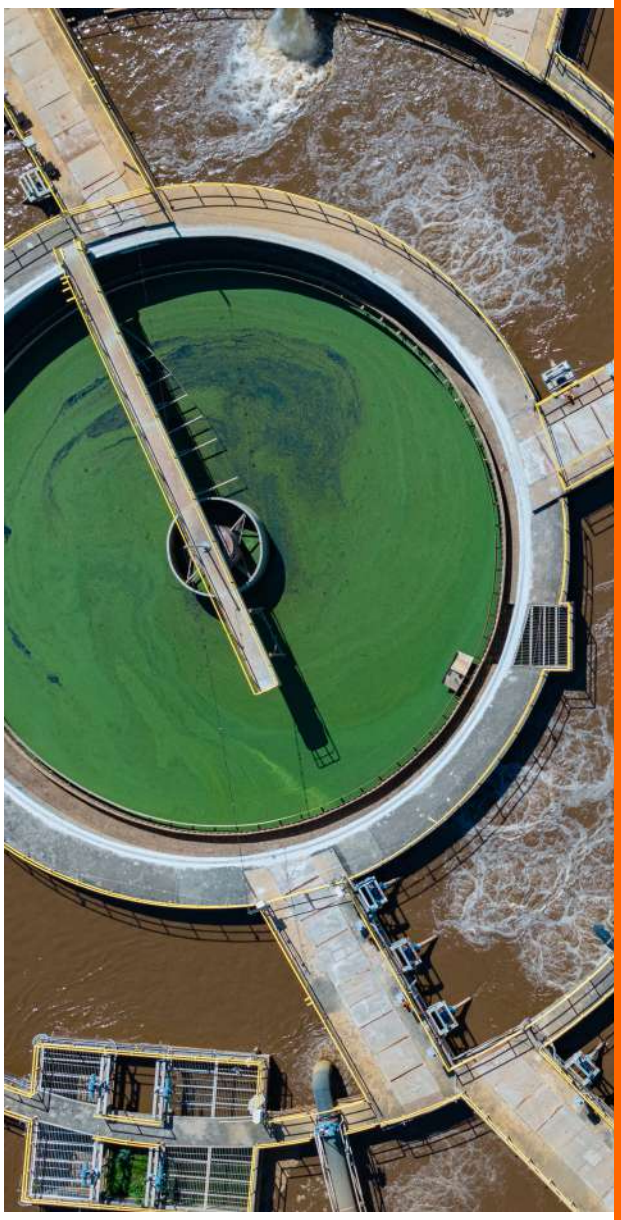
Adaptation Measure	Small Hospital Project Assumptions	Large Hospital Project Assumptions
Asset elevation	Assume elevation by 2.5 ft. is part of a new construction project for a hospital and the full square footage of the hospital is elevated.	
	Pre-Mitigation Flood Risk: 100-year flood event causes **3 ft. of flooding** and requires **90 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **20 repair days**.	**Pre-Mitigation Flood Risk:** 100-year flood event causes **3 ft. of flooding** and requires **180 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **40 days to repair**.
Dry floodproofing	Assume the dry floodproofing covers only the ground floor, and the ground floor is approximately 60% of the square footage of the building.	
	Pre-Mitigation Flood Risk: 100-year flood event causes **2 ft. of flooding** and requires **30 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **20 repair days**.	**Pre-Mitigation Flood Risk:** 100-year flood event causes **2 ft. of flooding** and requires **100 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **40 days to repair**.
Detention ponds for floodwater diversion and storage	Assume the detention pond is 8 feet deep. The same pre- and post-mitigation flood risk assumptions for asset elevation are assumed here.	
	Detention pond covers 0.5 acres.	Detention pond covers 8 acres.
Flood wall (5 feet tall)	Assume the flood wall surrounds the entire building. The same pre- and post-mitigation flood risk assumptions for asset elevation are assumed here.	
	Flood wall length is 800 linear ft.	Flood wall length is 6,000 linear ft.
Hurricane safe room	Assume the project is in a hurricane-prone region like Florida in the US. Assume the safe room is designed for wind speeds of 160 mph.	
	1,200 sq. ft. safe room designed to fit 200 people.	9,000 sq. ft. safe room designed to fit 1,500 people.
Defensible space and hazardous fuels reduction for wildfires	Assume a 100-foot perimeter of defensible space around the asset. Assume the project is located in a fire-prone area, specifically California, US. Project activities include clearing lightly forested areas (tree thinning, brush removal), adding fire-resistant plantings, hardscaping (gravel paths, rock mulch zones), and 3" of pea gravel. Each activity only covers part of the project area based on the CAL FIRE Zones. Assume clearing lightly forested areas covers 60% of the project area, fire-resistant plantings cover 25% of the project area, hardscaping covers 10% of the project area, and pea gravel covers 5% of the project area. Add 15–25% to total costs for design and permitting.	
	• Value of infrastructure vulnerable to fire: $8.5 million • Fire suppression costs of one typical fire within proposed project area: $1.2 million • Other costs mitigated by proposed project: $6 million	• Value of infrastructure vulnerable to fire: $210 million • Fire suppression costs of one typical fire within proposed project area: $3 million • Other costs mitigated by proposed project: $40 million

Table 58. Hypothetical school project assumptions for each climate adaptation measure

Adaptation Measure	Small School Project Assumptions	Large School Project Assumptions
Asset elevation	Assume elevation by 2.5 ft is part of a new construction project for a school, and the full square footage of the school is elevated.	
	Pre-Mitigation Flood Risk: 100-year flood event causes **3 ft. of flooding** and requires **60 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **10 repair days**.	**Pre-Mitigation Flood Risk:** 100-year flood event causes **3 ft. of flooding** and requires **120 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **20 days to repair**.
Dry floodproofing	Assume the dry floodproofing covers only the ground floor, and the ground floor is approximately 25% of the square footage of the building.	
	Pre-Mitigation Flood Risk: 100-year flood event causes **2 ft. of flooding** and requires **20 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **10 repair days**.	**Pre-Mitigation Flood Risk:** 100-year flood event causes **2 ft. of flooding** and requires **45 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **20 days to repair**.
Detention ponds for floodwater diversion and storage	Assume the detention pond is 8 feet deep. The same pre- and post-mitigation flood risk assumptions for asset elevation are assumed here.	
	Detention pond covers 0.4 acres.	Detention pond covers 3.3 acres.
Flood wall (5 feet tall)	Assume the flood wall surrounds the entire building. The same pre- and post-mitigation flood risk assumptions for asset elevation are assumed here.	
	Flood wall length is 440 linear ft.	Flood wall length is 1,280 linear ft.
Hurricane safe room	Assume the project is in a hurricane-prone region like Florida in the US Assume the safe room is designed for wind speeds of 160 mph.	
	1,650 sq. ft. safe room designed to fit 330 people.	11,000 sq. ft. safe room designed to fit 2,200 people.
Defensible space and hazardous fuels reduction for wildfires	The same defensible space assumptions used for hospitals are used here.	
	• Value of infrastructure vulnerable to fire: $14 million • Fire suppression costs of one typical fire within proposed project area: $1 million • Other costs mitigated by proposed project: $8 million	• Value of infrastructure vulnerable to fire: $126 million • Fire suppression costs of one typical fire within proposed project area: $2.5 million • Other costs mitigated by proposed project: $25 million

Water and Sanitation: Pump Stations, Desalination Plants, Lift Stations, and Wastewater Treatment Plants

The research team used the same approach used for energy and social infrastructure for water and sanitation, leveraging the US FEMA BCA Toolkit and available public literature on water resilience projects.



