Report

Low Cost, High Yield: *The* Adaptation *and* Resilience Investment Opportunity *for* Infrastructure

The financial case and how to access the opportunity

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AXA Climate
Scientific Climate Ratings
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About AXA Climate

AXA Climate is a subsidiary of the AXA Group that focuses on helping organizations adapt to climate change through risk analytics, advisory, and training services. It combines insurance expertise with data-driven insights to assess physical and transition climate risks, support resilient investment decisions, and develop adaptation strategies across sectors such as agriculture, infrastructure, and finance. For more information, visit www.climate.axa.

The information provided should be interpreted, read and understood as illustrative and indicative rather than as specific recommendations or positions from AXA Climate or the AXA Group. This report is intended to provide insights and guidance, and any application of the findings should be adapted to the specific context and needs of the reader.

About AXA Climate and Scientific Climate Ratings

The report was authored by AXA Climate with business case analytics carried out by Scientific Climate Ratings.

- AXA Climate coordinated and produced the overall study, including stakeholder engagement, institutional analysis, and synthesis of sectoral findings.
- Scientific Climate Ratings developed the methodological approach and quantitative analysis linking adaptation measures to infrastructure valuation and net asset value (NAV) impacts. The resilience valuation framework is grounded in infrastructure risk-adjusted performance metrics and investor-relevant financial modelling.

Business case modeling and data collection were undertaken in collaboration with SUEZ, Tractebel, and EGIS Conseil, which provided sectoral expertise, engineering validation, and hydrological and infrastructure modeling support.

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Acronyms

A&R	Adaptation and Resilience
ANA	Agência Nacional de Águas e Saneamento Básico (National Water and Sanitation Agency, Brazil)
ANEEL	Agência Nacional de Energia Elétrica (National Electric Energy Agency, Brazil)
BCR	Benefit-Cost Ratio
BNDES	Banco Nacional de Desenvolvimento Econômico e Social (Brazilian Development Bank)
CAPEX	Capital Expenditure
CatNat	Catastrophes Naturelles (France's natural disaster insurance scheme)
CREMA	Contrato de Recuperação e Manutenção (Performance-based road rehabilitation and maintenance contract, Brazil)
DFI	Development Finance Institution
EMDE	Emerging Market and Developing Economy
GCF	Green Climate Fund
IDB	Inter-American Development Bank
IFC	International Finance Corporation
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
KPI	Key Performance Indicator
MDB	Multilateral Development Bank
MIGA	Multilateral Investment Guarantee Agency
NAV	Net Asset Value
NGFS	Network for Greening the Financial System
NPV	Net Present Value
ONS	Operador Nacional do Sistema Elétrico (National Electric System Operator, Brazil)
OPEX	Operating Expenditure
PPP	Public-Private Partnership
RAP	Receita Anual Permitida (Permitted Annual Revenue, Brazil T&D)
RCP	Representative Concentration Pathway
SABESP	Companhia de Saneamento Básico do Estado de São Paulo (São Paulo State Basic Sanitation Company)
SSP	Shared Socioeconomic Pathway
T&D	Transmission and Distribution

Foreword

Resilient infrastructure is foundational for economic growth, job creation, service delivery, and private capital mobilization. Infrastructure is increasingly exposed to material physical risks: climate shocks like floods, droughts, wildfires, and storms are no longer temporary inconveniences. They disrupt operations, erode revenues, and impair asset values across infrastructure portfolios, with emerging markets and developing economies (EMDEs) bearing the greatest burden. For developers and operators, infrastructure that is not designed for future climate conditions could become a stranded asset rather than a stable, long-term investment.

By contrast, resilient infrastructure, which integrates climate adaptation upfront, is more reliable, bankable, and insurable; better positioned to deliver predictable cash flows over its lifetime. Designing for future climate conditions protects asset performance, reduces downtime, and lowers the probability of costly retrofits or premature failure.

This report, *Low Cost, High Yield: The Adaptation and Resilience Investment Opportunity for Infrastructure*, makes a clear financial and economic case: adaptation and resilience (A&R) investments protect value and enhance returns while maintaining essential services. The evidence shows that targeted A&R measures reduce losses, stabilize revenues, and improve risk-adjusted performance—outcomes that matter for investors, lenders, and operators alike.

Despite these compelling returns, private investment in A&R remains below what fundamental risk would justify. Unpriced climate risk, fragmented data, and regulatory uncertainty continue to deter capital. This report responds directly to these constraints by identifying investable resilience solutions, and highlighting policies, regulations, and financing structures that reduce uncertainty for private capital across EMDEs.

The cost of inaction is rising, even as the business case for investing in resilience is growing stronger. For the private sector, the question is no longer whether climate adaptation is relevant. Rather, the question is whether infrastructure portfolios can remain competitive without it. This report demonstrates that investing in resilient infrastructure has the potential to mobilize capital at scale—protecting assets, strengthening returns, creating jobs, and supporting long-term economic growth in EMDEs, while securing a livable future for all.

Nicolas Peltier-Thiberge

Director, Strategy & Operations, Infrastructure
World Bank Group

Institutional investors manage over USD 100 trillion globally, of which more than USD 30 trillion stems from the insurance sector. Deployed at scale toward adaptation, this capital could close a meaningful share of the estimated USD 300 billion annual adaptation financing gap, and yet, it largely does not.

For insurers, the imperative is particularly acute. Since 2020, we have crossed a threshold of natural catastrophe losses globally every single year, that was previously only exceeded every ten years. In emerging economies, where climate impacts hit hardest relative to GDP, less than 10% of losses are insured. At AXA Climate, we work across sectors to strengthen the risk management capacity of stakeholders facing these realities.

Against this backdrop, adaptation and resilience (A&R) represents a major untapped economic opportunity. These investments are not only necessary; they are investable—generating financial returns while delivering significant, often underestimated co-benefits. This is especially the case for resilient critical infrastructure, which serves as a lever of economic growth essential to preserving people's quality of life.

One concrete example of this opportunity in action: six insurers including AXA have joined IFC, through the Insurance Development Forum, to launch the Infrastructure Resilience Development Fund. The USD 340 million blended finance vehicle, managed by Global Infrastructure Partners, targets climate-resilient infrastructure in emerging markets where adaptation demonstrably reduces risk and creates financial value.

Yet, despite a clear and growing business case, private capital is not flowing at scale, least of all to the emerging markets where the need is greatest. This report identifies the structural barriers blocking private capital and the practical levers to unblock it. It makes the financial and non-financial case for integrating A&R into infrastructure design from the outset, an approach that strengthens long-term returns, secures essential services, and delivers social and economic co-benefits at scale.

The capital exists. The opportunity is identified. What follows is a roadmap for moving intent to deployment, and a call to every actor in the infrastructure financing chain to play their part.

Antoine Denoix

Chief Executive Officer
AXA Climate

Executive Summary

Infrastructure operators, investors, and financiers share common goals with governments: maximizing infrastructure uptime—keeping the lights on, the water supply flowing, and the roads open, among others—while optimizing operational efficiency, rationalizing end-user fees, and holding the line on maintenance and repair budgets. This report, "Low Cost, High Yield: The Adaptation and Resilience Investment Opportunity for Infrastructure," lays out a pathway to support these goals by embedding cost-effective adaptation and resilience (A&R) into infrastructure systems and services.

Climate impacts could cost

43 million

jobs across 49 countries by 2050—but targeted A&R can cut these losses by more than half.

The impact of natural hazards on infrastructure already costs low- and middle-income countries an estimated USD 390 billion annually in financial and economic losses. This is equivalent to 1–2 percent of GDP, and is projected to escalate as climate hazards intensify—such as volatile weather patterns that bring more frequent drought-flood cycles and, powerful storms. These disruptions undermine continuity of services essential to economic performance, eroding development gains, investor confidence, and undermining foundations for job creation, especially in emerging markets and developing economies (EMDEs).

At a time of rising climate risks, a heightened focus on A&R allows infrastructure stakeholders to anticipate, mitigate, recover from, and adapt to climate-related shocks and stresses while maintaining essential services. The findings in this report will help to catalyze action and increase public and private A&R investments, particularly in EMDEs, which are often more vulnerable to costly and cascading impacts of climate events.

Part I lays out the climate risks generally facing infrastructure assets of all kinds, translating to severe and costly damage, extensive downtime, and cascading impacts—possibly resulting in 43 million lost jobs across 49 countries by 2050. Targeted A&R interventions can reduce these job losses by more than half.[1] This section highlights the incentives to invest in A&R, including billions of dollars in savings from avoided losses and wider economic benefits. A&R upgrades can reduce operational risks, stabilize cash flows, and improve credit profiles. Thus, these measures can lower the cost of capital for operators and investors, enhance insurability, and increase bankability of key infrastructure. All of this enables private capital mobilization. But despite these drivers, four main gaps prevent A&R from attracting investment at scale:

- **Data gaps:** Data unavailability makes it more difficult for operators and investors to accurately quantify risks and benefits.
- **Incentive gaps:** Regulations may not allow A&R cost recovery while building codes continue to reflect historical, rather than projected climate conditions.
- **Financing gaps:** Financing channels are scarce and access to capital is rarely tied to effective A&R outcomes. However, most A&R costs are small additions to larger infrastructure investments, meaning modest catalytic funding could unlock significant resilience benefits.
- **Governance gaps:** Gaps across sectors and institutions lead to duplicated efforts and missed synergies.

In Part II, the report turns to Brazil as a representative emerging market country, to explore three use cases across three critical infrastructure sectors—power transmission and distribution, water and wastewater, and roads. Project-level business cases explore how real-world assets could gain from specific A&R investments, based on existing Brazilian assets that have experienced climate impacts or face high future climate exposure. Using open-source data, climate-hazard modeling and financial valuation, the case studies estimate physical damage, service-interruption costs, and avoided losses to assess the financial and operational performance of A&R investments through net asset value (NAV) and internal rate of return (IRR) metrics.

The research quantified the gains from various A&R interventions under selected climate scenarios: USD 8.6 protected per dollar invested for the transmission and distribution sector; USD 6.3 protected per dollar invested for the ater supply and sanitation; and USD 2.2 protected per dollar invested for the road sector:

- **Transmission and distribution:** For the transmission line, for example, firebreaks alone bring NAV impacts down from 30 percent to 7.6 percent for a cost of around 3 percent of NAV, while cutting annual service outages from 10.8 to 1.6 days.
- **Water:** For the water reservoir, a bundled package of storage and fire protection halves impacts on NAV for a 2.4 percent cost.
- **Roads:** For the motorway corridor, road elevation and fire protection zones safeguard 9.5 percentage points of NAV.

The analysis also revealed important new insights on the value of A&R measures, which should resonate with all stakeholders faced with financial constraints: business executives focused on the bottom line, governments with constrained budgets, and investors and financiers that want to mitigate their risks, especially in EMDEs.

The case studies demonstrate the importance of full corporate and strategic alignment in assessing A&R measures, not solely as engineering or design considerations, but as financial and capital allocation decisions. Such a shift will enhance long-term financial sustainability and strengthen climate risk management.

Among the cross-sectoral insights:

Climate impacts erode almost 30 percent of net asset value under certain climate scenarios.

Targeted, lower-cost A&R measures deliver the highest benefit-to-cost ratios.

Public co-investment is critical to support A&R measures that fall below private cost-efficiency thresholds but drive significant socioeconomic value.

Long-tenor financing dramatically improves A&R bankability; loan maturity matters more than interest rate reductions.

Lifecycle assessment of benefit-to-cost of selected interventions reveals true value, with A&R benefits evaluated across the full asset lifespan.

Part III identifies pathways to access the investment opportunities uncovered in Part II. It lays out practical steps stakeholders can take to unlock financing and overcome barriers to investment. These steps include addressing climate-risk data gaps, incentivizing investments to mitigate climate risks, expanding access to innovative finance instruments, and increasing systematic collaboration between public and private stakeholders across infrastructure sectors, and with financial intermediaries. Part III also highlights publicly available resources to support the A&R finance journey. It features global good practices and examples of successful investments that have catalyzed action. For instance, IFC's USD 120 million sustainability-linked loan to ENGIE Energía Perú links loan pricing to verified implementation of site-specific adaptation plans. And Africa Finance Corporation's USD 750 million Infrastructure Climate Resilient Fund, leverages USD 240 million in junior first-loss equity from the Green Climate Fund to attract capital from African pension funds, sovereign wealth funds, and insurance companies.

The paper concludes with recommendations for all stakeholders on how to unlock financing streams for A&R. Among the recommendations:

Governments should accelerate policy and regulatory action on risk understanding to enable and scale investment in A&R. This includes public-private partnership (PPP) and concession reforms that go beyond the lowest bid to reward climate resilience, allocate climate risk transparently in force majeure provisions, and allow efficient A&R cost recovery through tariffs, availability payments, and extended concession terms.

Operators should elevate their A&R focus to the strategy, finance, and risk decision-making level. Using methodologies such as the Physical Climate Risk Appraisal Methodology (PCRAM), they can quantify avoided losses, reduced O&M, asset-life extension, and lower insurance premiums alongside capital expenditures (CAPEX) and operating expenditures (OPEX).

Investors and financial institutions should integrate climate risks and resilience performance into their credit analysis, investment appraisal, portfolio management, and cost-of-capital models. By leveraging international frameworks such as PCRAM, and the Climate Bonds Resilience Taxonomy they can improve comparability and access to global capital.

Multilateral development banks (MDBs) and development finance institutions (DFIs) need to play a stronger role in enabling these changes. They can do so by scaling up concessional capital, first-loss tranches, guarantees, and project preparation facilities to derisk investments and crowd in private capital.

Key takeaways: The A&R dividend

THE BIG NUMBERS

The numbers speak for themselves: across three Brazilian infrastructure business cases, investing less than 10% of net asset value in A&R delivers a multiple of that cost in protected asset worth over the asset's lifetime.

Energy transmission and distribution sector

3.0% Cost of A&R → **22.7%** NAV saved

Investment in A&R: **$1**

Protected asset value: **$8.6**

85% **annual reduction in service outages** through low-cost firebreaks

886% IRR can be achieved for firebreaks due to their low cost

Water and sanitation sector

2.4% Cost of A&R → **12.9%** NAV saved

Investment in A&R: **$1**

Protected asset value: **$6.3**

54% **reduction in service disruptions** through enhanced water storage & fire protection

805% IRR achieved by a bundle of A&R measures

Road sector

8.0% Cost of A&R → **9.5%** NAV saved

Investment in A&R: **$1**

Protected asset value: **$2.2**

50% **reduction in roadway disruptions** through flood and wildfire protections

156% IRR achieved by a bundle of A&R measures

NOTE: The A&R measures analyzed represent a subset of possible interventions, selected based on cost-effectiveness (benefit-cost ratio >1), relevance to identified climate hazards, and effectiveness (degree of avoided losses). The high IRRs reflect the relatively modest investment cost, compared with substantial avoided climate-related losses. They do not reflect full project economics, including revenues, debt amortization and operating costs. The NAV saved includes the cost of the A&R measure.

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Introduction

Climate change is amplifying the physical risks facing infrastructure systems worldwide, with the most severe impacts concentrated in emerging markets and developing economies (EMDEs).[2] Slow-onset changes, such as sea level and temperature rise, degrade assets over time, while acute events, including floods, storms, droughts, heatwaves, and wildfires, can quickly cause extensive damage. As a result, infrastructure networks are experiencing longer and more frequent service disruptions. Power systems are compromised by damage to transmission and distribution lines. Reservoirs are running dry. Transport corridors are cut off by flooding. All of this affects not just the infrastructure assets themselves, but overall economic activity.

Efforts such as including adaptation and resilience (A&R) measures in infrastructure projects and undertaking projects that specifically address A&R are often perceived as public sector responsibilities. But as climate risks grow in scale, complexity, and financial impact, it becomes clear that A&R efforts must be a shared mandate across governments, infrastructure operators, financiers and investors. All of these actors face their own challenges, which must be overcome in order to mobilize the scale of investment required for greenfield projects and retrofits alike. Having in place clear definitions of climate risk and A&R, aligned incentives, adaptive financing frameworks, and a coordinated approach will be critical.

A&R investments in infrastructure fall into three main groups, each with distinct financing needs and opportunities:

1. **Public good measures:** Projects that are essential for protecting whole economies and communities but do not offer a direct financial return to private investors.
2. **Measures with direct financial benefits for private investors:** This includes measures that deliver clear financial benefits for operators and utility companies, making them suitable for private financing.
3. **High-cost, multi-benefit measures with shared financial benefits:** Such projects come with significant financial and socioeconomic value. However, due to their scale and complexity, they require substantial upfront investment, longer payback periods and are typically financed through PPP structures.

This report focuses on the second and third categories, where private investment can play a role in unlocking action at scale for A&R measures.

Part I — of the report demonstrates the business case for investing in resilience and identifies the key gaps faced by stakeholders.

Part II — of the report puts hard numbers around the A&R value, quantifying illustrative positive returns on A&R investments by modeling the effects of various A&R measures on three existing infrastructure assets in Brazil.

Part III — of the report highlights ways to access the A&R investment opportunities by overcoming the challenges that have constrained investment to date. It concludes with recommendations for all stakeholders on ways to accelerate the pace at which A&R considerations become mainstreamed in infrastructure-related policies, strategies, development, and investment going forward.

PART 1

The case for investing in infrastructure adaptation and resilience

The estimated average annual loss due to extreme weather events in infrastructure and buildings exceeds USD 700 billion, equivalent to around one-seventh of annual global GDP growth in 2021–2022.[3]

Although emerging markets and developing economies (EMDEs) hold only one-third of the value at risk, they bear more than half of global disaster losses.[4] Rapid urbanization in hazard-prone areas, climate-sensitive geographies, and socioeconomic fragility amplify vulnerability, while constrained fiscal space limits governments' ability to incentivize adaptation, invest in resilience, or finance rapid recovery.

The impact of climate risk on infrastructure already costs these countries an estimated USD 390 billion annually in financial and economic losses. This is equivalent to 1–2 percent of GDP and is projected to escalate as climate hazards intensify.[5] In fact, without action, infrastructure losses could increase by 12–22 percent in middle-income countries and by up to 33 percent in low-income countries by 2100.[6]

Because infrastructure systems are deeply interconnected, failures in one sector often cascade into others, escalating repair costs, constraining productivity, undermining fiscal stability, and eroding investor confidence, while also disrupting essential services, livelihoods, and mobility. Examples of these cascading damages are depicted in Figure 1.1.

Figure 1.1

Evidence from around the world: Impacts on infrastructure stakeholders when A&R measures are overlooked or underinvested

United States

The 2018 Camp Fire in California illustrates how deferred maintenance on aging infrastructure can catastrophically amplify the destructive potential of climate-intensified hazards. It was sparked by the failure of the 97-year-old Caribou-Palermo transmission line, owned by Pacific Gas & Electric, which had not been carefully inspected since 2001. The fire killed 85 people, destroyed nearly 14,000 homes, and generated USD 16.5 billion in liabilities that forced PG&E into bankruptcy. PG&E had deferred maintenance for years despite internal engineering reports documenting severe wear on critical infrastructure, regulators publicly highlighting wildfire risks from aging equipment, and California's regulatory framework explicitly allowing recovery of wildfire mitigation costs through customer rates.[7]

Brazil

The January 2019 collapse of Vale S.A.'s mining tailings dam in Minas Gerais during heavy seasonal rains resulted in the deaths of 270 people and extensive environmental damage, including 300 km of river contamination. A 2018 engineering audit had warned of saturation risks and mandated stability upgrades, which were not undertaken. Vale's mining concession was temporarily suspended over the affected complex and several dams, while the company had to pay more than USD 7 billion in fines and decided to sell assets. Executives, including the CEO, faced criminal prosecution. Following remediation, operations resumed under stricter federal oversight.[8]

Germany

In 2021, extreme rainfall overwhelmed critical infrastructure—roads, bridges, railways, utilities—that had been designed to historical climate standards, revealing regulatory and institutional gaps in upgrading infrastructure resilience to meet emerging climate risks. These dynamics mirror a wider pattern: infrastructure failures are often fiscal and regulatory failures to act on known risks, not engineering unknowns.[9]

Indonesia

In late 2025, heavy monsoon rains triggered flash floods and landslides across Sumatra, resulting in more than 1,000 deaths, the displacement of millions, and the destruction of infrastructure due to deforestation, unchecked riverbank development, and weak enforcement of spatial planning laws. Reduced budgets for disaster agencies amid central efficiency policies led to slow responses, poor coordination, and inadequate early warning.[10]

Why invest in A&R?

> When A&R measures are prioritized based on benefit-cost ratios, avoided losses, and long-term value, investing in climate-resilient infrastructure becomes a financially sound strategy.

Well-targeted A&R investments can mitigate damage and downtime from extreme weather events. They can reduce maintenance costs, extend asset lifetimes, and unlock significant co-benefits: protecting lives, preserving jobs, sustaining access to essential services, and strengthening economic competitiveness. Infrastructure built today will define development pathways for decades; embedding resilience into planning, design, construction, and operations is essential to avoid locking in systemic vulnerability.

This is particularly critical in EMDEs, where climate vulnerability is high, and where most of the infrastructure that will exist by 2050 has yet to be built. For instance, while upgrading Brazil's roads to resilient standards by 2050 would cost USD 19.26 billion, it would yield USD 40.59 billion in avoided losses—essentially doubling the return on the investment. Shifting from reactive to routine maintenance would lower long-term costs by up to 40 percent.[11]

For governments, A&R solutions deliver avoided climate-related losses, induced economic development, and social and environmental co-benefits. Since infrastructure underpins economic activity and employment, A&R investments that reduce service disruptions directly protect jobs and productivity, in addition to enabling delivery on national adaptation commitments.[12]

Investors and financiers also have sound financial reasons to invest in climate-resilient upgrades, such as reduced credit risk and fiduciary pressure, as well as compliance with regulatory disclosures. For multilateral development banks (MDBs) and development finance institutions (DFIs) such efforts contribute to their job creation, sustainable development and economic growth mandates. Table 1.1 summarizes the value of investing in A&R for the key stakeholders in the ecosystem.

Table 1.1

Key players in the infrastructure ecosystem and the value of investing in A&R

Governments & Regulators	Infrastructure Operators	Financiers & Investors
• Reduced fiscal liabilities from extreme weather events • Lower public spending on emergency response and reconstruction • Job protection and productivity through fewer service disruptions • Stabilized insurance markets in climate-exposed regions • Higher value for money from longer-lived public assets • Progress on national adaptation commitments	• Reduced repair, replacement, and penalty costs • More stable revenues and fewer service interruptions • Extended asset life and improved lifecycle performance • Improved insurability and access to finance • Lower operational and safety risks	• Reduced credit and default risk • More stable long-term cash flows • Preserved asset value under volatile climate conditions • Alignment with regulatory and fiduciary climate-risk requirements • Stronger long-horizon portfolio resilience

The A&R finance challenge

Recent assessments show that A&R needs for EMDEs are rising rapidly, but A&R efforts remain significantly underfunded. While needs are projected to reach about USD 310–365 billion per year by 2035, tracked international public adaptation finance remains only in the tens of billions annually.[13] This leaves a financing gap so large that public funding alone cannot close. Doing so requires mobilizing private capital, specifically for efforts where commercial returns are possible. But mobilizing private capital requires clearly demonstrated evidence that well-selected A&R measures can yield net financial gains through avoided revenue losses and reduced climate-related costs. It also requires a better understanding of the challenges faced by all stakeholders in the infrastructure ecosystem and clear pathways to overcome the challenges.

Box 1.1. Barriers to A&R investment

Infrastructure stakeholders face challenges across four areas. Combined, these challenges constrain A&R investment.

- Lack of climate risk data to understand and quantify future risks and opportunities.
- Misaligned regulatory and financial incentives that do not reward resilience.
- Limited access to capital tied to improved resilience.
- Lack of coordination across the infrastructure ecosystem to drive systemic change.

Infrastructure assets owners and operators

Even though there are strong financial incentives to invest in A&R—protecting revenues, reducing repair and penalty costs, extending asset life, increasing access to capital, and improving insurability—infrastructure owners and operators routinely underinvest.

One key challenge is that engineering teams typically rely on historical standards and development codes, which often do not account for future climate projections. Finance teams evaluate projects using net present value (NPV) and internal rate of return (IRR) models that account for capital expenditures (CAPEX) and operating expenditures (OPEX); however, these models do not typically capture any avoided future losses associated with A&R measures. The result is that A&R measures, which require upfront capital to avoid uncertain future losses, tend to lose out to investments with clearer, shorter-term payoffs.

Several factors create challenges in translating climate risk information into financially sound investment decisions, including lack of data, limited technical understanding, and a general disconnect among engineering, environmental, and financial teams.[14] For publicly owned utilities with limited fiscal space and restricted capital market access, these gaps are compounded by stark financing constraints.

Misaligned regulatory incentives exacerbate operators' underinvestment. EMDEs often lack robust regulations requiring climate risk assessments and A&R measures in PPP or concession contracts. Requirements for service restoration following extreme events can also be insufficient. In addition, procurement processes typically prioritize price over quality and resilience. Even where regulatory frameworks theoretically allow tariff recovery of prudent A&R costs, the absence of clear guidance on what constitutes A&R creates investment uncertainty.

Governments and regulators

Governments have a critical role to play in addressing these issues. They can boost public finance for A&R measures that do not attract private financing but protect economies and communities. They can also encourage private investment by strengthening the enabling environment.

Yet governments systematically underinvest in A&R, despite strong incentives to act: contingent fiscal liabilities from climate-related disasters continue to mount, with the global cost of inaction estimated at USD 1.27 trillion between 2022 and 2100.[15] And in many countries, the insurance market in climate-exposed regions is eroding, compounding the investment challenges.

Issues include insufficient data, limited capacity to assess climate risks quantify A&R benefits, and a lack of detailed infrastructure inventories and local climate projections. Competing budget priorities and short political cycles hinder long-term investment, while siloed mandates block coordinated planning. Subnational governments face financial constraints, and PPP contracts often shift climate risks back to public budgets, disincentivizing private sector A&R investment.

Financiers and Investors

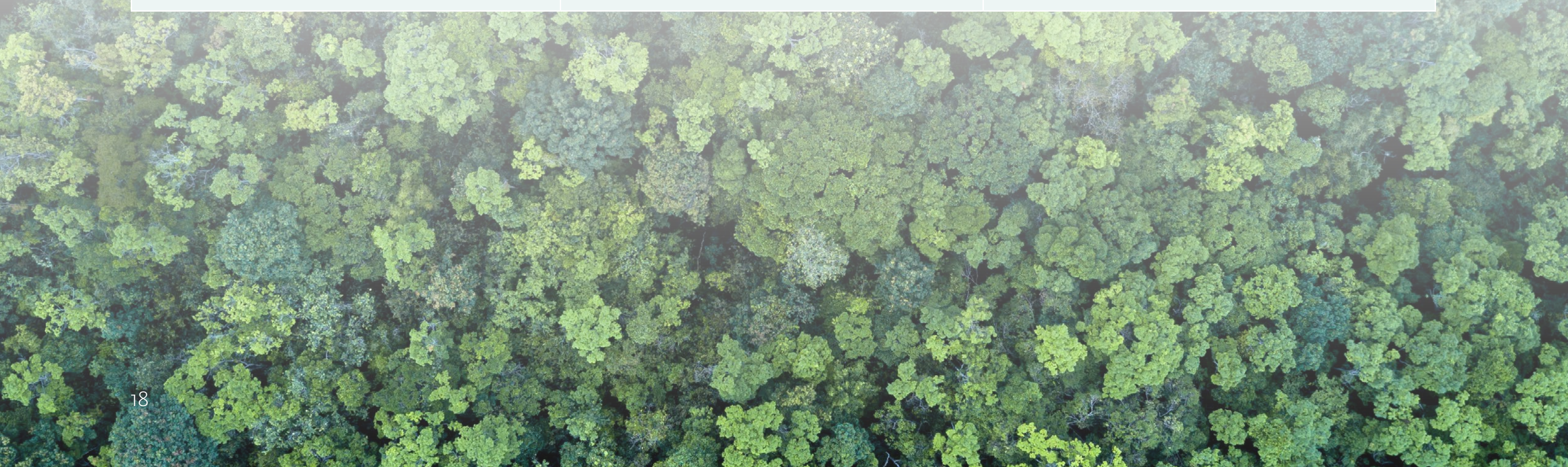
Investors and financial institutions typically do not incorporate physical climate risk into investment decisions, limiting their ability to value the benefits of A&R measures. In many cases, they also lack the metrics needed to bridge short payback horizons and longer-term value creation, or to support financing structures that appropriately reward resilience.

Table 1.2 summarizes the financing challenges for government and regulators, infrastructure operators, and investors.

Table 1.2

Challenges faced by key players in the A&R financing ecosystem

Governments & Regulators	Infrastructure Operators	Financiers & Investors
• Limited infrastructure data and localized climate projections • Budget constraints and competing priorities • Short political cycles vs. long payback periods • Financial limitations of subnational governments • Siloed institutional mandates • Climate risk transferred back to public budgets via PPP force-majeure clauses	• Engineering standards based on historical climate conditions • Difficulty quantifying and monetizing avoided future losses • Upfront capital costs competing with short-term investments • Misalignment between engineering, environmental, and finance teams • Limited fiscal space and capital market access, especially public utilities • Regulatory uncertainty over cost recovery for A&R	• Difficulty translating long-term, probabilistic climate risk into financial metrics • Short payback horizons that discount future avoided losses • Credit risk models based on historical data • Lack of standardized A&R metrics • Exit valuations that do not reward resilience • Policy and regulatory uncertainty in EMDEs



PART 2

Quantifying the returns on A&R for three Brazilian infrastructure assets

This section of the report explores how critical infrastructure stakeholders can assess their exposure to climate-related risks and measure the tangible value of investing in A&R measures. For the analysis, we turn to Brazil, an EMDE with strong data availability and a mature infrastructure investment landscape, supported by a complex enabling regulatory framework. A deep dive into the A&R opportunities here offers highly transferable lessons to other EMDEs. Like many other developing countries, it faces diverse physical climate risks across regions, while having a range of financial and technical capabilities at its disposal.

The analysis focuses on three climate-vulnerable and economically important sectors—transmission and distribution (T&D), water supply and sanitation, and roads—and an existing, highly important asset in each sector that has already experienced impacts from various climate hazards and faces high future climate exposure.

About the methodology

Case studies on each of the three assets were developed based on publicly available data and financial information. The analysis estimates physical damage, service-interruption costs, and avoided losses to assess the financial and operational performance of resilience investments through net asset value (NAV) and internal rate of return (IRR) metrics under various scenarios.[16]

The methodology combines climate hazard modeling, asset-level exposure and vulnerability analysis, and the financial valuation of avoided losses to assess the cost-effectiveness and wider socio-economic benefits of adaptation measures. Additional climate risk analysis made use of AXA Climate's Altitude tool.

Box 2.1.

About AXA Climate's Altitude tool

Altitude, AXA Climate's science-based digital platform, supports decision-makers in understanding and integrating climate and nature-related risks into their business strategy. Built on science and robust data, including the latest IPCC scenarios and proprietary downscaled datasets, the platform provides granular, site-level risk quantification tailored to each company's local context and sector.
Altitude assesses medium- and long-term physical risks facing companies' sites and operations and translates these findings into actionable adaptation and resilience pathways. Combined with a dedicated advisory service, it accompanies organizations across the full climate risk management journey, from measuring operational impacts to designing and evaluating adaptation strategies.

While the case studies focused on assessing the costs and benefits of A&R measures for individual assets, the same approach can be scaled up and applied across an entire portfolio of assets. This can help investors, operators, and regulators identify which assets and A&R measures should be prioritized for investment. The analysis follows a four-step framework:

1. **Data gathering and materiality assessment:** Global and regional climate hazard models combined with asset-level data identify the hazards that pose material risk to the asset under baseline and future climate scenarios.
2. **Identifying A&R options:** A range of A&R measures are evaluated for cost, effectiveness, and benefit-cost ratio (BCR), allowing prioritization of those with the highest financial and operational impact.
3. **Economic and financial analysis of adaptation investments:** Selected measures are tested under different financing scenarios to assess their impact on NAV and IRR, with sensitivity analysis on loan tenor and interest rate.
4. **Analysis of socioeconomic co-benefits:** The wider economic value of adaptation is quantified, including avoided service disruption days, value added preserved, and continuity of jobs and economic activity.

Combined, these case studies offer evidence that investing in A&R measures not only protects infrastructure, but also provides long-term cash flows, supports regulatory compliance, and ensures financial sustainability against climate risks. For an overview of the innovative methodology used in the analysis see Box 2.2, and for more details see Appendix 3.

How to use the findings

For operators and concessionaires: Incorporate the most cost-efficient measures into medium-term CAPEX planning to preserve and enhance asset value, then commission engineering analysis and local cost validation to confirm feasibility.

For investors and lenders: Use the relative ranking of measures to prioritize actions for further due diligence testing and to inform optimal financing mechanisms. High future risk could signal that the lender/investor should require the purchase of additional insurance.

For regulators and policymakers: Identify high-benefit but lower-commercial-return measures that may justify public cofinancing or tariff incentives, ensuring that resilience investments with strong social spillovers can proceed.

Box 2.2.

Connecting the case study methodology to PCRAM

The Physical Climate Risk Appraisal Methodology (PCRAM) is a well-accepted framework for conducting in-depth climate risk assessments for infrastructure. It requires extensive local data and customized analysis for each site. In contrast, the methodology developed by Scientific Climate Ratings for this report offers a streamlined approach for faster screening across multiple assets, which is easily replicated and can be used by infrastructure operators' finance and technical teams.

While both can be applied to individual assets or portfolios, PCRAM is more resource-intensive while this methodology enables quicker and broader analysis. The two are complementary: organizations can first use the approach showcased in this report to identify priorities and then apply PCRAM for deeper analysis of selected assets.

This methodology draws on Oxford Economics' climate scenarios, which are informed by the IPCC Representative Concentration Pathways (RCPs) and Shared Socioeconomic Pathways (SSPs) scenarios. Oxford's modeling is based on the Network for Greening the Financial System (NGFS) scenarios, which combine these same RCP–SSP pathways. The analysis looked at two main climate scenarios:

- **Intermediate-emissions scenario:** The baseline reference scenario modeled by Oxford Economics under current policies is broadly consistent with RCP4.5/ SSP2-4.5 warming temperatures of 2.9°C by 2100.
- **High-emissions scenario:** This climate catastrophe scenario is aligned with RCP8.5/SSP5-8.5, a pessimistic high-emissions pathway associated with warming temperatures of 4.8°C by 2100.

Some disclaimers

Scope: A&R measures were selected by partner engineering companies, which assessed implementation costs supplemented by the ClimaTech database—which catalogs the most relevant and effective adaptation options for various infrastructure asset classes exposed to storms, wildfires, and floods—where local cost data was not available. The effectiveness of the measures was evaluated using the ClimaTech database. Socioeconomic benefit ratios were sourced from the EXIOBASE Environmentally Extended Input-Output Table. The analysis uses simplified assumptions and hypothetical data, as inputs were not collected directly from operators. Existing risk-mitigating measures already implemented by operators are excluded but would further reduce projected losses.[17]

Interpretation: Results are illustrative and indicative, not precise forecasts. The modeling excludes compounding factors such as land-use change, cascading infrastructure failures, and current adaptation measures that could influence real-world outcomes.

Uncertainty: Climate and financial projections carry inherent uncertainty from climate variability (natural short-term fluctuations), model limitations (simplified representations of physical processes), and scenario divergence (SSP2-4.5 intermediate emissions vs. SSP5-8.5 high emissions).[18] The IPCC currently positions SSP2-4.5 as an intermediate emissions trajectory consistent with current policies and Paris Agreement commitments.

Financial metrics: IRR calculations reflect only avoided climate losses and investment costs for each adaptation measure, excluding project revenues, operating costs, and debt.They are not comparable to full project IRRs.

Transmission and distribution

Electricity grids face acute risks, mainly from storms, floods, and wildfires, as well as chronic stress from extreme heat. These hazards compromise asset integrity, increase outage frequency and duration, and drive up operating and maintenance costs. Globally, utilities are investing in hardening measures such as undergrounding, vegetation management, firebreaks, and grid automation. Yet, regulatory frameworks often lag behind, with tariff transfer for cost-recovery of A&R measures not always available, and performance metrics focused on frequent small outages rather than on rare but catastrophic events.

The Brazil context

Brazil's electricity grid is one of the world's largest and most interconnected systems, spanning about 180,000 km and reaching 98 percent of the population.[19] However, the prevalence of above-ground, overhead configuration creates vulnerability to floods, storms, extreme heat, and wildfires. Climate events accounted for 43 percent of all power outages between 2013 and 2023, imposing significant reconstruction costs and broader socioeconomic losses.[20] The Intergovernmental Panel on Climate Change (IPCC) projects more frequent and intense events, elevating failure risks that cascade into other sectors and impacts.[21]

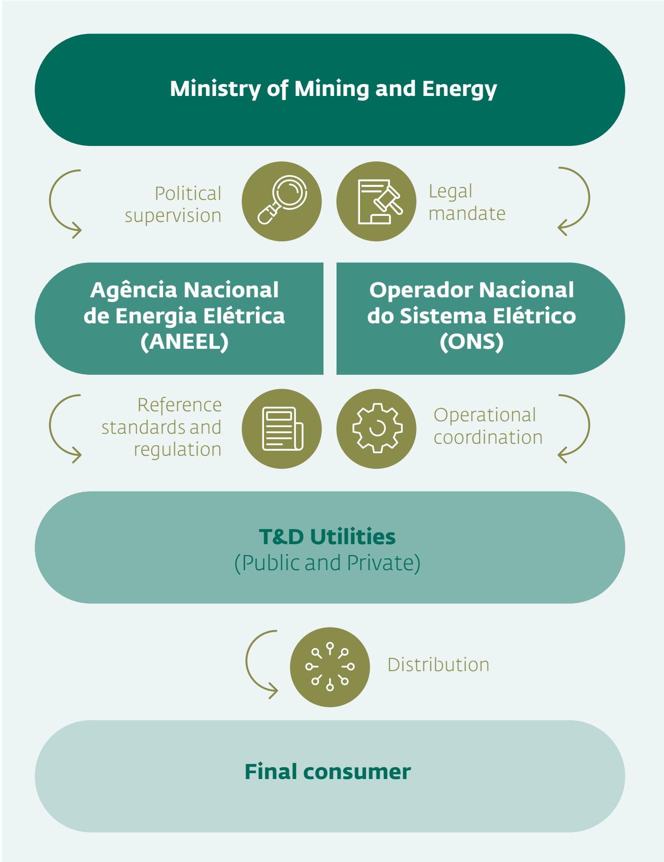
In fact, the World Bank estimates that 36.2 billion Brazilian reais (USD 6.24 billion) in additional CAPEX will be needed by 2050 to ensure that Brazil has a resilient, decarbonized power system.[22]

Brazil's T&D sector operates through state-owned and private concessionaires. The federal government awards transmission through long-term concessions coordinated with the national electric system operator (ONS). Concessionaires earn regulated revenues based on asset availability, facing payment reductions for outages.[23] Distribution operates as a regulated monopoly, with Agência Nacional de Energia Elétrica (ANEEL) regulating tariffs, approving investment plans, and setting performance standards.

In 2024, storms in the São Paulo metropolitan area left 3.1 million households without electricity for five days.[24] Following this event and other major floods across Rio Grande do Sul in the same year, ANEEL began reassessing resilience requirements in concession frameworks. Brazil's T&D operators are responding with significant investments, driven by the reality that more than three-quarters of electricity sector capital comes from the private sector—and public budgets are unlikely to expand in the near term.[25] Major operators are deploying substantial resources for resilience and modernization.