Drinking Water

We identified two hypothetical pump station projects and **two hypothetical desalination plant projects** to which the adaptation measures were applied:

1. A **small pump station** that is a local booster station on a main distribution line in a small town or rural settlement. The estimated total cost for a new construction project in Brazil is approximately $900,000.

2. A **large pump station** that is a major high-service or booster station feeding a large pressure zone in a big city. The estimated total cost for a new construction project in Brazil is approximately $6.5 million.

3. A **small desalination plant** that is a modular seawater or brackish water RO unit for a small coastal town or rural settlement. The estimated total cost for a new construction project in Brazil is approximately $16 million.

4. A **large desalination plant** that is a large seawater RO plant for a major coastal city. The estimated total cost for a new construction project in Brazil is approximately $70 million.



The tool inputs for the hypothetical pump station and desalination plant projects are listed in Table 59 and Table 60, respectively.

Table 59. Hypothetical pump station project features

Feature	Small Pump Station Project	Large Pump Station Project
• Square footage	1,000 sq. ft.	6,000 sq. ft.
• Number of customers served	6,000	220,000
• Daily design flow	0.5 MGD	20 MGD
• Building replacement value	$300/sq. ft.	$300/sq. ft.

Table 60. Hypothetical desalination plant project features

Feature	Small Desalination Plant Project	Large Desalination Plant Project
• Square footage	10,000 sq. ft.	50,000 sq. ft.
• Number of customers served	100,000	800,000
• Daily design flow	5 MGD	30 MGD
• Building replacement value	$500/sq. ft.	$500/sq. ft.



For flooding adaptation measures, the same depth damage function used for energy assets was used (see Table 52). Additionally, the research team made assumptions regarding the scale of each adaptation measure (i.e., the size of the detention pond needed for flood storage). The assumptions for each climate adaptation measure applied to the hypothetical pump station and desalination plant projects are listed in Table 61 and Table 62, respectively.

Table 61. Hypothetical pump station project assumptions for each climate adaptation measure

Adaptation Measure	Small Pump Station Project Assumptions	Large Pump Station Project Assumptions
Asset elevation	Assume elevation by 2.5 ft. is part of a new construction project for a pump station, and the full square footage of the station is elevated.	
	Pre-Mitigation Flood Risk: 100-year flood event causes **3 ft. of flooding** and requires **90 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **15 repair days**.	**Pre-Mitigation Flood Risk:** 100-year flood event causes **3 ft. of flooding** and requires **180 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **30 days to repair**.
Dry floodproofing	Assume dry floodproofing includes exterior wall waterproofing, joint sealing, penetrations/hatches treatment, etc. Focus on the exposed wall perimeter, 2 ft. high.	
	Dry floodproofing is used for a 260 sq. ft. wall area. **Pre-Mitigation Flood Risk:** 100-year flood event causes **2 ft. of flooding** and requires **60 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **15 repair days**.	Dry floodproofing is used for a 640 sq. ft. wall area. **Pre-Mitigation Flood Risk:** 100-year flood event causes **2 ft. of flooding** and requires **100 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **30 days to repair**.
Detention ponds for floodwater diversion and storage	Assume the detention pond can hold 3 ft. worth of flooding. The same pre- and post-mitigation flood risk assumptions for asset elevation are assumed here.	
	Detention pond covers 1,500 sq. ft.	Detention pond covers 9,000 sq. ft.
Flood wall (5 feet tall)	Assume the flood wall surrounds the entire building. The same pre- and post-mitigation flood risk assumptions for asset elevation are assumed here.	
	Flood wall length is 400 linear ft.	Flood wall length is 980 linear ft.
Hurricane safe room	Assume the project is in a hurricane-prone region like Florida in the US. Assume the safe room is designed for wind speeds of 160 mph.	
	60 sq. ft. safe room designed to fit 6 people.	120 sq. ft. safe room designed to fit 12 people.
Defensible space and hazardous fuels reduction for wildfires	Assume a 100-foot perimeter of defensible space around the asset. Assume the project is located in a fire-prone area, specifically California, US. Project activities include clearing lightly forested areas (tree thinning, brush removal), adding fire-resistant plantings, hardscaping (gravel paths, rock mulch zones), and 3" of pea gravel. Each activity only covers part of the project area based on the CAL FIRE Zones. Assume clearing lightly forested areas covers 60% of the project area, fire-resistant plantings cover 25% of the project area, hardscaping covers 10% of the project area, and pea gravel covers 5% of the project area. Add 15–25% to total costs for design and permitting.	
	• Value of infrastructure vulnerable to fire: $900,000 • Fire suppression costs of one typical fire within proposed project area: $150,000 • Other costs mitigated by proposed project: $1 million	• Value of infrastructure vulnerable to fire: $10 million • Fire suppression costs of one typical fire within proposed project area: $750,000 • Other costs mitigated by proposed project: $12 million

Table 62. Hypothetical desalination plant project assumptions for each climate adaptation measure

Adaptation Measure	Small Desalination Plant Project Assumptions	Large Desalination Plant Project Assumptions
Asset elevation	The same elevation assumptions used for pump stations are used here.	
	Pre-Mitigation Flood Risk: 100-year flood event causes **3 ft. of flooding** and requires **120 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **15 repair days**.	**Pre-Mitigation Flood Risk:** 100-year flood event causes **3 ft. of flooding** and requires **180 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **30 days to repair**.
Dry floodproofing	The same dry floodproofing assumptions used for pump stations are used here.	
	Dry floodproofing is used for an 800 sq. ft. wall area. **Pre-Mitigation Flood Risk:** 100-year flood event causes **2 ft. of flooding** and requires **60 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **15 repair days**.	Dry floodproofing is used for a 1,800 sq. ft. wall area. **Pre-Mitigation Flood Risk:** 100-year flood event causes **2 ft. of flooding** and requires **100 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **30 days to repair**.
Detention ponds for floodwater diversion and storage	The same detention pond assumptions used for pump stations are used here.	
	Detention pond covers 15,000 sq. ft.	Detention pond covers 75,000 sq. ft.
Flood wall (5 feet tall)	The same flood wall assumptions used for pump stations are used here.	
	Flood wall length is 1,265 linear ft.	Flood wall length is 2,828 linear ft.
Hurricane safe room	The same hurricane safe room assumptions used for pump stations are used here.	
	80 sq. ft. safe room designed to fit 8 people.	140 sq. ft. safe room designed to fit 14 people.
Defensible space and hazardous fuels reduction for wildfires	The same defensible space assumptions used for pump stations are used here.	
	• Value of infrastructure vulnerable to fire: $30 million • Fire suppression costs of one typical fire within proposed project area: $500,000 • Other costs mitigated by proposed project: $8 million	• Value of infrastructure vulnerable to fire: $150 million • Fire suppression costs of one typical fire within proposed project area: $2.5 million • Other costs mitigated by proposed project: $50 million

Wastewater



We identified **two hypothetical lift station projects and two hypothetical WWTP projects** to which the adaptation measures were applied:

1. A **small lift station** that serves a sub-basin of a town. The estimated total cost for a new construction project in Brazil is approximately $350,000.

2. A **large lift station** that serves a major urban sewer district sub-basin. The estimated total cost for a new construction project in Brazil is approximately $3.15 million.

3. A **small WWTP** located in a small town or rural settlement. The estimated total cost for a new construction project in Brazil is approximately $4 million.

4. A **large WWTP** located in an urban area. The estimated total cost for a new construction project in Brazil is approximately $300 million.

The tool inputs for the hypothetical lift station and WWTP projects are listed in Table 63 and Table 64, respectively.



Table 63. Hypothetical lift station project features

Feature	Small Lift Station Project	Large Lift Station Project
• Square footage	1,000 sq. ft.	3,600 sq. ft.
• Number of customers served	2,000	100,000
• Daily design flow	0.2 MGD	10 MGD
• Building replacement value	$250 /sq. ft.	$400/sq. ft.

Table 64. Hypothetical WWTP project features

Feature	Small WWTP Project	Large WWTP Project
• Square footage	12,000 sq. ft.	80,000 sq. ft.
• Number of customers served	11,000	700,000
• Daily design flow	1 MGD	60 MGD
• Building replacement value	$500 / sq. ft.	$500 / sq. ft.

For flooding adaptation measures, the same depth damage function used for energy assets was used (see Table 52). Additionally, the research team made assumptions regarding the scale of each adaptation measure (i.e., the size of the detention pond needed for flood storage). The assumptions for each climate adaptation measure applied to the hypothetical lift station and WWTP projects are listed in Table 65 and Table 66, respectively.

Table 65. Hypothetical lift station project assumptions for each climate adaptation measure

Adaptation Measure	Small Lift Station Project Assumptions	Large Lift Station Project Assumptions
Asset elevation	The same asset elevation assumptions used for drinking water assets are used here.	
	Pre-Mitigation Flood Risk: 100-year flood event causes **3 ft. of flooding** and requires **60 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **15 repair days**.	**Pre-Mitigation Flood Risk:** 100-year flood event causes **3 ft. of flooding** and requires **120 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **30 days to repair**.
Dry floodproofing	The same dry floodproofing assumptions used for drinking water assets are used here.	
	Dry floodproofing is used for a 260 sq. ft. wall area. **Pre-Mitigation Flood Risk:** 100-year flood event causes **2 ft. of flooding** and requires **30 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **15 repair days**.	Dry floodproofing is used for a 480 sq. ft. wall area. **Pre-Mitigation Flood Risk:** 100-year flood event causes **2 ft. of flooding** and requires **60 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **30 days to repair**.
Detention ponds for floodwater diversion and storage	The same detention pond assumptions used for drinking water assets are used here.	
	Detention pond covers 1,500 sq. ft.	Detention pond covers 5,400 sq. ft.

Adaptation Measure	Small Lift Station Project Assumptions	Large Lift Station Project Assumptions
Flood wall (5 feet tall)	The same flood wall assumptions used for drinking water assets are used here.	
	Flood wall length is 400 linear ft.	Flood wall length is 760 linear ft.
Hurricane safe room	The same hurricane safe room assumptions used for drinking water assets are used here.	
	40 sq. ft. safe room designed to fit 4 people.	80 sq. ft. safe room designed to fit 8 people.
Defensible space and hazardous fuels reduction for wildfires	The same defensible space assumptions used for drinking water assets are used here.	
	• Value of infrastructure vulnerable to fire: $750,000 • Fire suppression costs of one typical fire within proposed project area: $150,000 • Other costs mitigated by proposed project: $1 million	• Value of infrastructure vulnerable to fire: $8 million • Fire suppression costs of one typical fire within proposed project area: $750,000 • Other costs mitigated by proposed project: $12 million

Table 66. Hypothetical WWTP project assumptions for each climate adaptation measure

Adaptation Measure	Small WWTP Project Assumptions	Large WWTP Project Assumptions
Asset elevation	The same asset elevation assumptions used for drinking water assets are used here.	
	Pre-Mitigation Flood Risk: 100-year flood event causes **3 ft. of flooding** and requires **120 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **15 repair days**.	**Pre-Mitigation Flood Risk:** 100-year flood event causes **3 ft. of flooding** and requires **180 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **30 days to repair**.
Dry floodproofing	The same dry floodproofing assumptions used for drinking water assets are used here.	
	Dry floodproofing is used for a 1,200–1,500 sq. ft. wall area. **Pre-Mitigation Flood Risk:** 100-year flood event causes **2 ft. of flooding** and requires **60 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **15 repair days**.	Dry floodproofing is used for a 2,400 sq. ft. wall area. **Pre-Mitigation Flood Risk:** 100-year flood event causes **2 ft. of flooding** and requires **90 repair days**. **Post-Mitigation Flood Risk:** 500-year flood event causes **0.5 ft. of flooding** and requires **30 days to repair**.
Detention ponds for floodwater diversion and storage	The same detention pond assumptions used for drinking water assets are used here.	
	Detention pond covers 18,000 sq. ft.	Detention pond covers 120,000 sq. ft.
Flood wall (5 feet tall)	The same flood wall assumptions used for drinking water assets are used here.	
	Flood wall length is 1,385 linear ft.	Flood wall length is 3,578 linear ft.
Hurricane safe room	The same hurricane safe room assumptions used for drinking water assets are used here.	
	80 sq. ft. safe room designed to fit 8 people.	150 sq. ft. safe room designed to fit 15 people.
Defensible space and hazardous fuels reduction for wildfires	The same defensible space assumptions used for drinking water assets are used here.	
	• Value of infrastructure vulnerable to fire: $18 million • Fire suppression costs of one typical fire within proposed project area: $400,000 • Other costs mitigated by proposed project: $5 million	• Value of infrastructure vulnerable to fire: $120 million • Fire suppression costs of one typical fire within proposed project area: $2 million • Other costs mitigated by proposed project: $40 million

Appendix D: *Financing Instruments for Climate-Resilient Infrastructure*

This appendix describes six families of financing instruments relevant to climate-resilient infrastructure investment. For each instrument, the description covers what the instrument is, how it works, when it is most appropriate to use, and an illustrative example.

A. Commercial Financing Instruments

Commercial financing instruments are provided by private lenders and capital-market sponsors at market rates, without concessional subsidy. They form the base layer of most infrastructure capital structures and are the primary source of long-term debt for revenue-generating assets.

A.1 Senior Project Finance Loans

What It Is: A senior project-finance loan is a long-term debt instrument extended to a ring-fenced project company, secured against the project's assets and contracted cash flows rather than the balance sheets of its sponsors.[536]

How It Works: Lenders assess the project's ability to generate sufficient cash flow to service debt throughout the loan life. The loan is governed by a suite of financial covenants, a cash waterfall that prioritizes debt service before any equity distributions, and a debt service reserve account that can be drawn on if revenues temporarily fall short. In a non-recourse structure, lenders have no claim on the sponsors if the project fails; in a limited-recourse structure, sponsor support is provided only for defined construction-period risks. Tenors typically range from 10 to 20 years, aligned to the life of the project's revenue contract.[537]

When to Use It: Senior project-finance loans are appropriate for discrete, asset-heavy infrastructure projects with predictable, contracted revenue streams: power plants operating under power purchase agreements, toll roads with concession-based toll revenues, and water treatment facilities with offtake contracts. They are less suited to projects with uncontracted revenues or significant early-stage development risk.

Example:

A 150 MW wind farm has a 20-year power purchase agreement and a total cost of $200 million. Sponsors contribute $50 million in equity. A lender syndicate provides $150 million in senior debt secured against the wind farm assets and PPA cash flows, amortizing over 15 years on a schedule that keeps the debt service coverage ratio above 1.3x throughout. Lenders have no recourse to the sponsors' other businesses. If the project defaults, they can step in to operate or sell the asset.