Figure 2.1

Key stakeholders: Brazil's T&D sector



Box 2.3.

Recent A&R investments and initiatives by Brazil's T&D operators

Grupo Equatorial raised USD 250 million from IFC for low-carbon and resilient distribution upgrades in low-income regions, while engaging ANEEL on clearer cost-recovery pathways.

Eletrobras uses AI-enabled grid intelligence to detect wildfire and storm risks before they cause outages.

Enel São Paulo committed 24 billion Brazilian reais (USD 4.1 billion) for the period 2025–27 for network strengthening.

Neoenergia pledged 26 billion Brazilian reais (USD 4.48 billion) between the years 2024 and 2027 for resilience and automation.

CASE

Transmission line in the State of Mato Grosso

ASSET OVERVIEW

Asset

+1000 km 500 kV overhead high-voltage, double circuit transmission line connecting two substations through three consecutive segments in the State of Mato Grosso, Brazil. As of 2024, the line provides electricity to 8.8 million people and supports the economy of Mato Grosso, one of Brazil's largest producers of soy, corn, cotton, and cattle

Ownership

Privately operated through a 2012 awarded ANEEL-run concession valid until 2042.

Asset financing

Private equity and long-term debt from BNDES, Brazil's development bank.

FINDINGS AT-A-GLANCE

The do-nothing approach: Negative impacts from climate vulnerabilities

Without A&R, cumulative climate-related losses to the transmission line are projected to reach by 2042:

30%
of NAV under an intermediate emissions scenario

30.3%
of NAV under a high-emissions scenario

Most impacts are attributable to wildfires:

95%
of total losses in direct damage

5%
of losses related to asset disruption

Prolonged service disruptions can trigger broader system impacts. While not quantified in this study, these include:

- **Reduced power availability** for households and water-intensive industries
- **Economic losses** linked to curtailed supply
- **Potential regulatory consequences** such as reductions or non-payment of availability-based revenues under concession rules

FINDINGS AT-A-GLANCE (CONTINUED)

The do-something approach: Returns on A&R investments

Under a high-emissions scenario, with A&R, transmission line losses decrease dramatically, to 7.6 percent of NAV, as compared with 30.3 percent of NAV without.

Wildfire protection measures can significantly reduce damage, with a limited cost of 3 percent of NAV.

Installing firebreaks yields IRRs ranging from 445 to 886 percent, depending on the financing structure: The high IRR stems directly from the fact that the estimated cost is quite low compared to the efficiency of the measure and the losses that firebreaks can prevent.

Socioeconomic co-benefits

Without A&R, climate hazards are estimated to cause almost 11 days of service disruption per year on average. These decline to just 1.6 days with selected A&R measures.

Given the importance of the line to Mato Grosso's economy and its residents' well-being, A&R has a substantial positive impact on preserving economic activity and jobs.

Step 1: Data gathering and materiality assessment

By mid-twenty-first century, wildfires, floods, and storms will pose high risks to the transmission line, with each component showing different levels of vulnerability:[26]

Wildfires are projected to pose a high risk to the full length of the transmission line.

Flooding threatens substations and is projected to impact over half of the transmission line.

Storms show low risk, although historical data suggests higher impact specifically due to downbursts, which are not captured by the climate risk assessment.[27]

Without A&R, the three modeled hazards could erode around 30 percent of NAV under both intermediate-emissions and high-emissions scenarios over 2026-2042 through a combination of direct physical damage to assets and revenue losses from service disruptions. Wildfires are the main driver.

Table 2.1

Climate risk assumptions for the transmission line

Hazards	Wildfires, floods, storms
CAPEX	Not disclosed by the operator. However, comparable 500 kV transmission and substation projects from the same auction and regulatory benchmarks indicate capital costs in the range of USD 0.8–1.2 million per km. The CAPEX is thus estimated to be USD 800-1200 million.
Revenue	Permitted annual revenue (RAP) ranged between 239 million and 288 million Brazilian reais, 2021–2024 (USD 41.2-49.7 million).
Vulnerability	The study used damage functions—a quantitative curve that shows how an asset's losses increase as a hazard becomes more severe—to translate hazard intensity into expected physical and revenue impacts for this asset.[28]
Asset Lifetime	17 years (2026-2042 when the concession ends)
Discount Rate[29]	Intermediate emissions scenario ≈ 20.1 percent High-emissions scenario ≈ 20.2 percent[30]
Interest Rate[31]	13.17 percent for a hypothetical, 10-year, local currency loan
NAV definition	Discounted free cash flow to equity (FCFE) over the concession period (2026–2042), computed from regulated annual revenues scaled by Scientific Infra and Private Assets (SIPA) utility benchmarks, with fixed asset amounts derived from replacement supply capacity benchmarks from comparable 500 kV transmission projects.

Step 2: Identifying the A&R options

A&R measures analyzed: Firebreaks, vegetation management, fireproof building materials, vegetation buffers, elevation, structural reinforcement, and structural strengthening.

Various A&R measures were evaluated based on their ability to address the material hazards and their estimated costs and benefits. The analysis revealed that the greatest value could be found in addressing wildfire vulnerabilities:

- Measures such as vegetation management and firebreaks prevent losses equivalent to 18-25.7 percent of NAV. This comes by avoiding direct physical damage to transmission infrastructure and, by reducing revenue losses from wildfire-driven service outages. The measures remain cost-efficient, with benefit to cost ratios well above 1.
- A&R measures for floods and storms provide more modest avoided losses (<1 percent of NAV), given that the modeled climate risks are very low. So, these measures did not move forward into the financial analysis.
- Firebreaks are the clear frontrunner in terms of financial viability and potential to reduce hazard-related losses. When accounting for firebreaks' adaptation costs of around 3 percent of NAV, overall losses are cut by up to 22.7 percentage points under a high-emissions scenario.

Table 2.2 shows the full set of measures considered, along with their cost and benefit-cost ratio (BCR).

Table 2.2

A&R options and estimated costs and benefits for the transmission line

Hazard	A&RMeasure	Measure cost (% of asset CAPEX)	Measure cost (% of NAV)	Benefit - Avoided Losses (% of NAV)		Benefit Cost Ratio (BCR) over lifecycle	Description
				Intermediate emissions scenario	High-emissions scenario		
Wildfire	Firebreaks ✓	0.5	3.2	25.5	25.7	8.0:1	Clear vegetation-free buffer zones to block wildfire spread
Wildfire	Vegetation management	0.7	5.1	18	18.2	3.5:1	Fire-resistant landscaping and low-maintenance buffers
Wildfire	Fireproof building materials	9.8	55.5	9	9.1	<1:1	Use of fire-resistant coatings, steel, or concrete
Storms	Vegetation buffers	0.5	0.3	<1	<1	<1:1	Maintain vegetation to reduce storm debris risks
Floods	Elevation	2.7	19.0	<1	<1	<1:1	Raise substations and pylons above flood levels
Floods	Structural reinforcement	2.5	17.6	<1	<1	<1:1	Strengthen pylon foundations and substation structures
Storms	Structural strengthening	1.1	7.7	<1	<1	<1:1	Wind-resistant retrofits and reinforced foundations

The cost of each measure is expressed both in terms of % of total asset CAPEX and in % of impact on final net asset value, considering an internal cashflow of the measure cost. The benefit-to-cost ratio is presented as an internal cashflow of the measure cost, for a high-emissions scenario.

Step 3: Economic and financial analysis of A&R strategies

A&R measures are typically far more cost-effective when integrated by design at the planning stage, avoiding expensive retrofits later. However, in practice, such early investments may not present a compelling business case for concessionaires, as they can affect project competitiveness and rely on uncertain future climate projections. For this reason, the financial analysis modeled two realistic alternatives to capture how adaptation could be financed once assets are already operational:

1. Internal cashflow payment in 2026 financed from the operator's own resources
2. 10-year loan (2026–2036)

The findings revealed that both options proved worthwhile, with a slight advantage for the 10-year loan, which prevents 0.2 percent more losses than the internal cashflow payment (table 2.3).

Table 2.3

Financing scenarios for the firebreaks measure under a high-emissions scenario

Financing option	Total losses (% of NAV)	Avoided loss (% of NAV)	A&R cost (% of NAV)	Benefit to Cost Ratio
10-year loan ✓	7.6	25.7	3.0	8.6
Internal cashflow	7.8	25.7	3.2	7.9

Following on these findings, a sensitivity analysis was undertaken.[32] The sensitivity analysis showed that, depending on loan maturity and interest rate:

Firebreaks achieve internal rates of return (IRR) ranging from 445-886 percent.[33]

Longer loan maturities dramatically improve returns by spreading repayment while avoided-loss benefits compound.

Interest rate variations have minimal impact.

The findings confirm that when financing climate retrofits, securing longer loan tenors matters far more than marginal rate reductions.

Figure 2.2

Findings from the analysis of A&R measures for a Mato Grosso transmission line: visualized in 5 charts

Figure 2.2.1

Quantifying the value of A&R measures to address 3 major hazards[34]

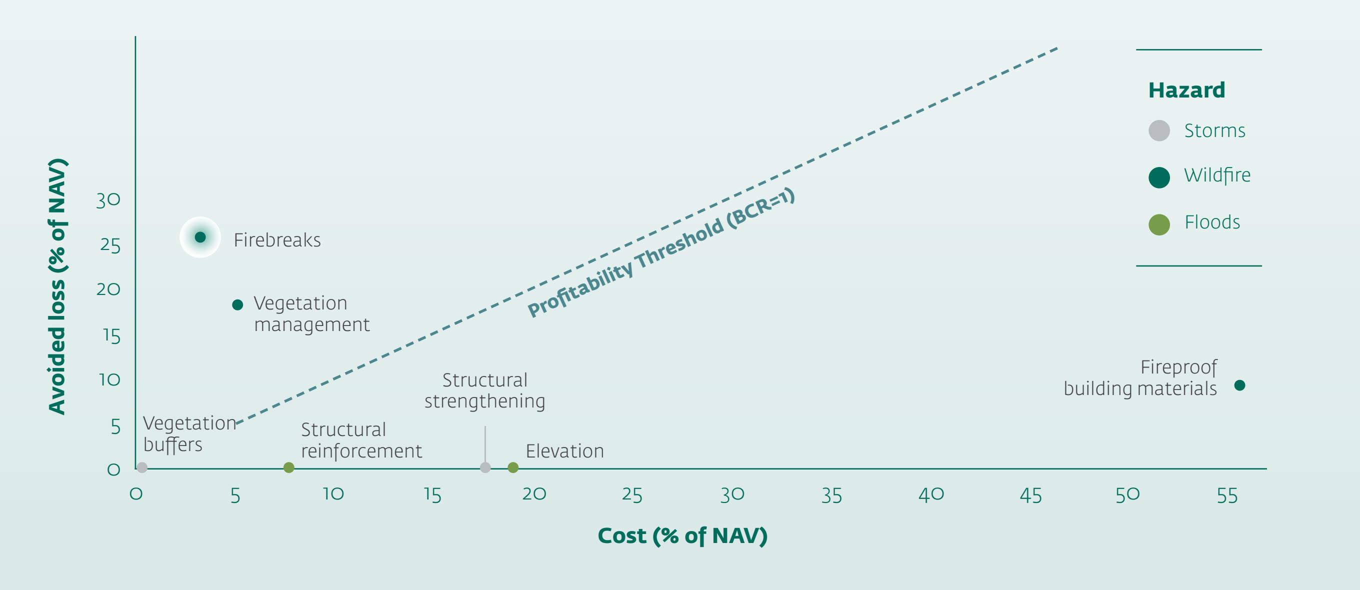


Figure 2.2.2

Ranking A&R measures to address climate risks from highest to lowest benefit-cost ratio

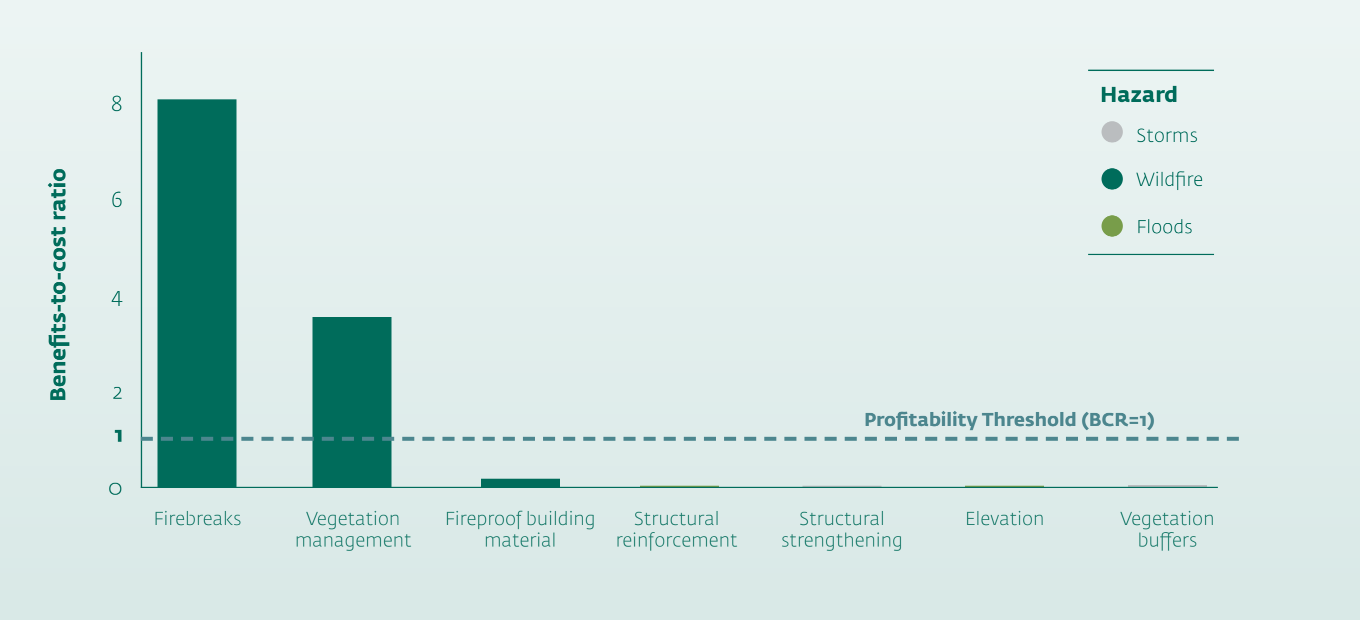


Figure 2.2.3

Comparing the financial impacts of climate hazards with and without A&R measures under a high-emissions scenario, financed by a 10-year loan

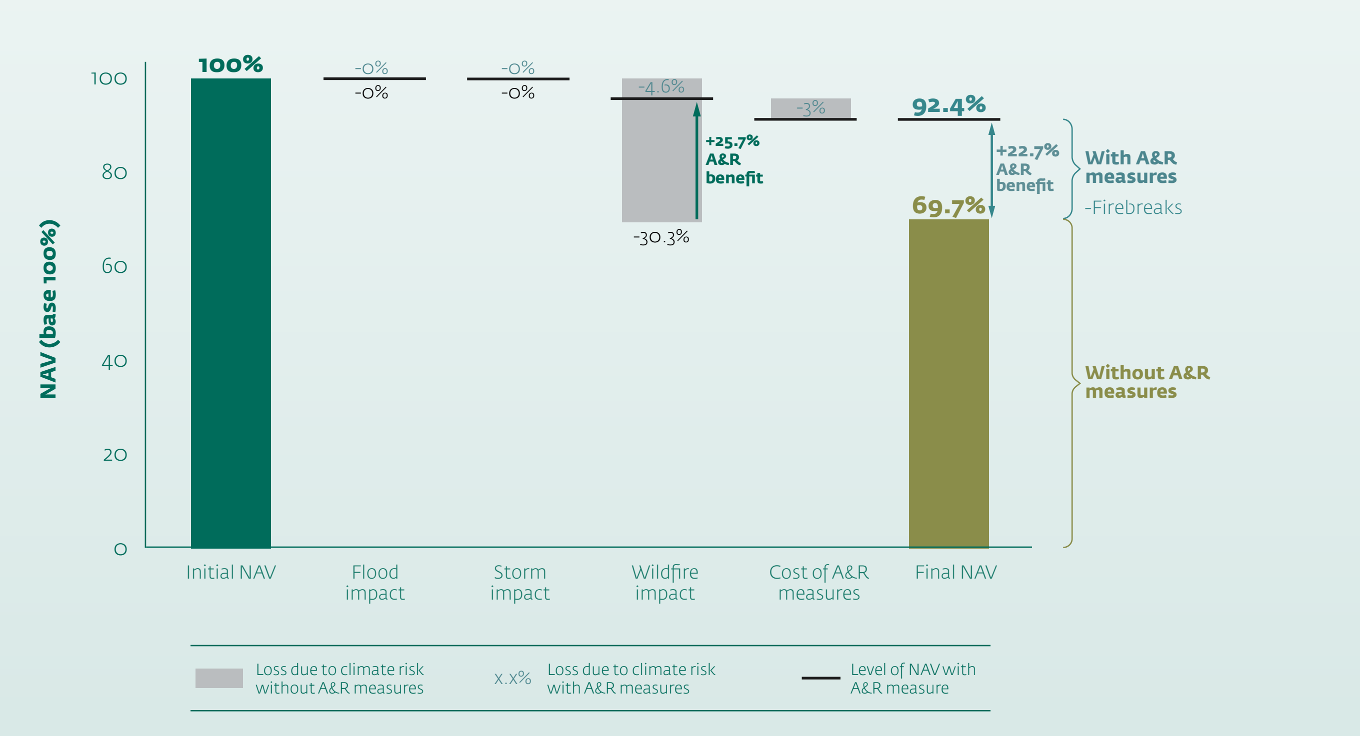


Figure 2.2.4

Identifying the optimal financing options for firebreaks to address wildfire impacts under a high-emissions scenario

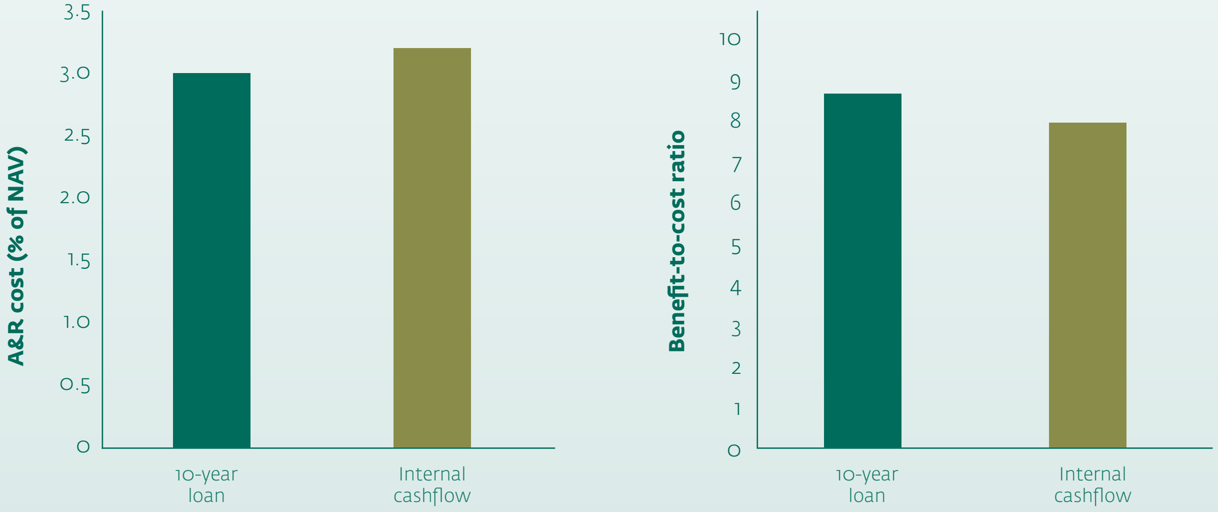
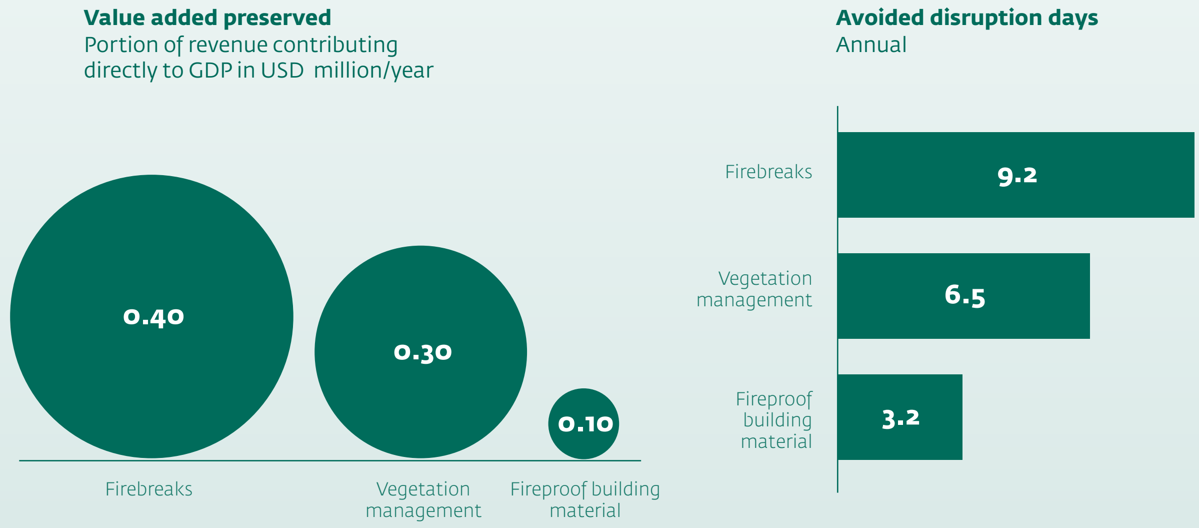


Figure 2.2.5

Quantifying the socioeconomic value of A&R measures to address wildfire hazards faced by the transmission line[35]



Step 4: Analysis of socioeconomic benefits

The transmission line serves roughly 8.8 million people, underpinning about USD 308 million in daily economic activity, and supplies Mato Grosso's economy—one of Brazil's largest producers of soy, corn, cotton and cattle.[36] Without A&R, climate-related hazards, especially wildfire, lead to approximately 10.8 days of service disruption per year.[37] With the addition of firebreaks:

Service disruptions reduce to about 1.6 days, avoiding roughly 9.2 days of outages annually, representing approximately an 85 percent reduction.