A.2 Commercial Bank Debt

What It Is: Commercial bank debt is a loan extended by one or more banks to a project company or corporate borrower at standard market terms, without concessional support from a development institution.[538]

How It Works: In a bilateral facility, a single bank provides the full loan amount. In a syndicated facility, a lead arranger structures the loan, sets the terms, and distributes participations to co-lenders who each take a share of the credit exposure. The loan carries a floating or fixed interest rate, is secured against project assets and revenue contracts, and follows an amortization schedule aligned to projected cash flows. Infrastructure loans typically carry tenors of 10 to 20 years, reflecting the long operating lives of the underlying assets.

When to Use It: Commercial bank debt is appropriate when the project has a creditworthy offtaker or concession grantor, a proven technology, and sufficient contracted revenues to service debt at market rates. Syndicated facilities are used when the loan size exceeds a single lender's credit appetite or internal concentration limit for a given borrower or country.



Example:

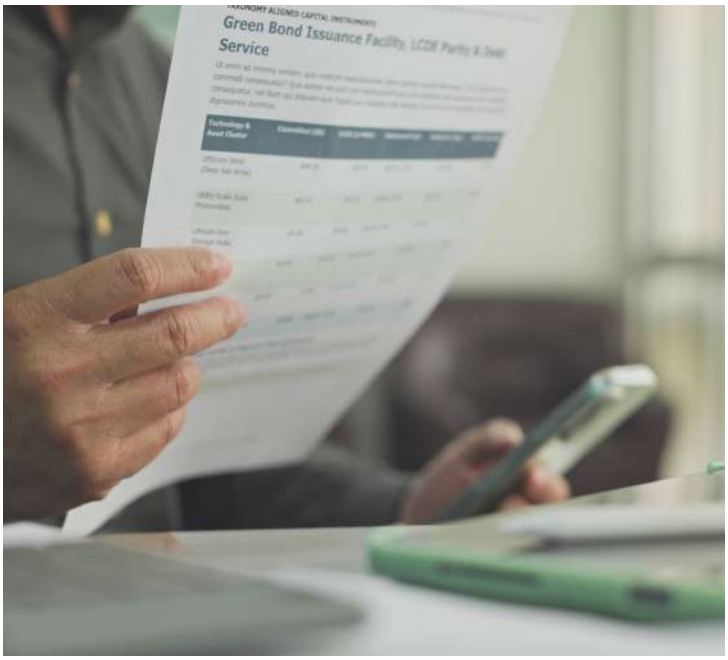
A project company needs $80 million over 18 years to finance a water treatment plant. One bank will lend the full amount but only for 7 years, producing a debt service burden that makes the project unaffordable. A lead arranger instead structures a syndicated loan: five lenders each take $16 million. With exposure spread across the group, participants are comfortable extending the tenor to 18 years. The longer repayment schedule reduces annual debt service to a level the project can sustain at an affordable tariff.

A.3 Green Bonds

What It Is: A green bond is a fixed-income instrument whose proceeds are contractually ring-fenced for projects with defined environmental benefits, most commonly renewable energy, clean transportation, water management, and climate adaptation.[539]

How It Works: The issuer designates eligible project categories, manages proceeds in a dedicated account, and reports annually on disbursements and environmental outcomes. An accredited second-party opinion provider verifies alignment with the Green Bond Principles before issuance. The instrument carries the same financial structure as a conventional bond: a face value, coupon, and maturity. It is marketed to a broader investor base than a conventional bond, which can include institutional sponsors with dedicated green mandates who are unable to buy non-labeled instruments.[540]

When to Use It: Green bonds are most suited to issuers with a portfolio of eligible green assets, sufficient scale to absorb the fixed costs of reporting and certification, and access to institutional sponsors with green investment mandates. They can unlock a more diversified investor base and sometimes achieve tighter pricing than conventional bonds of equivalent credit quality, a difference known as a "greenium."



Example:

An electricity utility raises $300 million to build three run-of-river hydropower plants. It issues a 10-year green bond at a 4.8% coupon. A second-party opinion provider confirms alignment with the International Capital Market Association (ICMA) Green Bond Principles. Institutional sponsors with green investment mandates who could not buy a conventional bond from this issuer without a policy waiver are able to participate. Demand is oversubscribed, and the utility prices the bond 15 basis points tighter than a comparable conventional bond issued one month earlier.



A.4 Sustainability-Linked Loans

What It Is: An SLL is a loan whose financial terms, typically the interest margin, are adjusted based on the borrower's performance against predetermined sustainability performance targets (SPTs) tied to measurable key performance indicators (KPIs).[541] Unlike a green loan, proceeds are not restricted to specific eligible expenditures.

How It Works: The borrower and lender agree on material KPIs, set ambitious SPTs, and define the margin adjustment that applies if targets are met or missed. An independent verifier assesses performance annually. If the borrower meets its SPT, the margin decreases by an agreed number of basis points. If it misses, the margin increases, with the penalty typically directed to a sustainability-related purpose. The adjustment mechanism creates a direct financial incentive for the borrower to achieve its stated sustainability targets.[542]

When to Use It: SLLs are best suited to corporate or portfolio-level borrowers seeking flexible financing without use-of-proceeds restrictions, but who want to create internal performance incentives and signal sustainability ambition to lenders. They work well for infrastructure operators managing a diverse asset base where ring-fencing proceeds to specific expenditures is impractical.

Example:

A toll road operator refinances a $400 million corporate credit facility as an SLL. The agreed KPI is the share of electric and hybrid vehicles in total network traffic. The SPT is 25% by 2027, rising to 40% by 2030. If each target is met, the loan margin decreases by 10 basis points. If missed, the margin increases by 10 basis points, with the premium contributed to a road safety fund. The operator's capital expenditure is unrestricted; the incentive operates entirely through pricing.

A.5 Sustainability-Linked Bonds

What It Is: A SLB is a bond instrument whose coupon or redemption terms vary depending on whether the issuer achieves predefined sustainability KPIs by specified target observation dates.[543] Proceeds are not restricted to eligible green expenditures.

How It Works: The issuer selects KPIs material to its business and sets SPTs representing meaningful, ambitious improvement. If the issuer misses an SPT, the coupon steps up, typically by 25 basis points, for the remaining bond life. The ICMA SLB Principles require the issuer to publish a KPI framework and SPT rationale before issuance and to provide annually verified performance reporting (ICMA, 2024). The instrument's credibility depends on the materiality of the KPIs and the ambition of the targets, not on how proceeds are spent.

When to Use It: SLBs are appropriate for corporate issuers with capital-market access who want to signal sustainability commitments without restricting use of proceeds. They suit infrastructure holding companies and concession operators with multiple assets and diversified capital expenditure programs, for whom a use-of-proceeds bond would be administratively complex.



Example:

An energy holding company issues a $500 million, 10-year SLB. The KPI is the share of installed generation capacity from renewable sources, with an SPT of 70% by 2028. If the company misses the target, the coupon increases from 4.5% to 5.0% for the remaining two years of the bond's life, representing approximately $10 million in additional interest cost. Sponsors accept the lower base coupon in exchange for the step-up protection; the company accepts the step-up risk because the penalty is manageable and the target is consistent with its existing strategy.

A.6 Results-Based Financing

What It Is: Results-based financing (RBF) is a funding mechanism that disburses payments only upon independent verification of pre-agreed outputs or outcomes, rather than upon completion of inputs or activities.[544] Subtypes include output-based aid (payment per verified service unit), performance-based grants (grant tranches conditioned on outcome milestones), and development impact bonds (in which private sponsors pre-finance delivery and are repaid by an outcome funder if results are achieved).

How It Works: The funder and implementing entity agree on a results framework specifying eligible outputs or outcomes, unit prices or disbursement thresholds, and the verification methodology. An independent verifier confirms achievement before each disbursement. The implementer finances delivery from its own resources and recovers costs only as results are verified. In a development impact bond, private sponsors bear the performance risk: if outcomes are not achieved, the outcome funder does not pay, and sponsors absorb the loss.[545]

When to Use It: RBF is most appropriate when strengthening delivery incentives matters as much as providing capital, when outcomes are independently measurable, and when the implementer has the organizational capacity and balance sheet to pre-finance operations. It is well suited to rural electrification, water and sanitation, and social infrastructure where past spending has not reliably translated into service delivery.

Example:

A government wants to extend electricity connections to 60,000 rural households. Rather than paying a utility upfront for construction, it signs an output-based aid agreement at $250 per verified new household connection, confirmed by an independent auditor in quarterly batches. The utility finances construction from its own working capital and recovers costs only as connections are verified. If the utility connects fewer households than planned, it is paid less. Payment is tied to actual service delivery, not to invoices or materials procured.



A.7 Environmental Impact Bonds

What It Is: An environmental impact bond (EIB) is a form of RBF in which private sponsors provide upfront capital for an environmental or infrastructure intervention and receive repayment from a government or utility funder that varies based on whether the intervention achieves measurable environmental outcomes.[546]

How It Works: The outcome funder, investor, and service provider agree on tiered repayment terms: a base repayment if outcomes meet expectations, a higher repayment if they exceed the target, and a lower repayment if they fall short. An independent evaluator measures and certifies results at specified intervals. The investor bears performance risk: if the intervention underperforms, the investor recovers less than the full principal; if it outperforms, the investor receives a premium.[547]

When to Use It: EIBs are suited to situations where the outcome funder wants to transfer performance risk to sponsors, where the intervention involves an innovative or unproven approach, and where environmental outcomes can be reliably measured and independently verified. They are particularly applicable to green infrastructure, ecosystem restoration, and nature-based solutions where performance uncertainty is high and outcome measurement is feasible.

Example:

A city finances a green infrastructure program—green roofs, permeable paving, and constructed wetlands—to reduce stormwater runoff. An impact investor provides $15 million upfront. If runoff falls by 30% or more over five years, the city repays $18 million. If the reduction is 15% to 30%, the city repays $15 million. Below 15%, the city repays $12 million. The investor accepts performance risk in exchange for an above-base return if the green infrastructure performs as intended; the city pays a premium only if outcomes are delivered.

B. Concessional and Blended Finance Instruments

Concessional and blended finance instruments combine below-market-rate public or philanthropic capital with commercial financing to improve the risk-return profile of transactions that would not attract purely commercial investment at standard terms.

B.1 Concessional Loans

What It Is: A concessional loan is a loan provided at an interest rate below the prevailing market rate, with an extended grace period and long maturity, by an MDB or bilateral development finance institution to a government borrower or a project with high development impact (World Bank Treasury, n.d.-a).

How It Works: The lender sets below-market rates, grace periods of 5 to 10 years during which no principal is repaid, and maturities of 20 to 40 years. The difference between the concessional rate and the market rate represents an implicit grant element that lowers the cost of financing and improves project affordability. Covenants typically require the borrower to maintain an agreed development program. Concessional resources are finite and allocated by development banks based on country eligibility and project development impact.

When to Use It: Concessional loans are appropriate for projects that generate high economic or social returns but insufficient financial returns to attract commercial debt at market rates: rural water and sanitation, coastal adaptation, urban flood protection, and social infrastructure in lower-income countries.

Example:

A government needs $40 million to build coastal flood defenses that protect 20,000 residents but generate no direct revenue. Commercial lenders will not finance a non-revenue asset. A development bank provides a 38-year concessional credit at 1.25% interest with a 6-year grace period. The extended tenor and low rate reduce annual debt service to a level the government can cover from general revenues. The same amount at a commercial rate of 7% over 10 years would require annual payments more than four times larger, making the project fiscally unviable.



B.2 Blended Finance

What It Is: Blended finance is the strategic use of public or philanthropic capital to improve the risk-return profile of an investment sufficiently to mobilize private commercial capital that would not otherwise participate.[548] It is a structuring approach, not a single instrument, combining concessional and market-rate financing layers within a single transaction or fund vehicle.

How It Works: A development institution or philanthropic entity contributes capital at a lower return or in a higher-risk position than commercial sponsors, typically as a first-loss tranche, subordinated debt, or grant. This reduces the expected loss and improves the risk-adjusted return for commercial co-sponsors in the senior layers, bringing the transaction within a range they can accept. The OECD DAC Blended Finance Guidance defines five core design principles: additionality, crowding-in, commercial sustainability, development impact, and transparency.[549]

When to Use It: Blended finance is appropriate where a genuine market failure exists: a project is commercially viable in the long run but cannot attract private capital at inception because perceived risks exceed what commercial sponsors can accept. It is not appropriate as a subsidy for investments that are already commercially viable at market terms.

Example:

A climate adaptation fund targeting solar and water projects in a frontier market finds that projects are financially viable over their asset lives but that commercial sponsors perceive country and offtake risks as too high. A development agency contributes $20 million as a first-loss tranche, accepting that it will absorb the first 20% of any losses before other sponsors are affected. With this protection, two pension funds commit the remaining $80 million at their target return. Without the concessional first-loss layer, the fund would not have closed.

B.3 MDB/DFI A/B Loans

What It Is: An A/B loan is a co-financing structure in which an MDB or development finance institution acts as lender of record for the entire loan, retains a portion as the A loan on its own books, and syndicates the remaining B loan portion to commercial co-lenders.[550]

How It Works: The MDB signs a single loan agreement with the borrower. Commercial B loan participants receive the same treatment as the MDB itself under the host country's preferred creditor agreements: exemption from capital controls, cross-default protections, and in some cases favorable withholding tax treatment. These privileges are unavailable to commercial lenders acting independently. The MDB retains a meaningful A loan on its own books, aligning its interests with those of B loan participants throughout the loan life.[551]

When to Use It: A/B loans are most effective in markets where commercial lenders have an appetite for the credit in principle but are deterred by specific country-level risks: currency transfer restrictions, political interference, or absence of bilateral investment treaty protection. The structure allows the MDB to mobilize significantly more private capital per dollar of its own exposure than direct lending alone.



Example:

An MDB lends $100 million to a project company in a country with a history of currency controls. The MDB retains $30 million as the A loan and syndicates $70 million to three commercial lenders as B loan participants. Those lenders would not commit directly to a borrower in this country because they cannot manage currency transfer risk on their own books. As B loan participants, they inherit the MDB's preferred creditor status: even if the government imposes capital controls, B loan payments are remitted with the same priority as the MDB's own A loan receipts.