About USD 2.8 billion in annual economic activity—representing 1.1 percent of annual State GDP—is sustained due to improved system resilience, alongside avoided emergency maintenance and improved fiscal stability: While this figure does not represent GDP directly preserved, the reduction in outage duration supports direct and indirect jobs across the area of influence of the asset and the continuity of economic activity. Qualitatively, the socioeconomic co-benefits of the selected adaptation measures are significant. However, quantifying these benefits is complex and can show a more limited impact depending on the model used. Since socioeconomic benefits represent public goods that extend beyond private A&R financial returns, governments should supplement financial models with social cost-benefit analysis that captures impacts like avoided health costs, maintained employment, and protection of vulnerable populations.

Insights from the analysis

- **Firebreaks are a low-cost, high-return A&R measure:** Financing through a 10-year loan is optimal, enabling the preservation of up to 22.7 percentage points of asset value.
- **Use of fireproof building materials** comes with moderate- to high- upfront costs relative to other adaptation options. However, it does deliver strong avoided-loss benefits, making it a potential candidate for targeted public/private co-financing.
- **Tariffs could support A&R investments.** Under Brazil's regulatory model, certain costs associated with reliability improvements, such as repairing transmission and distribution infrastructure after extreme weather events, can be passed on to consumers through tariff adjustments, subject to ANEEL's review.
- **Even when not fully recoverable through regulated tariffs or adjusted availability payments,** resilience upgrades reduce outage risks and stabilize cash flows and can enable increased access to insurance and improve credit profiles, lowering the perceived cost of capital for concessionaires and investors.
- **Analytical findings support decision making.** Findings on NPV, IRR, BCR, and payback can open up a dialogue with regulators on tariff recognition. They also can be used with investors and financiers to showcase how asset value can be preserved and increased, by implementing A&R measures. The findings also establish a baseline that can be refined through site-specific data.
- **Recent extreme weather-related outages** in Brazil have led regulators and authorities to open investigations and consider penalties and potential concession revocation for a distribution concession, highlighting the high stakes of insufficient network resilience.[38]

Water supply and sanitation

Globally, the water and sanitation sector is significantly exposed to extreme droughts and floods. Typically, A&R strategies for water systems include improving water-use efficiency, increasing wastewater treatment and reuse, reducing non-revenue water, deploying nature-based solutions, and strengthening storage, watershed management, and early warning systems. In many emerging markets, however, tariff structures remain politically sensitive and frequently fail to recover even the basic costs of water service provision, let alone the additional costs for A&R measures. System-level resilience interventions also include building new water sources — such as desalination plants, which, while presenting significant energy demands, can be a lifeline for water-intensive industries like agriculture and mining when drought conditions compromise water availability. Tariffs must be well designed. Otherwise, they could undermine investment in resilience by discouraging conservation or the additional CAPEX needed for new water treatment or production facilities.

The Brazil context

The water and sanitation sector is a priority for Brazil. It aims to increase water access from 83 percent to 99 percent and sewage collection from 60 percent to 90 percent by 2033, requiring an estimated 500–700 billion Brazilian reais (USD 86.2–120.7 billion) in new investment.[39]

Achieving access goals could be a challenge, however, given that drought-flood cycles are expected to intensify in the coming years. For instance, most water utilities rely on large reservoirs that are vulnerable to drought and sedimentation. Heavy precipitation frequently overwhelms and contaminates drainage and treatment infrastructure, and interrupting service.

Flood-related damage to electricity lines cascades into water outages because pumping and treatment both rely on power. These risks are compounded by aging assets, informal settlements, and inadequate maintenance, which tends to happen more in rural areas.

Revenue models and financing paths for A&R differ markedly. Public utilities, which serve the majority of water users globally, primarily depend on tariff revenues and budget transfers, and remain the principal vehicle for delivering resilient water services, particularly in low-income areas where tariff increases are not viable and A&R investments require direct public funding. Private concessionaires, by contrast, may receive availability payments to supplement tariffs in contexts of limited affordability, and where tariff recovery of A&R costs is not permitted, financing typically depends on access to capital markets or internal reserves.[40]

Figure 2.3

Key stakeholders in Brazil's water sector

The investment climate for resilience in Brazil's water sector remains largely reactive, often triggered by crises rather than as an embedded aspect of planning cycles. [41] However, given that most revenues come from tariffs, maintaining service continuity is financially critical, and signs of progress are emerging (see Box 2.4).[42]

Box 2.4.

Lessons from water crises drive A&R measures for São Paulo's Cantareira reservoir system

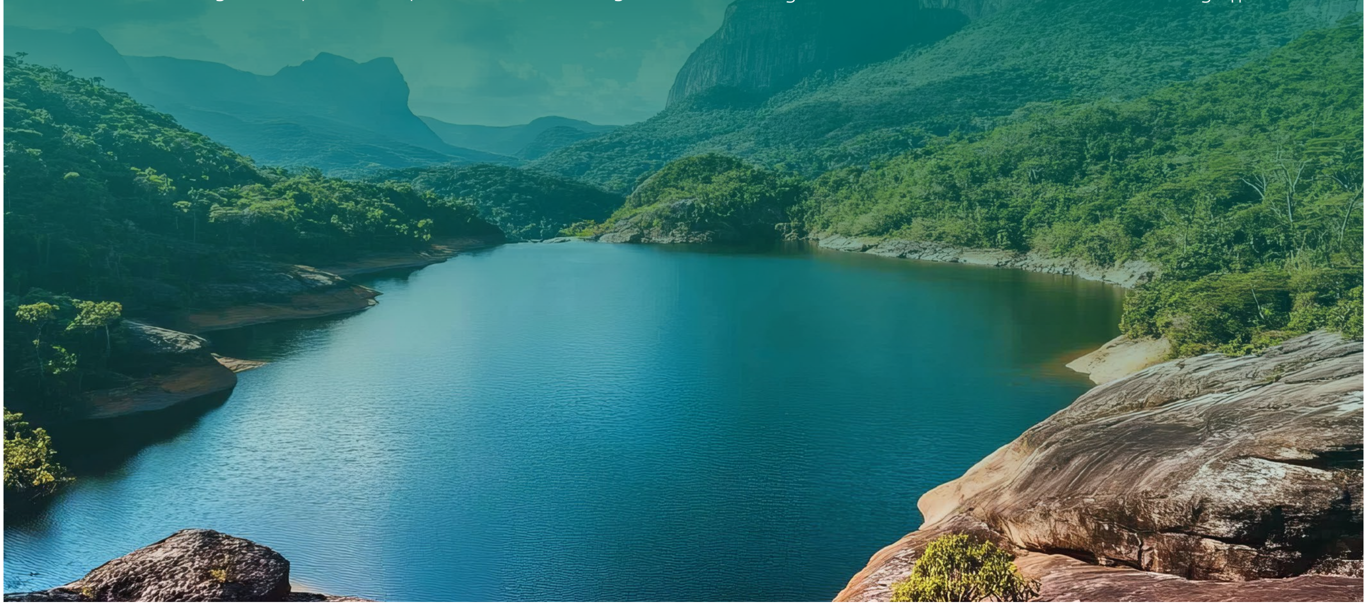
The 2014–2015 drought nearly collapsed São Paulo's main Cantareira reservoir system, threatening water security for 25 million people and causing job losses across the mining and agriculture sectors due to water restrictions. Economic costs mounted to USD 5 billion, with water restrictions causing 20 percent production drops in agriculture and mining, along with higher electricity prices from low hydroelectric production. An estimated 3,000 jobs were lost; diarrhea and hepatitis A cases rose 50 percent.[43]

Following this situation and earlier water crises, São Paulo implemented several major measures, including inter-basin water transfers and investments in nature-based solutions. Among the most significant measures: the USD 1.1 billion Sistema Produtor São Lourenço, a large-scale infrastructure project that channels water from a separate reservoir to the metropolitan area. Designed to diversify São Paulo's water sources, the new infrastructure also reduces dependency on the overburdened Cantareira system and strengthens regional water security and drought resilience.[44]

In addition, water operator SABESP established and preserved 33,000 hectares of forests around the Cinturão Verde watershed, although 20 percent was destroyed by drought-induced wildfires.[45] Other simple adaptation measures proved effective as well:

1. Pressure-reducing valves yielded 50 percent water savings.

2. Pricing incentives reduced demand with lasting effects.[46]



Box 2.5.

Recent A&R investment in Brazil's water and sanitation sector

Performance-based financing is playing a critical role in catalyzing A&R investment:

Corsan's 300 million Brazilian reais (USD 51.7 million) green loan from IFC comes with targets for non-revenue water reduction.

BRK Maranhão's 825 million Brazilian reais (USD 142 million) loan from IDB Invest and Proparco includes a USD 14 million incentive linked to climate performance.

SABESP:

2024 A 2024 1.06 billion Brazilian reais (USD 183 million) sustainability-linked loan from IFC includes KPIs tied to increased connection of water distribution and sewage networks, especially in low-income communities.

2026 In 2026, the water operator raised the world's largest blue bond to date through an A/B structure. The USD 1.5 billion bond links proceeds to sewage collection and treatment and water resilience outcomes.[47] The bond supports the growing blue finance space, which can help increase awareness about the importance of resilience in the water and sanitation sector.

Institutional investor CPP Investments committed 2.2 billion Brazilian reais (USD 379 million) in 2024 for a follow-on equity commitment to water and sanitation company Iguá, which included 100 million Brazilian reais (USD 17 million) for drought resilience measures in Sergipe state, benefiting more than 640,000 people in 30 municipalities.[48]

CASE

Water reservoir in Southeastern Brazil

ASSET OVERVIEW

Asset

The reservoir in Southeastern Brazil is the principal water source for more than 9 million people.

Ownership

The reservoir is managed through a water abstraction permit "outorga", granted by ANA and the water permit authority, while a private operator operates the associated water supply infrastructure under regulatory oversight.

Asset financing

Public utility model with revenues from water tariffs reinvested; adaptation financing would rely on regulated tariffs and/or concessional support.

FINDINGS AT-A-GLANCE

The do-nothing approach: Negative impacts from climate vulnerabilities

Without A&R, cumulative climate-related losses to the water reservoirs are projected to erode 21.9 percent under an intermediate-emissions scenario and 22.4 percent of NAV under a high-emissions scenario by 2050.

Two major climate hazards impact asset value: Droughts, with a 9.6–9.8 percent impact on NAV and wildfires with an 8.1–8.3 percent impact.

Failure of the reservoir system could jeopardize water security for millions, affecting domestic consumption, industry, and agriculture, with potential GDP and employment impacts across the region, as well as triggering regulatory penalties (not quantified here).

The do-something approach: Returns on adaptation investments

Targeted A&R measures can lower impacts to 9.5 percent of NAV through a set of actions that mitigate drought and wildfire impacts for a cost of 2.4 percent of NAV.

This bundle of measures yields IRRs ranging from 431 to 805 percent, depending on loan maturity and interest rate.

Socioeconomic co-benefits

A&R measures that strengthen water availability and wildfire risk reduction contribute most to value-added preservation and jobs, suggesting these criteria should inform option selection. Digital adaptation like smart metering, and drought-related measures add particularly important value.

Step 1: Data gathering and materiality assessment

The material exposure of the water reservoir to droughts, wildfires, floods, and storms were calculated under baseline and future climate scenarios, using global and regional climate hazard models and asset-level data. The findings reveal that without A&R, cumulative climate-related losses to the reservoir are projected to erode 21.9 percent of NAV under an intermediate emissions scenario and 22.4 percent of NAV under a high-emissions scenario respectively by 2050.[49]

Droughts and wildfires are responsible for the bulk of these impacts. For example, under different scenarios:

Droughts cause an estimated 9.6-9.8 percent reduction in NAV.[50] Land-use changes, such as deforestation, pasture expansion, and urban growth threaten to heighten drought risk.

Wildfires cause an estimated 8.1–8.3 percent reduction in NAV.

Floods contribute about 4 percent of NAV loss, due to overtopping, spillway stress, and damage to ground-level infrastructure.

Storms show minimal direct impacts, at about 0.04 percent of NAV, but remain relevant for operational reliability.

Table 2.4

Climate risk assumptions for the water reservoir

Hazards	Droughts, wildfires, floods, storms
CAPEX	≈ 7 billion Brazilian reais (USD 1.21 billion) in fixed assets (estimated)
Revenue	≈ 3 billion Brazilian reais (USD 517 million) in annual revenue (2025 baseline)
Vulnerability	The study used damage functions—quantitative curves that show how an asset's losses increase as a hazard becomes more severe—to translate hazard intensity into expected physical and revenue impacts for this asset.[51]
Asset Lifetime	26 years (2025-2050)
Discount rate[52]	Intermediate emissions scenario ≈22.9 percent High-emissions scenario ≈23.0 percent
Interest rate[53]	15.5 percent for a hypothetical 10-year loan
NAV definition	NAV is calculated as discounted FCFE over the analytical period (2025–2050), based on tariff-driven revenues scaled to the reservoir's delivery share of the overall water system, with fixed asset amounts derived from replacement supply capacity benchmarks from comparable water infrastructure.

Step 2: Identifying the A&R options

A&R measures analyzed: Structural hardening, defensible space management, additional reservoir and connection works, managed aquifer recharge, non-revenue water, digital, pumping dead volume, firebreaks, desalination, reuse, elevation of critical assets, reservoir capacity expansion, spillway enhancement, drainage system upgrades, vegetation wind breaks, structural wind breaks, and building strengthening.

Table 2.5 shows the full set of measures considered, along with their cost and benefit-cost ratios (BCR).

Table 2.5

A&R options and estimated costs and benefits for the reservoir

Hazard	A&R Measure	Measure cost (% of asset CAPEX)	Measure cost (% of NAV)	Benefit - Avoided Losses (% of NAV)		Benefit Cost Ratio (BCR) over lifecycle	Description
				Intermediate emissions scenario	High-emissions scenario		
Wildfire	Structural hardening ✓	0.2	0.3	5.4	5.5	22.2:1	Reinforcing infrastructure with fire-resistant materials
Wildfire	Defensible space management	0.6	0.8	5.4	5.6	7.1:1	Managing vegetation around assets to reduce fire intensity and spread
Drought	Additional Reservoir & Connection Works ✓	1.3	2.3	9.8	9.8	4.3:1	Expanding storage capacity or interconnecting existing systems
Drought	Managed Aquifer Recharge	1.9	3.3	9.6	9.8	3.0:1	Intentionally restoring groundwater storage through infiltration basins, recharge wells, or riverbank filtration—a nature-based solution
Drought	Non-Revenue Water	2.3	4.1	9.6	9.8	2.4:1	Reducing physical water losses through leakage control, metering, and improved billing efficiency
Drought	Digital	0.9	2.4	4.8	4.9	2.1:1	Deploying smart monitoring, sensors, and data analytics to optimize system operation, detect anomalies, and improve water efficiency
Drought	Pumping dead volume	4.7	6.4	9.6	9.8	1.5:1	Installing equipment to extract water from the lower levels of reservoirs
Wildfire	Firebreaks	11	14.8	6.5	6.7	<1:1	Establishing vegetation-free buffer zones to slow or block the spread of wildfires

Table 2.5

Adaptation measures, costs, and benefits for the Reservoir (continued)

Hazard	Adaptation Measure	Measure cost (% of asset CAPEX)	Measure cost (% of NAV)	Benefit - Avoided Losses (% of NAV)		Benefit Cost Ratio (BCR) over lifecycle	Description
				Intermediate emissions scenario	High-emissions scenario		
Drought	Desalination	11.3	15.5	9.6	9.8	<1:1	Converting seawater or brackish water into potable supply using energy-intensive treatment processes
Drought	Reuse	10.5	38.4	9.6	9.8	<1:1	Treating and recycling wastewater for non-potable or potable purpose
Floods	Elevation of critical assets	21	28.2	4.0	4.2	<1:1	Raising vulnerable infrastructure above projected flood levels
Floods	Reservoir capacity expansion	21	28.2	2.0	2.1	<1:1	Modifying the dam or constructing additional storage
Floods	Spillway enhancement	21	28.2	2.0	2.1	<1:1	Improving spillway design and capacity to safely release excess water during extreme flows
Floods	Drainage system upgrades	11	14.8	0.7	0.7	<1:1	Upgrading drainage systems to handle more intense and frequent flood events
Storms	Wind breaks – vegetation	3	4.0	<1	<1	<1:1	Planting tree/shrub barriers to reduce wind speed and protect facilities
Storms	Wind breaks – structural	21	28.2	<1	<1	<1:1	Constructing engineered barriers to reduce wind damage
Storms	Building strengthening	21	28.2	<1	<1	<1:1	Retrofitting buildings with stronger, wind-resistant features

Wildfire protection delivers the most resilience gains:

5.5%
LOSS OF NAV

Structural hardening and defensible space management both prevent losses of around 5.5 percent of NAV at a relatively minimal cost.

5.6%
LOSS OF NAV

Defensible space management (firebreaks) are below a benefit-to-cost ratio of 1, due to their high CAPEX cost, although they avoid more than 6.5 percent of losses.

Most drought protection measures, including managed aquifer recharge, non-revenue water reduction and pumping dead volume, could each fully reduce drought-related projected losses, delivering avoided losses of 9.8 percent of NAVs. Most drought A&R measures are considered profitable as their BCR ratios reach levels above 1, except for reuse and desalination.

Flood measures provide important protection:

- Elevation of critical assets prevents about 4 percent of NAV losses.
- Reservoir capacity expansion and spillway enhancement each preserve around 2 percent of NAV from avoided losses.

Storm-related measures yield only marginal avoided losses but still support operational continuity and reliability.