B.4 Subordinated Debt and Mezzanine Finance

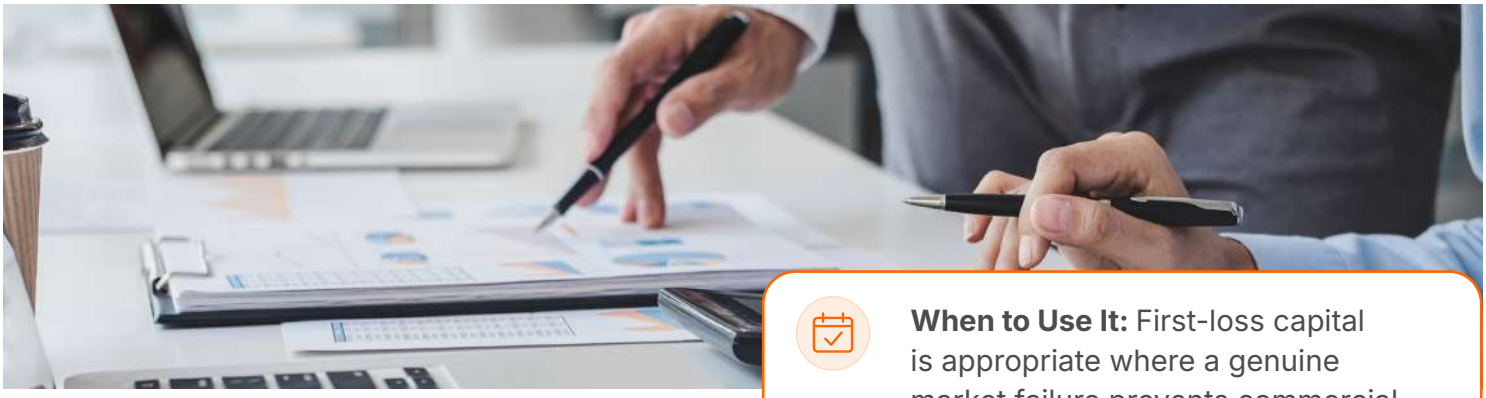
What It Is: Subordinated debt is a loan or bond that ranks below senior debt in the repayment waterfall: in default, subordinated creditors are paid only after senior lenders have been made whole. Mezzanine finance covers instruments that occupy the intermediate layer between senior debt and equity, including subordinated loans, payment-in-kind instruments, and convertible notes.[552]

How It Works: Because subordinated creditors bear more risk than senior lenders, they require a higher return, structured as a higher interest rate, an equity conversion option, or both. In a project-finance capital structure, the subordinated layer absorbs losses that would otherwise reach senior debt, providing a protective cushion that improves the senior tranche's credit quality. This allows senior lenders to offer lower rates and higher advance ratios, reducing the project's overall cost of capital (World Bank PPP Resource Center, n.d.-b).

When to Use It: Mezzanine finance is appropriate when a project's senior debt capacity falls short of the total financing need and sponsors cannot or will not contribute sufficient additional equity. It is commonly deployed to bridge the gap between senior debt and sponsor equity in PPP capital structures, particularly where a development institution can provide the mezzanine layer at below-market returns to improve overall project affordability.

Example:

A solar project requires $120 million. Senior lenders provide $80 million at 6% secured against project assets. Sponsors contribute $20 million in equity. A development finance institution fills the remaining $20 million gap with a subordinated loan at 10% interest. Senior lenders accept the structure because the subordinated tranche absorbs losses before reaching them. Sponsors benefit because they avoid diluting their equity stake. The WACC produces a competitive tariff under the power purchase agreement.



B.5 First-Loss Capital

What It Is: First-loss capital is a tranche of a blended finance structure that is explicitly designed to absorb the first losses of a portfolio or project before any other investor is affected.[553] It is provided by a concessional or philanthropic investor who accepts a below-market or zero return in exchange for the development impact generated by enabling commercial investment.

How It Works: The first-loss investor contributes capital subordinated to all other layers. Any losses realized by the portfolio are allocated to the first-loss tranche first, protecting senior sponsors up to the size of the cushion. This protection improves the expected return of senior sponsors and may allow them to accept a lower coupon or a longer tenor than they would otherwise require. The appropriate size of the first-loss tranche depends on the expected loss distribution of the underlying portfolio and the return threshold required by commercial co-sponsors.[554]

When to Use It: First-loss capital is appropriate where a genuine market failure prevents commercial investment: early-stage markets, sectors with high perceived risk, or projects with strong development impact but insufficient financial return. It should not be used to subsidize investments that can already attract commercial capital on reasonable terms.

Example:

A climate fund raises $100 million to invest in coastal adaptation projects in small island states. A development agency contributes $15 million as a first-loss tranche, accepting that its capital is wiped out before any other investor loses money. Commercial sponsors commit the remaining $85 million at a 7% target return, knowing that the first $15 million of any portfolio loss is absorbed before reaching them. Without the first-loss layer, those sponsors would require a 12% return that the underlying projects cannot support at affordable tariff levels.



B.6 Viability Gap Funding

What It Is: Viability gap funding (VGF) is a one-time capital grant or phased construction subsidy provided by a government to a PPP project that is economically and socially justified but financially unviable on market terms without support.[555]

How It Works: The government calculates the minimum grant required to make the project financeable at a competitive return for private sponsors, then runs a competitive tender in which sponsors bid for the concession with VGF as the variable: the bidder requiring the lowest grant wins. The grant is disbursed in tranches during construction, reducing the effective project cost that the private operator must recover over the concession life from users or availability payments. The operator retains construction, operational, and revenue risk.[556]

When to Use It: VGF is appropriate for infrastructure PPPs that serve a clear social or economic purpose but cannot generate revenues sufficient to attract private investment unaided. It extends the reach of private capital into lower-density corridors, underserved regions, or sectors where tariff levels are politically constrained.

Example:

A government awards a 25-year highway concession for a road connecting a remote agricultural region to a port. Traffic is sufficient to justify construction on economic grounds but too low to support a toll-based concession at market returns. Sponsors bid for the concession by naming the minimum VGF they require. The winning bidder asks for $50 million, disbursed in three construction-stage tranches. With the grant reducing the effective capital cost, the operator can service project debt and earn a market equity return at a toll level the government considers affordable.

C. Credit Enhancement and Risk-Sharing Tools

Credit enhancement instruments reduce the risk borne by private lenders or sponsors, making transactions that would otherwise be unbankable accessible to commercial capital. Unlike direct financing instruments, they operate through the contingent use of a guarantor's balance sheet rather than through disbursement of funds.

C.1 Partial Credit Guarantees

What It Is: A partial credit guarantee (PCG) is an irrevocable commitment by a guarantor, typically an MDB or development finance institution, to cover a specified percentage of a borrower's debt service obligations if the borrower defaults, regardless of the cause of the default.[557]

How It Works: The guarantor assesses the borrower and transaction, then issues a guarantee covering a defined portion of principal or debt service. If the borrower defaults, the guarantor pays the covered amount to the lender or bondholder and then seeks recovery from the borrower. The guarantee is a contingent liability for the guarantor and is sized to provide lenders with sufficient credit comfort to extend financing on terms, at tenors, or in currencies that they would not otherwise offer.[558]

When to Use It: PCGs are appropriate when lenders have appetite for a credit in principle but are constrained by maturity limits, currency risk, or concentration limits that prevent participation without enhancement. They are particularly effective for enabling long-dated local-currency bond issuances by infrastructure borrowers who cannot attract institutional sponsors at the required tenor without credit support.

Example:

A water utility wants to issue a 15-year local-currency bond. Domestic institutional sponsors will only buy bonds from this utility up to a 7-year maturity. A development bank provides a PCG covering 50% of the principal on bonds maturing after year 7. With half the post-year-7 principal guaranteed, sponsors accept the full 15-year term. The utility achieves the long-dated funding it needs; the guarantor commits no cash, only a contingent liability on its balance sheet that is called only in the event of default.



C.2 Partial Risk Guarantees

What It Is: A partial risk guarantee (PRG) is a guarantee against the risk of a government or state-owned entity failing to meet its contractual obligations to a private project: events such as regulatory change, license cancellation, expropriation, or failure to pay under a concession or offtake agreement.[559]

How It Works: The guarantor, typically an MDB, issues a guarantee to private lenders covering losses caused by specific sovereign or quasi-sovereign non-performance events. Unlike a PCG, the PRG covers only politically caused default, not commercial default by the project company. The government typically provides a counter-indemnity to the MDB, creating a backstop obligation on the sovereign. This structure effectively transfers political default risk from private lenders to the MDB, which can better absorb and manage it through its sovereign relationships.[560]

When to Use It: PRGs are most appropriate for projects that depend on government performance, such as build-operate-transfer concessions or projects with government offtake agreements, in countries where regulatory risk or policy reversals are material concerns. They protect lenders against the risk of a future government renegotiating or canceling the agreements that underpin the project's cash flow.

Example:

A private power producer signs a 20-year power purchase agreement with a state utility. Lenders are willing to finance the plant on its financial merits but are concerned a future government could terminate the PPA. An MDB issues a PRG covering the lenders in the event the government causes the PPA to be abrogated or materially altered. The government provides a counter-indemnity to the MDB. With the PRG in place, lenders extend a 15-year project loan on terms they would have otherwise declined, treating the political default risk as effectively transferred.

C.3 Political Risk Insurance

What It Is: Political risk insurance (PRI) compensates sponsors or lenders for losses caused by political events in the host country beyond their control: currency inconvertibility and transfer restrictions, expropriation and nationalization, war and civil disturbance, and breach of contract by the host government.[561]

How It Works: The insured pays an annual premium, typically calculated as a percentage of the insured exposure. If a covered political event occurs and causes a verified financial loss, the insurer pays the indemnity up to the policy limit. The insurer then exercises subrogation rights against the host government. PRI is available from multilateral providers, principally the Multilateral Investment Guarantee Agency (MIGA), and from private insurers in the Lloyd's and company markets. Policy tenors typically range from 3 to 20 years.[562]

When to Use It: PRI is most valuable when a project's economics are sound, but investor or lender perception of country risk is preventing capital from flowing. It is particularly effective for equity sponsors entering frontier markets, lenders providing cross-border loans in countries with capital control risk, and projects where the government is both a counterparty and a potential source of political interference.

Example:

An infrastructure fund wants to invest $60 million in equity in a hydropower plant in a politically volatile country. The investment committee approves the project on financial merit but requires protection against expropriation. MIGA issues a policy covering the $60 million equity stake against expropriation and breach of contract for 15 years, at an annual premium of 0.7% of the insured amount. With the policy in place, the fund's board approves the investment. If the government expropriates the plant without adequate compensation, MIGA pays the fund and pursues recovery from the government.

D. Liquidity and Disaster-Response Instruments

These instruments address the acute liquidity needs that arise from climate shocks and natural disasters. They are designed to be arranged in advance and deployed rapidly once a triggering event occurs, bridging the gap before slower-moving reconstruction financing becomes available.

D.1 Liquidity Facilities and Debt Service Reserve Accounts

What It Is: A DSRA is a cash reserve maintained by a project company, funded from operating revenues, that can be drawn on to make debt service payments when project revenues temporarily fall short. A liquidity facility is a standby credit line from an external provider serving the same function.[563]

How It Works: Project-finance loan covenants require the project company to keep the DSRA at a specified minimum balance, typically six months of senior debt service. If revenues fall short in any period, the shortfall is covered from the DSRA or the liquidity facility. Once revenues recover, the reserve is replenished to the required level before any distributions are made to equity holders. A standby liquidity facility is drawn and repaid as a revolving credit rather than from the project's own accumulated cash.[564]

When to Use It: DSRAs are a standard requirement in all project-finance transactions. In climate-exposed projects in hurricane-, flood-, or drought-prone regions, reserve accounts are increasingly sized to cover longer disruption windows than the conventional six-month standard, reflecting the potential for extended revenue interruption following a major climate event.

Example:

A wind farm financed under a 15-year project loan holds a DSRA funded to $8 million at financial close. When a hurricane takes the plant offline for four months, the project company draws the DSRA to continue paying principal and interest to lenders, avoiding a technical default. When the plant returns to service, operating cash flows replenish the reserve over the following eight months before any dividend is paid to equity holders.



D.2 Catastrophe Deferred Drawdown Option

What it Is: A Development Policy Loan (DPL) with a Cat DDO is a contingent sovereign credit line provided by the World Bank that is approved before a disaster occurs and can be drawn down rapidly once a qualifying event is declared.[565]

How it Works: A government negotiates and signs the Cat DDO during a period of fiscal stability. The facility sits in reserve, with the government paying a standby fee. When a qualifying natural catastrophe or public health emergency is declared, and a predefined trigger condition is met, the government can draw the full facility within days, without undergoing a new loan appraisal. The borrowing limit is 0.5% of GDP or $1 billion, whichever is lower. The facility must be renewed every three years and requires the borrower to maintain a satisfactory disaster risk management program and macroeconomic framework.[566]

When to Use It: The Cat DDO is designed for governments with material exposure to natural catastrophes or pandemic risk who want guaranteed immediate liquidity at the moment of a crisis. It is most appropriate for World Bank-eligible countries with a credible disaster risk management framework, and complements, rather than replaces, medium-term reconstruction financing.

Example:

A Caribbean government negotiates a $100 million Cat DDO with the World Bank before any disaster occurs, paying a 0.5% annual standby fee. When a Category 4 hurricane strikes the island, the government declares an emergency, triggers the facility, and receives $100 million within five days. The funds restore power and water services and cover emergency expenditures while bilateral aid pledges and reconstruction loans, which take weeks to mobilize, are being confirmed.

E. Revenue Support and Payment-Security Instruments

Revenue support instruments are contractual government commitments that stabilize or guarantee the revenue stream of a privately operated infrastructure asset. They reduce the demand risk borne by private sponsors and lenders, making PPP financing viable in markets or sectors where user-fee revenues are uncertain or politically constrained.

E.1 Availability Payments

What It Is: An availability payment is a periodic payment made by a government to a private operator under a PPP concession, contingent solely on the infrastructure asset being available and performing at a contractually defined standard, regardless of actual usage levels.[567]

How It Works: The concession agreement defines performance standards, availability metrics, and a deduction mechanism: if the operator misses a standard, the availability payment for that period is reduced by a specified penalty. The operator finances the project through equity and project debt, using the stream of availability payments as the primary revenue source for debt service. Demand risk is borne entirely by the government: the operator's revenue is not affected by how many users use the asset.[568]

When to Use It: Availability payments are the standard mechanism for PPPs in sectors where user-fee revenues are not applicable or appropriate, such as hospitals, schools, and prisons, and for transport assets where demand risk is too uncertain for private sponsors to bear. They provide lenders with a predictable, government-backed revenue stream that can support investment-grade project credit ratings.