Step 3: Economic and financial analysis of A&R strategies

The analysis modeled two realistic alternatives to capture how A&R could be financed once assets are already operational:

1. Internal cashflow payment in 2026 financed from the operator's own resources
2. 10-year loan (2026–2036)[54]

As shown in Table 2.6, both deliver material benefits, with the 10-year loan providing slightly more.

Table 2.6

Financing scenarios for the A&R measures under a high-emissions scenario

Financing option	Total losses (% of NAV)	Avoided loss (% of NAV)	Adaptation cost (% of NAV)	Benefit to Cost Ratio
10-year loan ✓	9.5	15.3	2.4	6.3
Internal cashflow	9.6	15.3	2.5	6.1

A sensitivity analysis explored the loan financing option in greater detail to understand the impact different loan maturities and interest rates would have on the IRR. Sensitivity testing examined nine combinations: loan maturities of 6, 10, and 15 years against interest rates of 14.05 percent, 15.55 percent, and 17.05 percent — reflecting the analysis of the reservoir's financing as a corporate loan with a parent guarantee rather than a project finance structure.

The analysis determined that depending on loan maturity and interest rate, a portfolio of drought- and wildfire-focused measures that includes additional reservoir and connection works along with structural hardening:

Cuts overall losses by more than 12.9 percentage points.

Lowers impacts to 9.5 percent of NAV under a high-emissions scenario, with total cost requirements of around 2.6 percent of NAV.

Achieves IRRs of 431-805 percent depending on financing terms.[52]

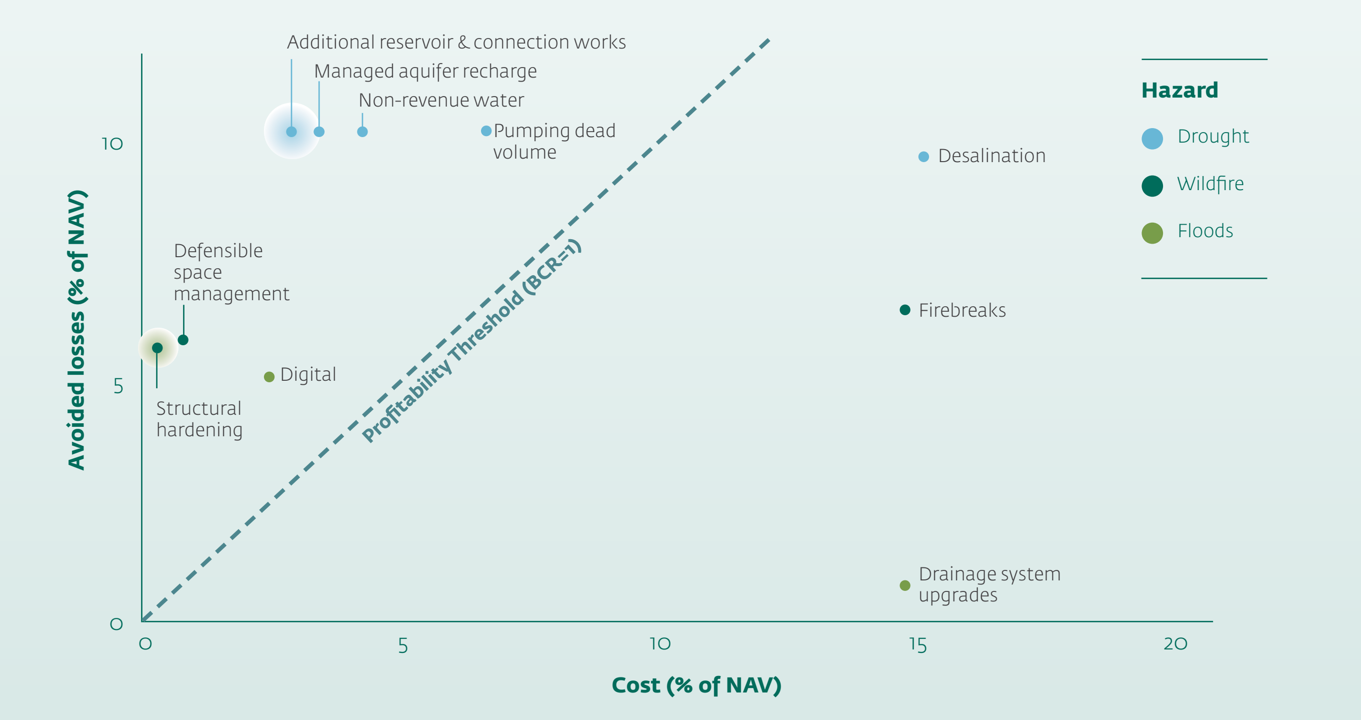
When the loan option is selected, longer loan terms substantially improve returns and benefit-cost ratios, while interest rates and climate scenarios have secondary effects. This means that patient capital proves essential for A&R investment viability.

Figure 2.4

Findings from the analysis of A&R measures for the Reservoir: visualized in 5 charts

Figure 2.4.1

Quantifying the value of A&R measures to address 3 major hazards[53]



NOTE: Four adaptation measures (elevation of critical assets, reuse, spillway enhancement, and reservoir capacity expansion) are not graphed due to high cost as percentage of NAV.

Figure 2.4.2

Ranking A&R measures to address climate risks from highest to lowest benefit-cost ratio

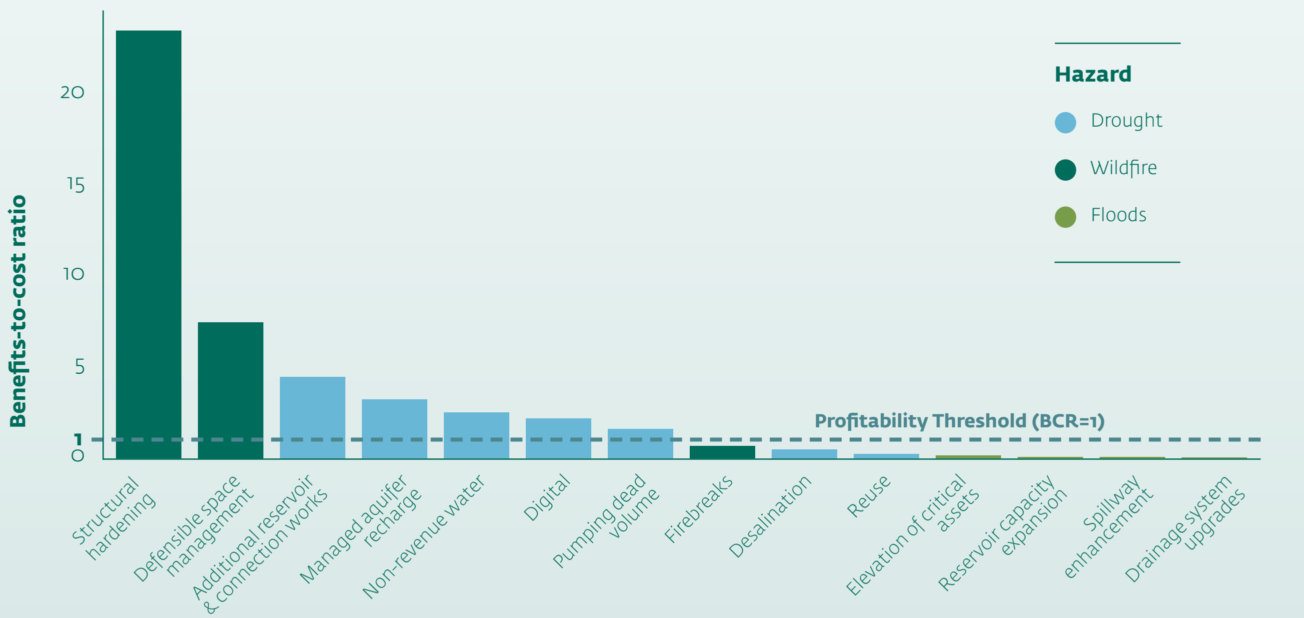


Figure 2.4.3

Comparing the financial impacts of climate hazards with and without a bundle of A&R measures under a high-emissions scenario, financed by a 10-year loan

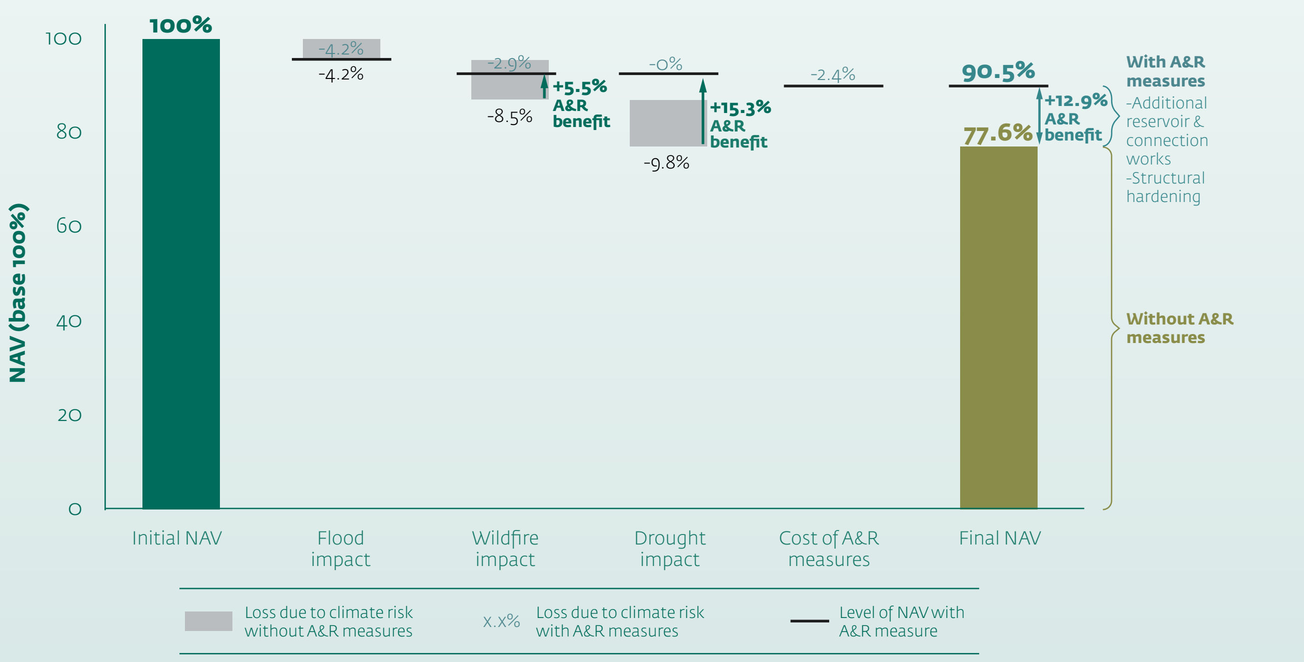


Figure 2.4.4

Identifying the optimal financing options for the A&R bundle to address climate hazards under a high-emission scenario

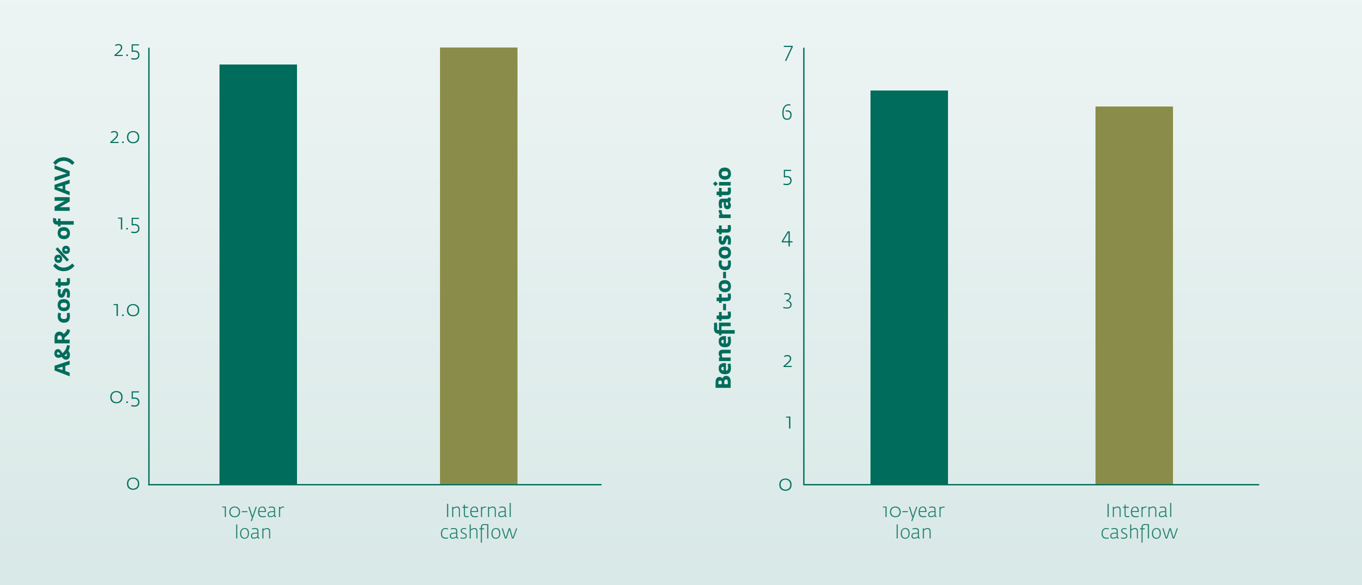
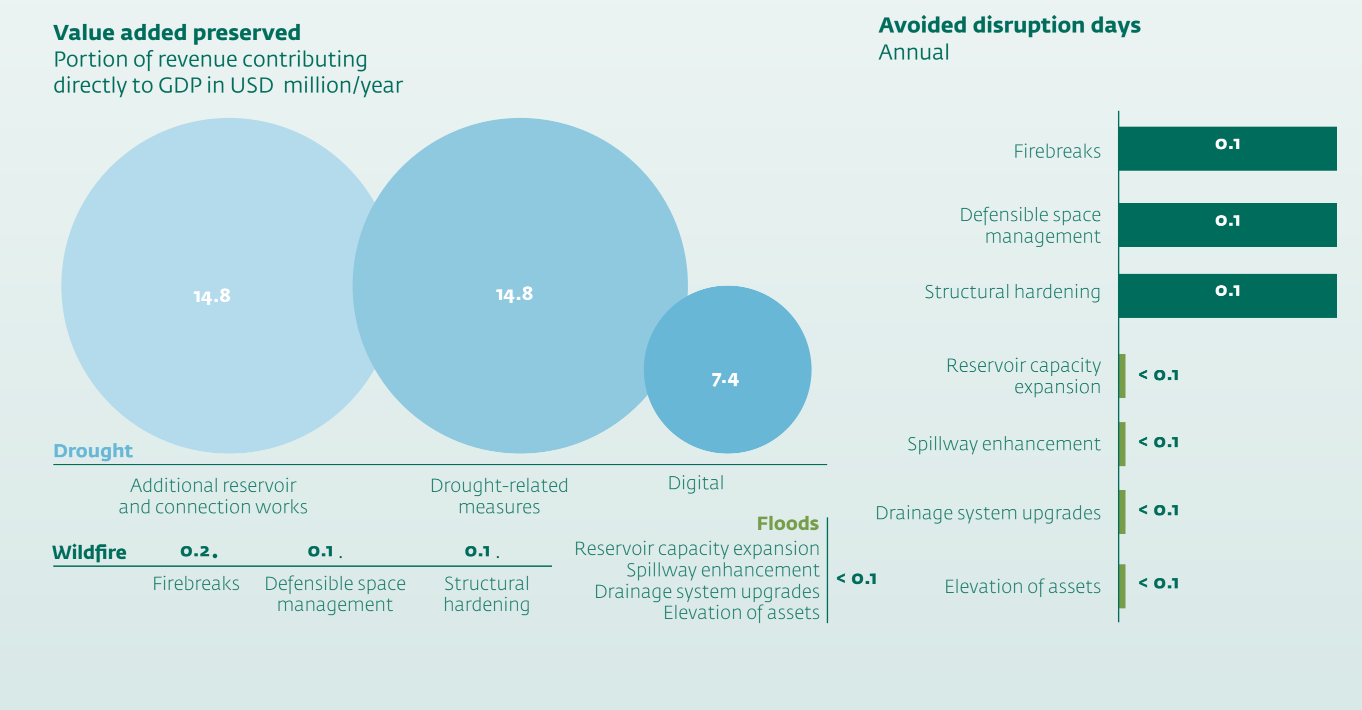


Figure 2.4.5

Quantifying the socioeconomic value of A&R measures to address wildfire, drought, and flood hazards faced by the reservoir[54]



Step 4: Analysis of socioeconomic co-benefits

The socioeconomic benefits of A&R extend well beyond what models can capture. The reservoir provides water to more than 9 million people across Southeastern Brazil, underpinning about USD 329 million in daily GDP in a high-productivity urban and industrial zone. The resilience of the system is an important concern for a region where water intensive industries and urban services alike are heavily dependent on reliable water, making them highly vulnerable when such service disruptions occur. Under baseline conditions, combined drought and wildfire hazards cause about 0.26 days of annual service disruption. Implementing an integrated bundle of A&R measures avoids about 0.12 days of interruption annually, reducing the disruption by 54 percent.

In economic terms, the inclusion of A&R helps sustain about USD 39 million in annual activity. Although this figure represents less than 1 percent of Southeastern Brazil's GDP, the interventions help to stabilize utility revenues and reduce emergency operational costs, strengthening access to essential services and the resilience of households and industry across the metropolitan region.[58]

Insights from the analysis

- **Bundling several measures**, including additional reservoir and connection works and structural hardening, represents a limited cost, high benefit strategy, cutting losses by 12.9 NAV percentage points.
- **Managed aquifer recharge, non-revenue water, pumping dead volume, reuse, and desalination represent high-cost A&R measures, requiring substantial upfront investment**. However, their avoided-loss potential is significant, suggesting that such interventions could warrant public co-financing or blended support given their broader systemic and social benefits.
- **Access to long-tenor, low-cost finance** is the strongest determinant of financial viability for water-sector adaptation. It can amplify IRR by over hundreds of percentage points compared to short-term, high-interest borrowing. A 10-year loan offers a satisfying balance between cost and A&R gain.
- **When framed as service-quality or risk-management improvements**, these measures could be incorporated into tariff base revisions.
- **If regulators do not approve cost recovery**, blended finance or public support might be needed to make these investments attractive and bankable for utilities and investors.
- **Because of the gains in long-term resource security achieved** and given the major sensitivity to water supply, there is a strong rationale for governments to support financing A&R measures that might not be as cost-efficient from a pure financial perspective.
- **For utility CFOs**, A&R measures provides both financial resilience and investment-grade stability, ensuring sustained value over long asset horizons.

Roads

Road networks are highly vulnerable to floods, landslides, and extreme heat, which damage pavements, embankments, and bridges. Global A&R practices include improved drainage, slope stabilization, elevated roadbeds, and performance-based maintenance contracts. Yet design standards often rely on historical rather than forward-looking climate data, leaving systems exposed to escalating risks.

The Brazil context

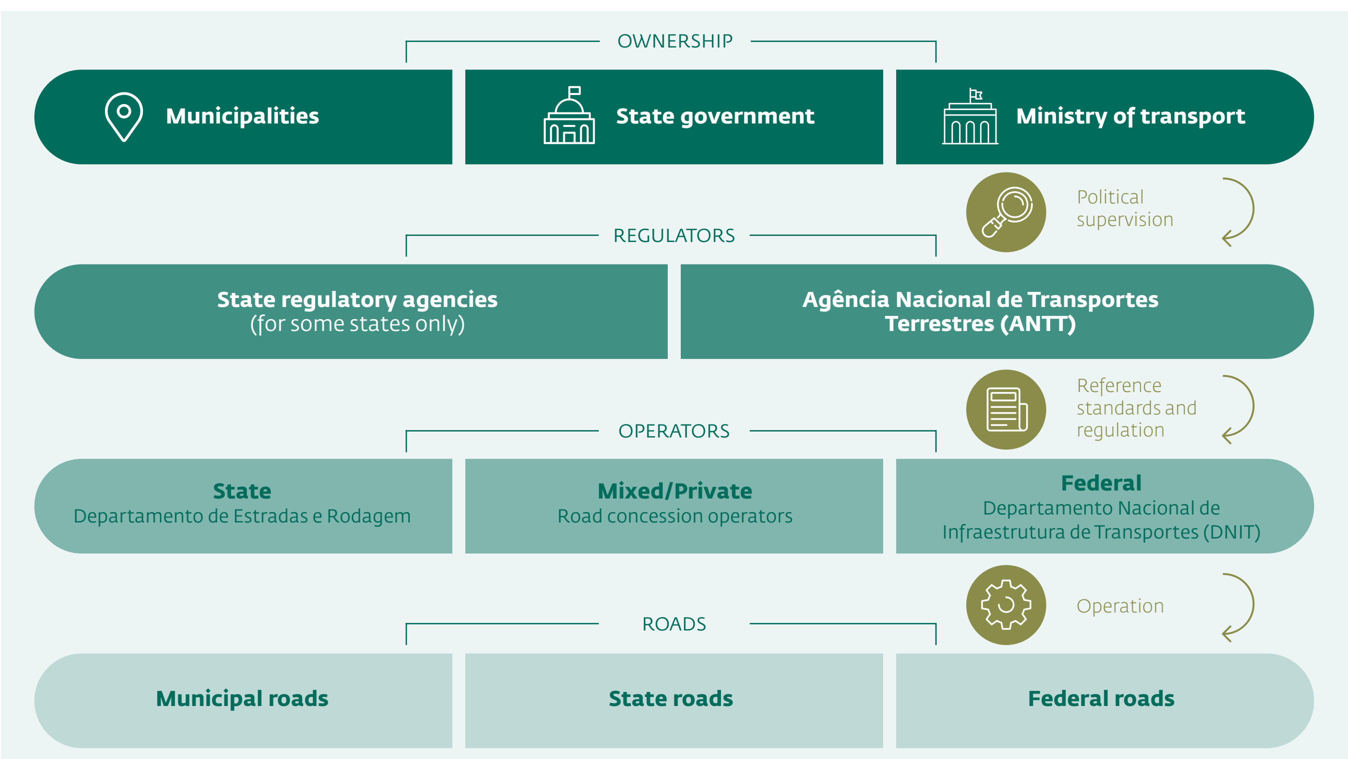
Brazil has nearly 2 million kilometers of roads, but only 12 percent are paved.[59] More than 5 percent (120,000 km) are exposed to material flood risks.[60] In May 2024, catastrophic flooding in the Southern state of Rio Grande do Sul submerged highways, cutting off its capital, Porto Alegre, for weeks and halting agricultural exports, which are essential to the local economy.[61]

There is strong value for Brazil by investing in a resilient road network. According to World Bank estimates, the 111.7 billion Brazilian reais (USD 19.26 billion) in additional CAPEX needed by 2050 to climate-proof roads in the country would yield USD 235.4 billion Brazilian reais (USD 40.59 billion) in avoided losses—a return of twice the needed investment.[62]

The 2023 federal AdaptaVias program is a first step in mainstreaming climate risk by conducting a survey of the impacts and risks of climate change on existing and planned federal land transport infrastructure, including highways and railways, as a basis for developing A&R strategies in the sector.

Figure 2.5

Key stakeholders in Brazil's road sector



Box 2.6.

Recent A&R investments in Brazil's road sector

Development finance is accelerating A&R investment through performance-linked models:

Two projects under the World Bank's USD 1.66 billion Pro-Roads initiative, the USD 300 million Santa Catarina road project and the USD 200 million Mato Grosso do Sul road project, use performance-based CREMA contracts.[63] The entire initiative ties financing to the achievement of resilience KPIs.

The 14 billion Brazilian reais (USD 2.41 billion) Piracicaba–Panorama Highway integrates climate standards. IFC advised on the project, which was supported by BNDES, commercial banks, and infrastructure debentures.[64]

CASE

Motorway concession in the State of São Paulo

ASSET OVERVIEW

Asset

Motorway corridor in the State of São Paulo that provides connectivity for freight transport, commuting, and regional trade. Estimated number of daily users: 75,566.

Ownership

Under a concession auctioned by the State of São Paulo. Concession length: 30 years, beginning in 2025.

Asset financing

Structured as a PPP, with the private operator financing, constructing, and operating the asset in exchange for toll revenue. The state provided no direct capital contributions.

FINDINGS AT-A-GLANCE

The do-nothing approach: Negative impacts from climate vulnerabilities

Without A&R, cumulative climate-related losses to the road concession are projected to reach 28.1 percent of NAV under an intermediate emissions scenario and 28.7 percent under a high-emissions scenario by 2050.

Wildfires account for about two-thirds of the losses, floods less than one third, and storms for only a marginal share.

Failure of the highway corridor exposes the operator to financial penalties and, indirectly, could paralyze freight and commuter flows, disrupt supply chains, and inflate logistics costs, thereby constraining regional productivity.[65]

The do-something approach: Returns on adaptation investments

Implementing two A&R measures to counter wildfires and flood impacts reduces cumulative losses to 19.2 percent of NAV under a high-emissions scenario, for a cost of 8 percent of NAV.

The bundle of A&R measures IRRs range from 56 to 156 percent depending on loan tenor and interest rate.

Socioeconomic co-benefits

Without A&R, climate events could result in up to 3.3 days of annual service disruption per year. Implementing the identified A&R measures would cut these disruption days in half, preserving jobs and daily economic activity.

Step 1: Data gathering and materiality assessment

The climate risk assessment shows that the motorway faces high risks of flooding—both from surface water accumulation during extreme rainfall (pluvial flooding) and from rivers, lakes, and streams overflowing during rainfall (fluvial flooding)—and wildfires:

Flooding, particularly for road segments near rivers, threatens to expose assets such as bridges, culverts, and drainage systems to structural damage and traffic disruption. Brazilian highways are usually designed for floods that statistically happen once every 50 years on average, with a 2 percent chance of occurring in a given year. Bridges are designed to withstand floods expected about once every 100 years on average, with a 1 percent chance of occurring in a given year. However, under future climate scenarios, these thresholds could be exceeded more frequently, increasing the likelihood of infrastructure stress.[66]

Wildfires threaten both the physical integrity of road surfaces and structures and are projected to intensify.[67]

Without A&R measures, cumulative losses from wildfires, storms, and floods from 2025-2050 are estimated to impact 28.1 percent of NAV under an intermediate emissions scenario and 28.7 percent under a high-emissions scenario, with wildfire as the primary driver.[68]

Table 2.7

Climate risk assumptions for the São Paulo motorway

Hazards	Floods, storms, wildfires
CAPEX	Estimated concession grant value 2.1 billion Brazilian reais (USD 400 million). Mandatory investments under concession ≈8 billion Brazilian reais (USD 1.38 billion).
Revenue	Permitted annual revenue from toll receipts ≈1.059 billion Brazilian reais (USD 183 million) (median of forecast, 2025 real terms).
Vulnerability	Reflects Brazilian risk-free rates from Oxford Economics' scenarios plus an asset-specific risk premium derived from comparable Brazilian road concessions using SIPA metrics.
Asset lifetime	The study used damage functions—a quantitative curve that shows how an asset's losses increase as a hazard becomes more severe—to translate hazard intensity into expected physical and revenue impacts for this asset.[69]
Discount rate	30 years (2025-2055)

Step 2: Identifying the A&R options

A&R measures analyzed: Drainage system upgrades, blue-green infrastructure, elevation of road sections, vegetation management and landscaping, firebreaks, defensible space management, structural improvements such as strengthening street furniture, wind breaks such as terrain/landscaping, and natural infrastructure such as vegetation management.

Table 2.8 features the full set of measures considered, along with their benefit-cost ratios.

Table 2.8

A&R options and estimated costs and benefits for the São Paulo motorway[70]

Hazard	A&R Measure	Measure cost (% of asset CAPEX)	Measure cost (% of NAV)	Benefit - Avoided Losses (% of NAV)		Benefit Cost Ratio (BCR) over lifecycle	Description
				Intermediate emissions scenario	High-emissions scenario		
Floods	Drainage system upgrades	0.1	0.3	0.8	0.8	2.5:1	Expand drainage to handle larger floods
Floods	Blue-green infrastructure	0.4	1.0	1.8	1.8	1.9:1	Add ponds, swales, and basins to absorb and redirect floodwaters
Floods	Elevation of road sections ✓	1.5	3.2	4.7	4.8	1.5:1	Raise critical road sections above flood levels
Wildfire	Vegetation management and landscaping ✓	2.6	5.6	8.3	8.5	1.5:1	Implement fire-resistant landscaping with plants that are less prone to burning
Wildfire	Firebreaks	7.1	15.4	11.8	12.1	<1:1	Build vegetation-free buffer zones to block fire spread
Wildfire	Defensible space management	6.4	14.0	9.7	9.9	<1:1	Ensure that trees, shrubs, and other flammable materials are well-managed within a certain radius around the facility
Storms	Structural improvements - street furniture strengthening	4.8	10.4	0.1	0.1	<1:1	Reinforce signage and lighting with stronger materials
Storms	Wind breaks: terrain/ landscaping	6.1	13.3	0.1	0.1	<1:1	Add berms or landforms to shield against wind
Storms	Natural infrastructure: vegetation management	6.4	13.9	0.1	0.1	<1:1	Conduct regular maintenance of any vegetation next to the asset, such as trees and bushes

After evaluating various A&R measures based on their ability to address the material hazards and their estimated costs and benefits, the analysis revealed that addressing wildfire and flood vulnerabilities offers the greatest value for the road corridor.

Measures such as firebreaks, vegetation management, and landscaping to protect against wildfires deliver the largest reduction in losses under a high-emissions scenario.

Firebreaks alone prevent losses representing about 12.1 percent of NAV. However, with a cost of 15.4 percent of NAV, their benefit–cost ratio remains below one, making them financially unattractive.

Vegetation management and landscaping offer smaller absolute benefits, avoiding 8.5 percent of losses. But at a cost of 5 percent of NAV, they emerge as particularly profitable.

Elevating critical road sections above flood levels prevents about 5 percent of NAV losses associated with floods. With a BCR above 1, this measure represents a solid investment.

Blue/green infrastructure improvements, such as ponds, swales, and basins to absorb and redirect floodwaters also offer potential to mitigate flood risks, albeit delivering fewer avoided losses than other measures. They do demonstrate good financial performance, while also generating environmental co-benefits such as carbon sequestration and biodiversity support, making them an interesting option to consider. Drainage system upgrades show a high benefit-cost ratio, but they yield very low avoided losses in absolute value.

Box 2.7.

Reducing the risk of unintended consequences through system-wide solutions

Individual A&R measures that make sense for a single asset can create unintended problems when viewed across the broader system. For example, upgrading drainage at one road segment may reduce local flooding but accelerate runoff downstream, increasing flood risk for other communities or infrastructure. For this reason, a system-level approach is essential to identify these trade-offs and ensure that local interventions don't amplify wider risks.

Sustainable drainage systems and nature-based catchment solutions that slow, store, and filter water across the watershed can complement or replace traditional grey infrastructure while addressing risks at the system scale.

Step 3: Economic and financial analysis of A&R strategies

For purposes of this study, a bundled road A&R package, combining elevation of road sections, and vegetation management and landscaping, was selected for analysis because of the positive impact on NAV retention and relative cost-effectiveness. This bundle safeguards 9.5 percentage points of NAV under a high-emissions scenario, with total cost requirements of about 8 percent of NAV.

To capture how to finance these A&R measures for the already-operational roadway, the analysis modeled two realistic alternatives:

1. Internal cashflow payment in 2026 financed from the operator's own resources
2. 10-year loan (2026–2036)[71]

This analysis revealed an advantage for the 10-year loan, given that spreading the cost over time better aligns financing with the period over which the adaptation measures deliver their benefits.

Table 2.9

Financing scenarios for the A&R measures under a high-emissions scenario

Financing option	Total losses (% of NAV)	Avoided loss (% of NAV)	Adaptation cost (% of NAV)	Benefit to Cost Ratio
10-year loan ✔	19.2	17.4	8.0	2.2
Internal cashflow	20.0	17.4	8.8	2.0

A further sensitivity analysis showed that the bundled road adaptation package is highly profitable and resilient to financing stress:[72]

- IRRs range from 56 to 156 percent depending on loan tenor and interest rate.
- Longer maturities play a decisive role: Extending loan terms from 6 to 15 years substantially improves returns.
- Moderate interest rate increases have a comparatively minor effect.

Sensitivity testing examined nine combinations: loan maturities of 6, 10, and 15 years against interest rates of 11.67 percent, 13.17 percent, and 14.67 percent — consistent with the project finance structure of the concession.

Figure 2.6

Findings from the analysis of A&R measures for the São Paulo Motorway: visualized in 5 charts

Figure 2.6.1

Quantifying the value of A&R measures to address 2 major hazards[73]

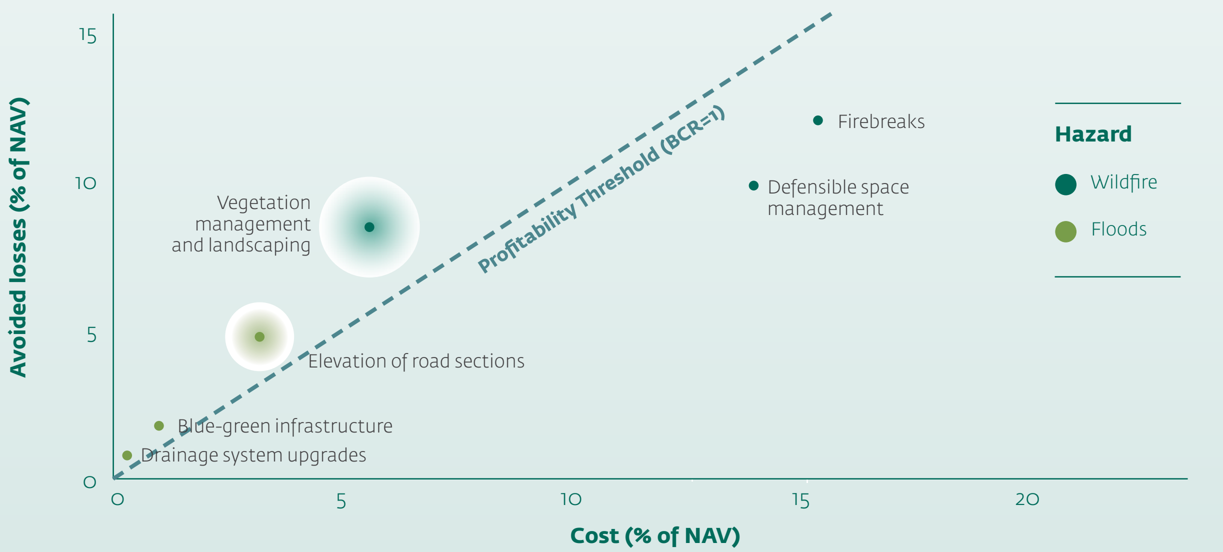


Figure 2.6.2

Ranking A&R measures to address climate risks from highest to lowest benefit-cost ratio

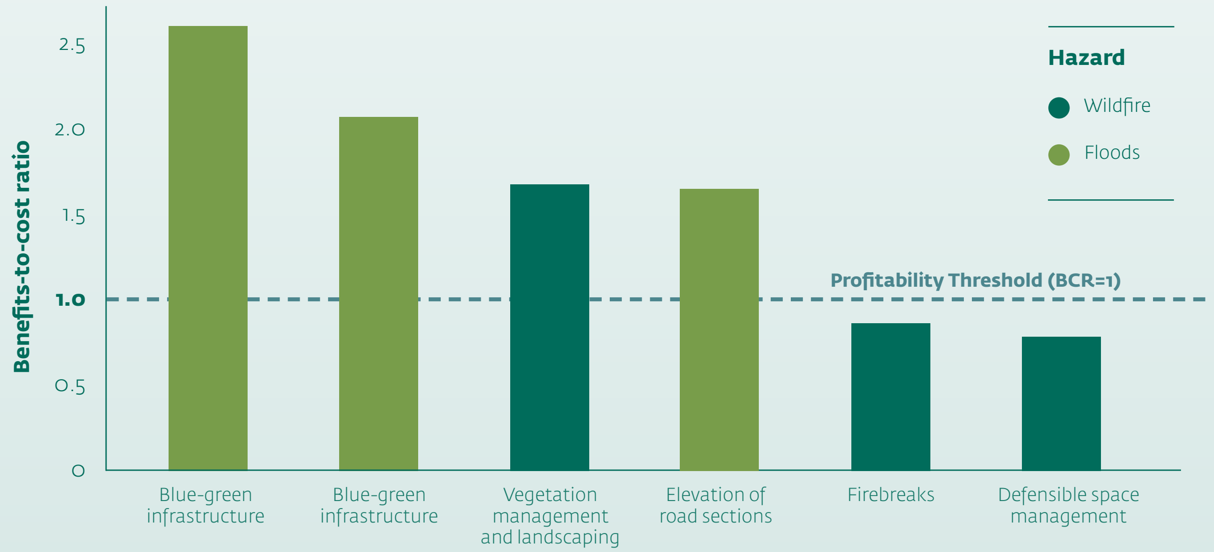


Figure 2.6.3

Comparing the financial impacts of climate hazards with and without a bundle of A&R measures under a high-emissions scenario, financed by a 10-year loan

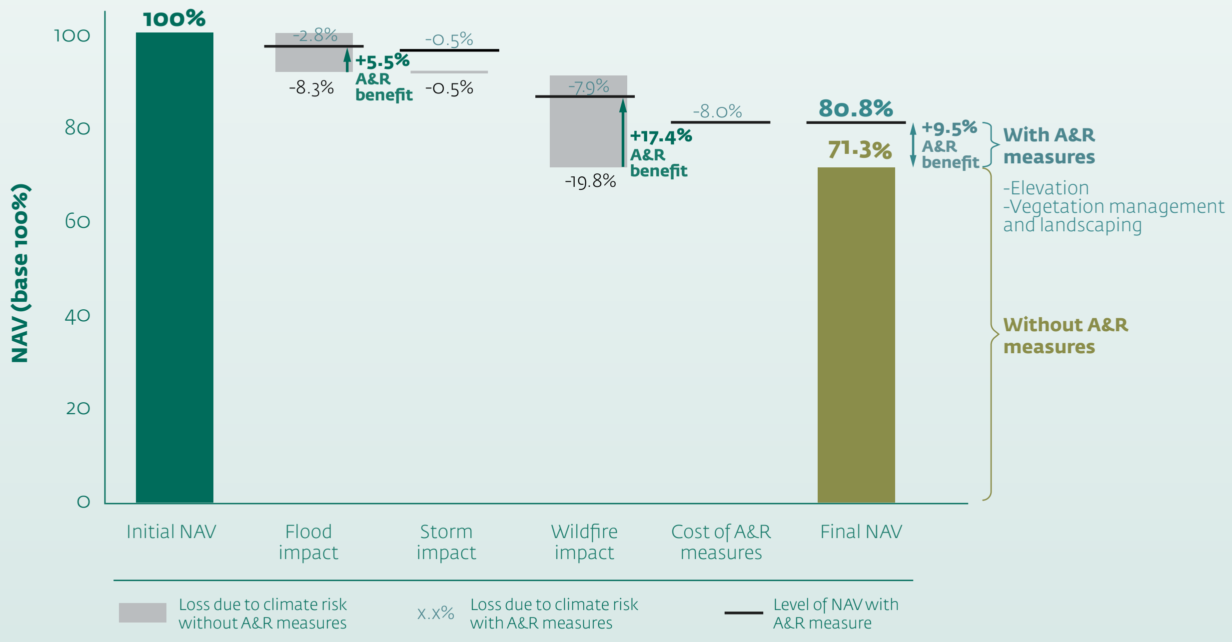
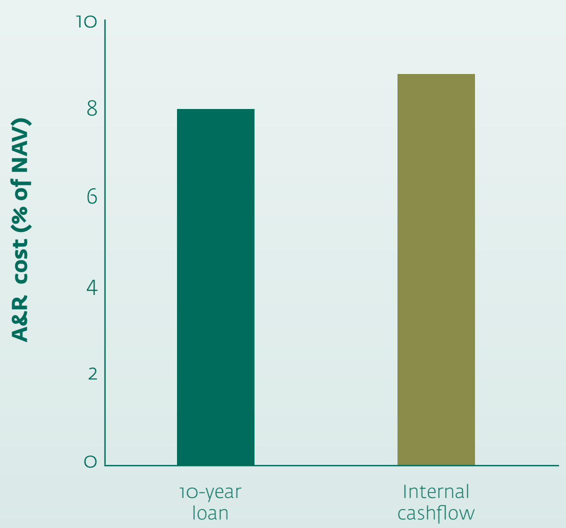