Example:

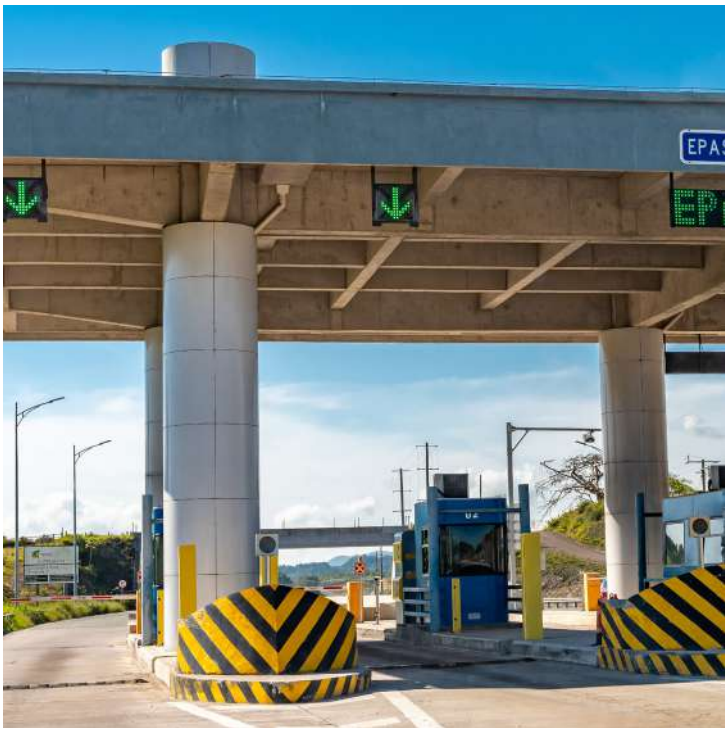
A government awards a 25-year PPP concession to design, build, finance, and operate a regional hospital. The operator raises project-finance debt and equity, builds the facility, and is paid a monthly availability fee of $2 million as long as the hospital meets defined standards for equipment uptime, cleanliness, and patient response times. If any standard is missed, the fee is reduced by a defined penalty. Patients pay nothing directly. The operator's revenue depends entirely on whether the building performs, not on patient volumes.

E.2 Minimum Revenue Guarantees

What It Is: An MRG is a government commitment to compensate a private concession operator if actual user-fee revenues fall below a contractually defined floor, protecting the operator and its lenders against demand risk below a specified threshold.[569]

How It Works: The concession agreement defines a minimum revenue level, often as a percentage of the base-case traffic or usage forecast. If revenues fall below the floor in any measurement period, the government compensates the operator for the shortfall. Many MRG structures include a revenue-sharing mechanism: if revenues exceed a defined ceiling, the upside is shared between the operator and the government. The MRG is a contingent fiscal liability; payment is triggered only if demand falls short of the contractual floor.[570]

When to Use It: MRGs are appropriate for demand-risk concessions in sectors with material traffic or usage uncertainty, where lenders require downside protection to extend long-term project-finance debt. They enable private operators to take on concessions in markets where the base-case demand is credible but the range of possible outcomes is too wide for lenders to accept without a floor.



Example:

A private operator takes a 30-year toll road concession. The base-case forecast is 15,000 vehicles per day, sufficient to service project debt. Lenders require downside protection. The government agrees to an MRG: if traffic falls below 10,000 vehicles per day in any year, it compensates the operator for the shortfall. If traffic exceeds 20,000 vehicles per day, the surplus is split equally between the operator and the government. The operator bears demand risk between the floor and the ceiling; the government backstops below and participates above.

F. Equity and Quasi-Equity Instruments

Equity and quasi-equity instruments provide risk capital that absorbs losses ahead of all debt. They are the most subordinated layer of the capital structure and therefore the highest-risk instruments. Their presence is essential for any project-finance transaction: without equity, lenders have no loss-absorbing cushion and will not lend.

F.1 Sponsor Equity

What It Is: Sponsor equity is the risk capital contributed directly by the project developers or concession holders. It is the most subordinated layer of the capital structure: equity holders receive returns only after all debt service and operating costs have been paid, and have no guaranteed income (World Bank PPP Resource Center, n.d.-a).

How It Works: Sponsors contribute equity at financial close, typically covering 20% to 40% of total project cost. Returns are generated through dividends from operating cash flows after debt service, and through capital gains if the project is refinanced or sold. In a project-finance structure, equity is locked in during construction and the early operating period when the project is most vulnerable to cost overruns and performance risk. Equity holders control the project company through their shareholding.[571]

When to Use It: Sponsor equity is required in every project-finance transaction. Its size is determined by lender requirements: lenders will typically not advance more than 70% to 80% of total project cost, so sponsors must contribute at least 20% to 30% as equity. Higher-risk projects or frontier market transactions require larger equity contributions to demonstrate sponsor commitment and provide adequate loss coverage for lenders.

Example:

Three sponsors jointly develop a 200 MW solar park with a total cost of $180 million. Lenders provide $130 million in senior debt secured against the project assets and a 25-year PPA. The sponsors contribute $50 million in equity. If construction overruns occur or the project underperforms, the sponsors' $50 million is at risk before lenders lose a dollar. In exchange, if the project performs well over its 25-year life, all distributable cash after debt service goes to the equity holders.



F.2 DFI and Climate Fund Equity

What It Is: DFI and climate fund equity is a minority equity stake taken by a development finance institution or multilateral climate fund in an infrastructure project company or fund vehicle, typically at the project preparation or early development stage when commercial equity is scarce.[572]

How It Works: The DFI invests as a minority shareholder alongside commercial sponsors on terms reflecting the project's risk profile, which may be below what a purely commercial investor would accept. The DFI's presence signals project credibility, brings technical assistance and political risk protection, and in some structures, concessional layers from climate funds are combined with the DFI's market-rate equity to lower the overall cost of capital. The DFI typically exits its stake once commercial viability is established, recycling capital to the next investment.[573]

When to Use It: DFI equity is most valuable when a project cannot attract commercial equity at the development stage because the technology is unproven, the market is immature, or the country risk profile discourages early-stage sponsors. The DFI's investment serves as a catalyst, reducing risk perception sufficiently for commercial equity to follow.

Example:

A geothermal developer cannot attract commercial equity for exploration because early-stage drilling carries a high probability of a dry well. A development finance institution takes a 20% equity stake in the project company at a valuation reflecting exploration risk. This gives the project sufficient credibility for a regional bank to provide an exploration loan. When drilling confirms the resource, commercial sponsors buy in at a higher valuation, the DFI reduces its stake, and exploration financing is replaced by a full project-finance structure.



F.3 Preferred Equity and Mezzanine Instruments

What It Is: Preferred equity is an equity instrument that ranks above common equity in the payment waterfall, typically carrying a fixed preferred return that must be paid before common equity holders receive any distributions. Mezzanine instruments occupy the same intermediate layer and include convertible notes, payment-in-kind instruments, and hybrid securities that combine debt and equity characteristics (World Bank PPP Resource Center, n.d.-b).

How It Works: Preferred equity sponsors receive a defined return, either as a cash dividend or an accrued amount, before common equity holders. In some structures, preferred equity converts to common equity at the investor's option if defined performance thresholds are met, providing participation in the upside. Mezzanine instruments may accrue interest paid in kind rather than in cash, reducing the cash drain on the project during early operating periods when revenues are lower.[574]

When to Use It: Preferred equity and mezzanine instruments are used to bridge a gap between senior debt capacity and the equity sponsors are willing or able to contribute. They reduce the equity burden on sponsors while providing an additional loss-absorbing layer for senior lenders. They are common in large PPP structures and infrastructure holding company transactions where a tiered capital structure is needed to attract different categories of sponsors at different points in the risk-return spectrum.

Example:

A port concession requires $250 million. Senior lenders provide $160 million. The sponsor group contributes $50 million in common equity. A pension fund fills the remaining $40 million gap with preferred equity carrying a 9% preferred return paid quarterly before any common equity distribution. The preferred equity converts to a 15% common equity stake if port revenues exceed a defined threshold by year 10. The pension fund receives a fixed return in the base case and an equity upside in the outperformance scenario; sponsors avoid raising additional senior debt, which would breach their leverage covenants.

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