Figure 2.6.4

Identifying the optimal financing options for the A&R bundle to address climate hazards under a high-emission scenario



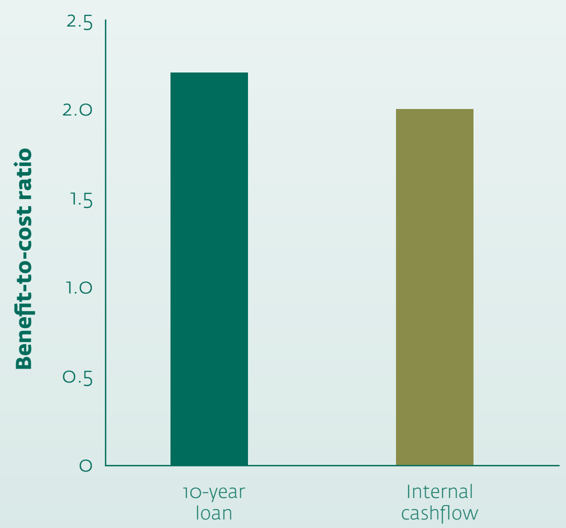
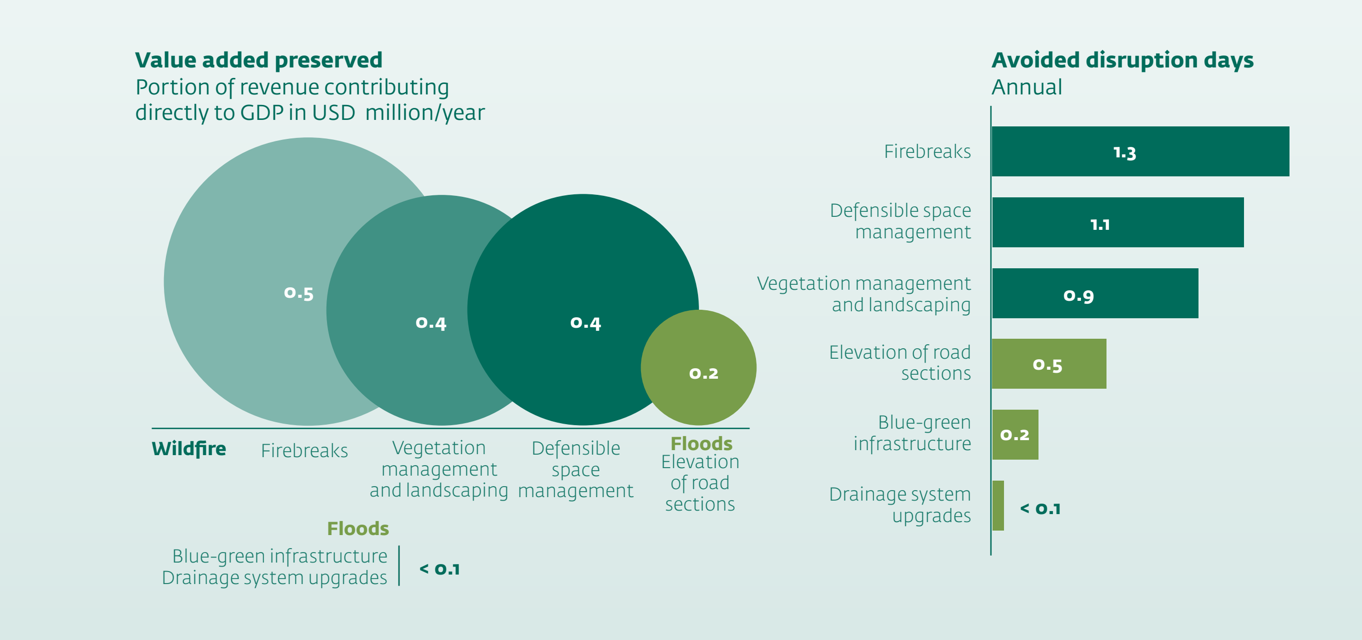


Figure 2.6.5

Quantifying the socioeconomic value of A&R measures to address wildfire and flood hazards faced by the road corridor[68]



Step 4. Analysis of socioeconomic co-benefits

With about 75,000 people using it daily, the road corridor underpins an estimated USD 2.8 million in daily economic activity.[75] With no A&R measures, climate-related events are projected to result in 3.1 days of annual service disruption under the intermediate emissions scenario and 3.3 days of annual service disruption under the high-emissions scenario.

Implementing a combined A&R package of elevating road sections and vegetation management and landscaping reduces disruption to about 1.5–1.6 days per year, avoiding close to 1.6–1.7 days of outage annually, or a 52 percent reduction. Minimizing travel disruptions and hazard-related roadway damage by improving A&R through the bundled package of adaptation measures yields substantial socioeconomic benefits, including:

- Helping sustain about USD 4.6 million in annual economic activity
- Reducing the time and cost associated with detours
- Accelerating post-event recovery
- Reducing emergency repair expenditures
- Delivering tangible employment benefits:

1. Elevating flood-prone road sections protects an estimated 12–14 full-time jobs annually.
2. Vegetation management around wildfire zones protects 24–27 jobs per year.[76]

Insights from the analysis

- **Bundling road section elevation, vegetation management and landscaping** could reduce total climate-related losses by 9.5 percent of NAV and are most financially viable when financed through a 10-year loan.
- **Firebreak construction and maintenance** represent relatively high-cost adaptation measures for road corridors, involving substantial land management and upkeep expenses. .
- **Given the significant avoided-loss potential of firebreak construction and maintenance**, state co-financing in concessionary A&R programs could be a viable option to explore.
- **Proactively integrating adaptation into maintenance and safety plans** can strengthen the concessionaire's prudent management of operational risks and secure toll revenue. Although A&R cost recovery is not guaranteed through toll/availability payment increases, improved reliability supports concession stability, creditworthiness, and long-term investor confidence.
- **In regulated sectors** such as water and electricity, tariff adjustment can offer a potential pass-through mechanism to recover A&R CAPEX. Conversely, sectors that rely on toll revenue and availability payments, such as roads) can make cost recovery for A&R measures less certain, therefore increasing the case for public/government co-financing or blended finance.

Summary takeaways from the case studies

The analysis of the three critical infrastructure assets has yielded several important takeaways for stakeholders, applicable across infrastructure sectors and economies.

- **Climate impacts are material:** Cumulative climate hazards are projected to erode 22 percent of NAV under an intermediate emissions scenario and 30 percent of NAV under a high-emissions scenario for certain assets assessed, confirming that adaptation is a core investment necessity for infrastructure operators.
- **Small measures, large value:** Targeted, lower-cost actions, such as vegetation management, elevation, and network interconnections, deliver the highest benefit-to-cost ratios. The business cases quantify the combined potential for avoiding NAV losses. But in practice these measures could be implemented selectively and in phases, based on feasibility, asset criticality, and financing capacity, if not all integrated at project design phase.
- **Public co-investment is critical:** High-cost measures, such as firebreaks for roads, desalination for water, and fireproof materials for T&D, deliver substantial societal value but fall below private cost-efficiency thresholds. Public co-financing is essential to unlock their economic and social potential.
- **Smart financing matters:** Longer loan tenors are more beneficial than lower interest rates. Although integrating adaptation at the design stage typically yields the best BCR, financing adaptation through a 10-year loan offers slightly better outcomes than internal cashflow. This approach smooths CAPEX while maintaining strong avoided-loss benefits. Extending financing from 6 to 15 years can double IRRs.
- **A&R yields broader economic dividends:** Although this study did not quantify larger indirect impacts, the positive impacts on GDP and job creation reinforce that adaptation delivers systemic socioeconomic value.
- **Resilience must be assessed over the full asset life cycle:** Good practice in physical climate risk and resilience analysis requires evaluating hazards and adaptation options across the entire lifespan of an asset, not only at design stage. For example, the EU's Environmental Impact Assessment Directive requires projects to consider how climate change could affect them over their expected lifetime.[77] Having a flexible approach to A&R and implementing measures only when certain climate thresholds are exceeded would allow for better decision making. This is particularly useful for situations in which more pessimistic climate scenarios would improve the hazard.

PART 3
Enabling the conditions for resilience financing

With the value in investing in A&R established, the question becomes: How to access the opportunity? This section offers pathways to overcome the barriers to investment and take advantage of the A&R opportunity.

See the risk
Data & metrics

Price the risk
Incentives & allocations

Deploy capital
Financing & scale

Coordinate
Governance & planning

See the risk: *Climate risk data, metrics, and valuation*

Operators and investors face several issues in accurately quantifying risks and benefits, including lack of access to climate models, limited capacity to downscale global projections into localized, asset-specific climate data, lack of standardized metrics on A&R costs and benefits, and low climate risk awareness. Boosting climate risk data capabilities enables a deeper understanding of what the material risks look like, which will help to turn climate risk from abstract projections—often based on historical patterns rather than on future potential impacts—into investment decisions. Concrete actions here include:

Build climate risk data infrastructure: Most EMDEs lack the foundational climate data needed to channel capital toward adaptation. Governments should establish platforms that translate climate science into asset-level hazard projections, exposure mapping, and also provide historic loss records. This should be linked to mandatory disclosure frameworks and clear adaptation taxonomies that define what qualifies as resilience investment. MDBs and DFIs should prioritize supporting low-income countries in building these platforms, which serve as the foundation for all subsequent investment decisions.

Translate data into financial value: With data infrastructure in place, operators can systematically conduct climate risk assessments that demonstrate A&R's true value through full asset lifecycle costing, showing how avoided losses and reduced maintenance offset higher upfront costs. Investors should incorporate these climate projections into financial models, using probabilistic tools that reflect climate considerations to quantify how adaptation improves debt service capacity and asset value.[78] Closing this gap requires targeted capacity building, especially for smaller operators and utilities, and clearer market signals that reward climate analysis and resilience, such as better financing terms.

Embed data into standards and create feedback loops: Mandating climate risk screening for all publicly funded infrastructure projects and updating building codes and engineering standards to reflect projected climate conditions will enable better protection against future hazards. Similarly, regulations that require operators and investors to undertake climate risk assessments and create adaptation plans will support more sustainable private infrastructure projects. MDBs and DFIs can play a role by developing A&R KPIs with third-party verification, along with benchmarks on A&R costs and benefits to enable evaluations, which can underpin pay-for-performance contracts. Taken together in an ecosystem approach, such actions ensure that A&R is embedded at the design stage, when it is most cost-efficient. To make the case for A&R, operators can share performance data (outages, disruptions, repair costs) with regulators and financiers to show climate risk's financial impacts and A&R benefits. For examples of KPIs that could be used to measure performance, please see Appendix 3.

Box 3.1.

International climate risk assessment initiatives and resources

INITIATIVES

Colombia's integrated A&R approach includes:

- Climate change plan that sets overall adaptation goals
- Disaster management plan to address acute climate risks
- The Resilient Investment Toolbox features practical methodologies for incorporating resilience into project preparation.
- Climate finance broker facility matches resilient projects with appropriate financing sources.[79]

The Netherlands' national adaptation platform, KNMI'23, provides official hazard and impact projections that infrastructure designers must use. Dutch municipalities and water boards are required to develop adaptation plans that directly inform infrastructure investment decisions.[80]

RESOURCES

- **Institutional Investors Group on Climate Change:** Physical Climate Risk Appraisal Methodology 2.0 (PCRAM), guidelines for integrating physical climate risks into investment decision-making.
- **C40 Cities, the Global Resilient Cities Network, International Water Association:** Peer-learning platforms, knowledge exchange, and standardization
- **Climate Bonds Initiative:** Climate Bonds Resilience Taxonomy
- **European Commission:** Climate Risk Assessment (CRA), Risk Data Hub, Climate-ADAPT database and the DestinE Digital Twin for Climate Change Adaptation
- **IFC:** Building Resilience Index
- **International Organization for Standardization:** ISO 14090, Adaptation to Climate Change
- **UK:** The Climate Resilience Indicators Programme (with UKCP18) and Climate Risk Mapping Platform
- **US:** Climate Mapping for Resilience and Adaptation (CMRA), the Network for Greening the Financial System database, and the Oxford Economics Scenario database
- **World Bank Group:** Climate and disaster risk screening tools

Price the risk: *Financial and regulatory incentives*

Aligning financial and regulatory incentives ensures that A&R costs can be recovered and A&R performance is rewarded. Actions here include:

Establish predictable cost-recovery mechanisms: Private operators will not scale adaptation without clear pathways to recover costs. Regulators must explicitly recognize cost-efficient, climate-related expenditures in tariff structures, availability payments, and concession contracts. Costing out A&R measures over the lifecycle of the asset, in combination with quantifying secondary benefits increases returns on the investment and can enable access to climate finance. Where affordability constraints limit tariff adjustments, governments can deploy complementary mechanisms, including cross-subsidization from wealthier users, public co-investment funds, and land-value capture. Unregulated private companies in infrastructure value chains, which cannot rely on cost recovery, should quantify A&R's financial and operational benefits to justify investments to investors and lenders. Tax incentives for green, resilience, and sustainability bonds and infrastructure debt instruments, conditioned on verified targets, can further lower capital costs while steering investment toward priority assets. A&R can also be phased dynamically as climate risk increases to align with financing capacity.

Box 3.2.

Quantifying secondary benefits increases overall returns on investment and unlocks access to climate finance

- Avoided losses
- Reduced operations and maintenance costs
- Potentially reduced insurance premiums
- Lower downtime penalties
- Extended asset life

Box 3.2.

International good practice: Equitable and predictable cost recovery

United States

- In Florida, state regulation requires both public and private utilities to implement 10-year storm protection plans, funded through dedicated user surcharges that raise electricity bills by about 6 percent. Funds are earmarked for infrastructure hardening to mitigate hurricane restoration costs and improve service reliability during extreme weather.[81]
- In California and New York, public utility commissions have specified the use of tariffs for A&R cost recovery.

South Africa

- During Cape Town's 2017-2018 drought, the municipality introduced dynamic, inclining-block water tariffs that charged progressively higher rates to high-consumption users, which were typically higher-income households. This approach generated additional revenue for emergency resilience measures while maintaining affordable baseline rates for essential consumption.[82]

Reform PPP frameworks and procurement standards: With cost recovery pathways established, incentives in PPP contracts and procurement processes can shift toward resilience. Governments should require climate risk screening at project inception and mandate detailed and forward-looking A&R plans with clear KPIs for hazard tolerance and maintenance integrated into contracts. Procurement should move beyond least-cost bidding toward resilience-based award criteria, with performance payments linked to measurable outcomes like reduced outages or faster recovery times. Contracts should clarify climate risk allocation through clearer and explicit force majeure thresholds, with operators managing foreseeable risks through A&R measures or insurance, and extreme events reverting to the state.

Expand insurance access and requirements: Insurance markets complete the incentive framework by transferring and pricing residual risk. EMDEs with shallow insurance markets will need international reinsurance to spread large climate risks that local insurers cannot cover alone. Governments can facilitate access to global reinsurance markets and regional risk pools while encouraging catastrophe insurance in PPPs to ensure proper risk management. Operators should secure coverage for climate-exposed assets and ensure that premiums reflect A&R investments. Including clear force majeure definitions in policies will reduce disputes and improve claims certainty. Smaller utilities facing prohibitively high premiums can pool risks through mutualized mechanisms, sharing exposure across participating entities to achieve affordable coverage.[83]

Box 3.3.

International good practice: Resilience-embedded PPP frameworks

Chile

Given their frequency, the PPP law excludes earthquakes from force majeure definitions entirely and states that catastrophic risk must be covered by insurance. This places financial responsibility fully on operators.[84]

Colombia

The concession for the Ruta del Cacao toll road, which crossed flood-prone areas, combined traditional toll revenue with availability payments—fixed government payments conditional on the road meeting defined service standards. This directly incentivized the operator to invest in flood resilience, as service disruptions from flooding directly reduced revenue through lost availability payments.[85]

Jamaica

The 2023 PPP reform mandated climate risk assessments during project preparation and disaster response plans as part of operations and appropriate insurance coverage. It established updated force majeure guidelines tailored to project-specific climate risks rather than generic clauses.[86]

Tanzania

A revised PPP law mandates that project proponents and contracting authorities must assess climate risks and identify specific adaptation measures during project preparation. Climate risk exposure serves as a formal screening criterion in project selection, so projects demonstrating inadequate climate risk management can be rejected at the approval stage.[87]

Japan

The PPP law scales obligations on private partners based on seismic intensity thresholds. These practices have enhanced private sector responsibility for risk management and improved emergency responsiveness by creating clear expectations.[88]

Box 3.4.

Innovation in insurance markets speaks to importance of covering climate risks

Risk-transfer

- Several US states, including Alabama, mandate premium discounts for homes built to fortified construction standards such as wind-resistant roofs and impact-resistant windows, supported by state grants to incentivize upgrades.[89]
- France's CatNat system, managed by Caisse Central de Réassurance, provides climate catastrophe coverage to insured property and infrastructure. It is funded by a surcharge and backed by a state-owned reinsurer with an unlimited government guarantee.[90]
- New York City's Metropolitan Transportation Authority issued a USD 100 million parametric catastrophe bond in 2023 to cover storm-surge risk.[91]

Other novel solutions and approaches

- AXA's sustainability-linked insurance in Asia explicitly reduces premiums and improves coverage terms when clients meet verified, hazard-specific resilience targets.[92]
- FM Global, a major commercial property insurer, conducts detailed on-site engineering assessments and bases premiums on verified risk-reduction actions rather than solely on historical loss data, creating a direct financial return on resilience investment.
- A California wildfire fund mutualizes risks across participating utilities.[93] For operators with restricted financial resources, creating such risk pools with peer operators spreads risk across multiple assets and potentially multiple geographies, reducing the aggregate premium burden while maintaining coverage.

Deploy capital: *Financial instruments, scale, and project preparation*

Realigning financing structures so they better reflect A&R's long-term economics can increase access to finance. A range of innovative financial instruments, available to both public and private infrastructure investors, operators, and utilities, have proven effective in incentivizing A&R investments when adapted to local contexts. Specific actions to increase access to A&R finance include:

Embed climate risk analysis in project preparation: A&R investments are generally characterized by higher upfront costs with benefits accruing over decades, making early-stage preparation critical to establish their financial viability. MDBs and DFIs can enhance preparation facilities to ensure climate risk analysis is embedded at the design stage, when adaptation measures are most cost-efficient and effective, with funding covering climate assessments, resilient project design, and the set-up of alternative cost recovery mechanisms. Operators can support this process by providing technical expertise, risk modeling, and feasibility studies, co-developing solutions with public authorities to ensure adaptation measures are both technically and financially sound. Incorporating A&R planning into project preparation allows for phasing of measures and activation of additional CAPEX/OPEX as conditions evolve throughout project lifetime.[94] Smaller and public utilities will likely need dedicated technical support from national development banks or DFIs/MDBs to build this capacity.

Align financing frameworks: Financing structures need to match A&R's long-term economics. Including adaptation in addition to mitigation in green finance frameworks—aligned with international standards—can help attract global capital. Loan maturity is a decisive factor: as demonstrated in the Brazil case studies, extending tenors often improves project viability more than marginal rate reductions. Longer-term loans match debt service with the longer-term realization of avoided losses and operational savings. Operators can also explore alternative cost recovery mechanisms, such as land value capture, carbon credits, and ecosystem service revenues from nature-based solutions, to strengthen the A&R business case, and if possible, diversify revenue streams.

Leverage resilience-linked finance instruments and targeted co-financing: With frameworks in place, deploying the right instruments at the right scale becomes possible.

- MDBs and DFIs can make strategic use of instruments such as concessional capital, resilience-linked finance, guarantees, and first-loss tranches to reduce risk and crowd in private investment, particularly for high-cost measures that deliver substantial social value. For example, IFC's sustainability-linked loans incentivize resilience through interest rates that become more favorable upon achieving verified resilience KPIs.
- Governments can deploy federal guarantees to help creditworthy subnational governments access capital markets at lower borrowing costs.
- Operators with sufficient scale can access resilience-linked instruments tied to verified A&R KPIs, so A&R outcomes are directly rewarded through better financing terms.
- Investors can condition capital access on achievement of verified resilience metrics and support performance-based contracts where payments depend on achieving KPIs. For investors, bundling smaller A&R investments into larger vehicles reduces transaction costs and attracts institutional investors otherwise deterred by scale and due diligence complexity.

Box 3.5.

International good practice: How tailored finance can catalyze resilience

Green/blue and sustainability-linked finance

SABESP benefitted from a 1.06 billion Brazilian reais (USD 183 million) IFC sustainability-linked loan in 2024, a USD 600 million IFC-led blue loan in 2025, and a record-breaking USD 1.35 billion blue bond in 2026, with pricing tied to water and sanitation resilience targets led by IDB Invest.[95]

Maynilad and Manila Water, two Philippines water and waste firms, successfully issued sustainability/ blue bonds to fund water security, wastewater treatment and climate-resilient infrastructure. The USD 500 million Manilla Water bond was oversubscribed four times when it was issued in 2020, with tighter interest rates than the initial guidance. Maynilad's 215 billion Philippine peso (USD 255 million) blue bond was more than two times oversubscribed when issued in 2024. It was followed by a 2025 IFC equity investment of USD 100 million, a cornerstone investment as part of the Maynilad's initial public offering.[96]

IFC's USD 120 million sustainability-linked loan to energy operator ENGIE Energia Peru links loan pricing to verified implementation of site-specific adaptation plans. The company's adaptation approach is phased, covering risk identification, baseline assessment, KPI design, target setting with time-bound milestones, and implementation with robust governance and reporting.

Santa Catarina, Brazil's USD 300 million World Bank financing supports the rehabilitation of a 1,262 km road. The financing comes with a performance-based infrastructure contract, which combines rehabilitation and routine road maintenance under a single, long-term contract, and embeds climate-resilient design.[98]

In 2015, the city of Paris, France, issued a EUR 300 million climate bond, which allocated EUR 85 million to urban heat island reduction projects that achieved adaptation targets by 2021. The success achieved required robust municipal expertise, external advisors, strong reporting/ transparency frameworks, strategic timing, and political commitment.[97]

In October 2025, Tokyo, Japan issued the world's first resilience bond certified under the Climate Bonds Initiative's Resilience Taxonomy. Proceeds of the 50 billion Japanese yen (USD 340 million equivalent) bond will fund flood infrastructure upgrades, coastal protection facilities, utility pole undergrounding, and seismic reinforcement.[99] Note that replicating this bond in smaller municipalities would require support from development partners, given resource requirements and the need for pre-existing climate plans.

Box 3.5.

International good practice: How tailored finance can catalyze resilience (continued)

Cost- and Revenue-sharing

A joint venture between the government of Mauritania and private infrastructure investor Meridiam will design, develop, and share costs and benefits of coastal resilience projects. Revenue-sharing mechanisms enable Meridiam to benefit from the economic value generated by improved resilience, such as new development opportunities enabled by the resilient infrastructure.[100]

The Malaysia government covered two-thirds of the cost of a stormwater management and road tunnel project in Kuala Lumpur, with private companies paying for the remaining one-third. The private operators recoup their investment by collecting tolls on vehicles, while the project delivers important flood protection benefits to maintain traffic flow during storms.[101]

Concessional finance

Indonesia's state-owned infrastructure finance company uses public and donor funds as first-loss capital to mobilize private investors, including for climate-resilient infrastructure. [102]

Grant funding from The United States Millennium Challenge Corporation covered 50 percent of the construction costs for Jordan's As-Samra wastewater treatment plant, boosting the reuse of wastewater for agriculture, and reducing water-stress risk in an arid country. The remaining finance comes from local-currency commercial debt and sponsor equity, backed by a MIGA guarantee.[103]

A USD 500 million World Bank credit-enhancement platform strengthens the guarantees for Mexico's national infrastructure fund, enabling an estimated USD 1 billion in mobilized private capital for resilient transport infrastructure.[104]

In Barbados, the upfront loans and grants from GCF and the Inter-American Development Bank (IDB) enabled a debt-for-resilience swap with a sustainability-linked loan from regional banks. This freed up USD 165 million for wastewater, agriculture resilience, and mangrove conservation.[105]

Blended finance facilities

Infrastructure investor Africa Finance Corporation's USD 750 million Infrastructure Climate Resilient Fund leverages USD 240 million in junior first-loss equity from the Green Climate Fund and USD 13.7 million for private and public project preparation. The fund aims to attract institutional investors, including African pension funds, sovereign wealth funds and insurance companies.

The Infrastructure Resilience Development Fund, created by several insurers that are part of the Insurance Development Forum, uses blended finance to support small- to medium-sized climate-resilient commercial infrastructure projects in EMDEs. IFC, among others, has signed onto the fund, which has a first close of USD 340 million.[106]

The USD 1.3 billion Scaling Resilient Water Infrastructure Facility, jointly supported by the Green Climate Fund and IFC, combines concessional loans and resilience project preparation support for water systems in EMDEs. The project structuring component is a grant facility to assist PPPs, helping to overcome the lack of public funding for project preparation and inadequate capacity to plan and prepare large-scale water projects.[107]

Coordinate: *Governance and system-level planning*

Fragmented governance can undermine otherwise sound financial and technical solutions. Increased coordination and collaboration across the ecosystem will enable the capture of system-wide benefits and reduce the risk of duplicated effort or fragmented, siloed efforts. Actions here include:

Mainstream A&R into planning and decision-making at all levels:

- Governments should integrate A&R into national and subnational infrastructure plans, explicitly addressing compound climate risks and interdependencies across sectors through climate stress testing. Include the private sector, financiers, and investors in planning processes to contribute technical knowledge and challenge feasibility, with mechanisms like national implementation alliances helping bridge gaps between national plans and local action.
- At the operator level, climate risk should be embedded into enterprise risk management and board-level decision-making, supported by staff training and, where feasible, dedicated resilience units. Operators should develop adaptation roadmaps with clear metrics, cost estimates, and implementation timelines, linking climate risk assessments directly to capital planning and operational practices.
- Institutional investors should treat resilience as part of their fiduciary duty to safeguard beneficiaries' long-term returns.

Pursue system-level approaches: Individual asset-level adaptation is insufficient when risks and benefits span multiple assets or sectors. Establishing centralized governmental resilience units can help to align sectoral plans, define resilience thresholds, and coordinate financing strategies. This approach will embed climate expertise within existing institutions—particularly PPP units, line ministries, and regulatory agencies—to mainstream A&R rather than siloing it. Operators within sectors should co-invest at the system-level—grid or watershed, for example—or across interdependent sectors to achieve economies of scale, with relevant public actors coordinating these efforts. Smaller public utilities should consider pursuing collaborative approaches, as the benefits of system-level action are greatest where individual operator capacity is most limited.

Strengthen DFI support for governance and planning: Building governance capabilities requires sustained technical support, particularly in lower-income EMDEs and least-developed countries. MDBs and DFIs can provide dedicated support to governments and regulators on integrating A&R into planning frameworks, PPP reform, and regulatory standards. DFIs can support operators to develop adaptation roadmaps that include clear KPIs, targets, and sustainability-linked finance opportunities, while helping design governance models that embed climate leadership across the organization. This includes supporting capacity building across the full value chain, from national planning through to operational implementation, to make sure that governance improvements translate into bankable, investment-ready projects. Please see Appendix 3 for examples of resilience KPIs.

Box 3.7.

International good practice: Panama Canal elevates climate resilience to the strategic level

With help from IFC, the Panama Canal Administration developed a comprehensive climate strategy to embed resilience into the organization's governance and decision-making at every level. The roadmap includes KPIs and targets tied to sustainability-linked finance opportunities. At the governance level, the strategy introduced climate leadership across the C-suite through the appointment of a chief sustainability officer and the development of structured stakeholder engagement plans.[108]

Recommendations

This study of investment opportunities in adaptation and resilience for infrastructure has yielded several recommendations on how to turn positive A&R potential into beneficial reality.

For governments

- Embed climate risk and A&R in public investment planning.
- Integrate future climate projections into building and engineering codes.
- Mandate climate risk assessments and A&R in PPPs and concessions.
- Clarify tariff and cost recovery rules for A&R.
- Improve data systems to unlock private capital.
- Use MDBs/DFIs to de-risk early investments.

For operators

- Integrate future climate projections into asset planning.
- Align engineering design with financial decision making.
- Use resilience investments to strengthen creditworthiness.
- Leverage regulatory allowances for cost recovery.
- Partner with insurers and financiers to demonstrate value.

For investors and financiers

- Integrate physical climate risk into due diligence and credit analysis.
- Develop and apply standardized resilience metrics.
- Incentivize resilience through pricing, tenor, or covenants.
- Partner with MDBs/DFIs to mitigate policy risk.
- Differentiate portfolios through proactive climate risk management.

APPENDICES

Appendix 1

Financial instruments across the asset lifecycle that enhance A&R

The global landscape of A&R financing is rich in instruments but fragmented in use. Concessional loans, PPP instruments, insurance schemes, and capital-market innovations are increasingly available for adaptation; however, in many countries their use remains limited, and a substantial share of adaptation-related spending continues to occur after climate shocks, rather than being systematically integrated into planning and investment cycles.

The best practice in terms of optimizing the use of these instruments is by developing a disaster risk financing strategy in which financing is used to first absorb and reduce the risk through A&R measures and then a range of instruments are used to finance the residual risk as well as to transfer a portion of it.

This appendix synthesizes A&R financing mechanisms into five categories, focusing on their financial implications: Lowering the Weighted Average Cost of Capital (WACC), stabilizing revenues, transferring risk, broadening investor access, and facilitating financing at scale. Each category is illustrated by practical global examples and provides guidance on which type of entities could access each mechanism.

1. Early-Stage Finance

Early-stage preparation is the most important in A&R finance, but often the weakest link. Robust climate risk studies and feasibility assessments inform location, necessary A&R measures, the set-up of alternative cost recovery mechanisms (like land value capture, and other key factors which are much more cost effective when integrated at the design and preparation-phase. The lack of project preparation funding in EMDEs, including for climate risk analysis, acts as a barrier for investing in A&R measures.

Which entities can access these funding opportunities?
National governments, municipalities, state-owned utilities, infrastructure funds accredited with climate funds (e.g. Meridiam, Africa Finance Corporation), project sponsors.

Financial implications
Concessional resources reduce project preparation costs, improve bankability, and attract co-financing. They lower the weighted average cost of capital (WACC) by blending grants or soft loans with commercial capital, while funding essential but non-revenue-generating activities such as hydrological modeling or vulnerability assessments. They also allow alternative A&R cost recovery by funding the set-up of land value capture systems and vehicles into which corporates in the area which benefit from an A&R measure can co-invest.

Examples

Project preparation funding is typically from Multilateral Development Bank (MDBs), especially if involved upstream, national Development Finance Institution (DFIs) for target sectors, and early-stage development funds, where there is off taker interest from government and sponsors have vested interest. These may include a climate component otherwise a few dedicated climate facilities have been set up including by climate funds.

- GCF-IFC's Scaling Resilient Water Infrastructure (RWI) Facility also provides project-preparation support for water utilities, including climate risk assessments and early-stage feasibility work, helping EMDE utilities integrate A&R considerations before capital investment decisions are made.
- City Climate Finance Gap Fund (European Investment Bank): Technical assistance to low- and middle-income cities for low-carbon, climate-resilient project preparation. EUR 100 million (USD 110.99 million) targeting a pipeline of EUR 4 billion (USD 4.4396 billion) in infrastructure projects.
- Project Preparation Facility (Green Climate Fund): Up to USD 1.5 million per application in grants, reimbursable and non-reimbursable, as well as equity, to support project/programme proposals to GCF. USD 66.6m for 107 grants to date.

2. Concessional Funding

Blended finance mobilizes private capital by using specific instruments and funds to improve the risk-return investment profile of a project including concessional loans, first loss tranches and guarantees. Evidence shows that blended structures can be effective mechanisms for mobilizing institutional and private finance into resilience-related infrastructure.

Which entities can access these funding opportunities?

- National governments can directly access concessional sovereign loans/grants
- State-Owned Enterprise (SoEs) can access via government guarantees or MDBs; private operators/concessionaires can access indirectly through PPPs, infrastructure funds or national development banks
- Local banks/funds can access on-lending concessional credit lines from MDBs or DFIs
- Municipalities/subnational entities access concessional/blended finance through development banks or climate funds and sometimes through sovereign guarantees
- PPP Special Purpose Vehicles (SPVs, project-level company under a PPP or concession) can structure blended finance at project level

Instruments

- Grant and Concessional loans: Below-market-rate financing that reduces WACC for public or quasi-public projects
- Viability Gap Funding (VGF): Public subsidies to close affordability gaps in critical projects.
- Blended finance: Public or philanthropic concessional funds to mobilize private capital by improving project risk return profile.
- First-loss tranches: Absorbs initial losses to protect senior investors improving their risk-return profile, and making investments more attractive to commercial investors by providing a de-risking mechanisms.
- Guarantees: Risk coverage for specific risk such as credit, political, or performance risks that enables private sector participation including commercial lenders

Financial implications
These tools lower operators' WACC for resilience retrofits or new climate-resilient infrastructure. For private or mixed operators, first-loss capital can absorb early risks, making projects bankable for commercial investors.

Examples

- Solengy Haiti (2025): International Finance Corporation (IFC) and IDB Invest (Inter-American Development Bank Group) provided USD 13.5m including a subordinated loan from the Canada-IFC Blended Climate Finance Program and a grant from the Korea Green, Resilient and Innovative Development (K-GRID) program to support solar-plus-storage resilience in a fragile market.
- The World Bank's International Development Association (IDA) Private Sector Window Blended Finance Facility combines concessional IDA funding with IFC investments. It supports infrastructure projects in high-risk markets, using first-loss capital, subordinated debt, and risk-sharing guarantees to attract private investment. These projects would not otherwise meet commercial financing terms.
- India VGF: The Indian government provided public subsidies to renewable energy PPPs which included climate resilience components through flood-proof plinths and resilient evacuation systems.

3. PPP and Regulatory Levers

Public–private partnerships (PPPs) are central to embedding A&R into infrastructure. How contracts reward resilience and allow it to be reimbursed determines whether resilience is systematically built in or sidelined.

Which entities can access these funding opportunities?
Public and private concessionaires in major infrastructure sectors like transport, water, and energy.

Instruments

- Availability payments: Reward service continuity under climate stress.
- Performance-based contracts: Link remuneration to resilience metrics (e.g., leakage reduction, uptime, maintenance).
- Adjustable tariffs/tolls: Allow A&R CAPEX to be recovered through regulated reviews.

Financial implications
Availability payments and Performance Based Contracts (PBCs) align the asset's performance and revenue which incentivizes revenue stability. Allowing A&R cost recovery through tolls/tariffs improves the Internal Rate of Return (IRR) and therefore the bankability of a project as investors would see regulated cost recovery as a stable revenue stream.

Examples

- National Grid Corporation of the Philippines (NGCP): Private utility NGCP is implementing grid upgrades including storm hardening and substation reinforcements which is treated as regulated CAPEX by the regulator. The A&R costs will therefore be recovered. The regulator uses performance-based regulation which strengthens financial incentives to provide efficient services.

- Metro Manila concessionaires' blue bonds: Maynilad Water Services, a private water utility under concession for Metro Manila, issued a Blue Bond in 2024, for water security, wastewater treatment, and climate-resilient investments. Under the Metropolitan Waterworks and Sewerage System's concession model, capital expenditures, including those financed through sustainable bonds and loans, are deemed recoverable through tariffs if they meet prudence and performance criteria.

4. Capital Market Instruments

Capital markets, with their expansive reach and deep pools of long-term liquidity, offer an unparalleled opportunity to attract private sector investment into climate resilient infrastructure. For example, green bonds, resilience bonds, and sustainability-linked loans can tap into the growing appetite among investors for climate-resilient investments. This not only helps bridge the financing gap but also aligns the interests of investors with the long-term goals of sustainable development. Within green finance, A&R has been much less of a focus than mitigation but its recent integration into green finance taxonomies such as the Climate Bond Initiative is set to accelerate investment.

Which entities can access these funding opportunities?
Any entity with borrowing capacity such as large utilities and SoEs, private corporates and operators, financial institutions, national and subnational governments, creditworthy municipalities, investment funds and asset managers, MDBs/DFIs.

Instruments

- Green bonds / loans: Use of proceeds is for climate projects that could include A&R.
- Sustainability-linked bonds / loans: Ties borrowing costs to the borrower's performance on sustainability metrics. This could be a step up where rates increase if metrics are not met or a step down where rates decrease if metrics are met. Resilience could be one of the sustainability metrics.
- Resilience bonds: Use of proceeds is for climate resilient projects.
- Resilience-linked bonds or loans: Ties borrowing costs to the borrower's performance on resilience metrics (e.g., outage reduction). This could be a step up or step down as described above.
- Infrastructure debentures/bonds: Long-maturity, instruments for infrastructure that can be tax-incentivized in certain countries (like Brazil) and could be adjusted to have resilience requirements (e.g. Brazil's Ministry of Transport has included climate resilience requirements for all tax-incentivized infrastructure debentures).

Financial implications
Green, sustainability-linked, and resilience bonds diversify the investor base, lower borrowing costs (WACC) for issuers, and strengthen transparency through performance-linked pricing. The enhanced A&R reduces credit risk for investors. Tax-incentivized infrastructure bonds would also lower the WACC.

Examples

- IFC – Georgia Global Utilities Green bond (2024): IFC anchored a USD 300m green bond for private utility GGU that will refinance its existing loans. This will establish a sustainable capital structure to finance its green CAPEX program including water loss reduction .Other MDBs and DFIs are also participating.

- IFC – Sabesp's Sustainability-linked loan (2024): IFC is providing a BRL 1.06 billion (USD 183 million) sustainability-linked loan to Sao Paulo water utility SABESP that will improve wastewater collection and treatment facilities and reduce wastewater in the largest river in Sao Paulo state. This will enhance the water supply reliability and therefore its resilience to future water scarcity. The SLL includes price incentives tied to increase the percentage of households connected to sewage collection and treatment systems. It also incentivizes targeting low-income communities.
- IFC - Engie Energia Peru's Green and Sustainability-Linked Loan (2025): IFC is providing a Green and Sustainability linked loan of USD 120m to Engie Energia Peru for renewable energy investments. It has three sustainability KPIs, one of which is to develop and implement advanced adaptation plans for all the company's sites by 2030. An external party will monitor progress every two years. This is the first tranche of the total loan that could go up to USD 600 million.

5. Risk-Transfer Tools

Climate risks in infrastructure projects can be substantially reduced through A&R but not fully eliminated. A disaster risk financing strategy allows for financial resources to avoid and reduce the risk (through adaptation), to absorb the risk (through resilience) and then to finance the residual risk through a mix of financing tools including reserve funds, debt and risk transfer tools. The latter are most cost efficient when covering very extreme events. Risk-transfer mechanisms provide liquidity after disasters, protecting balance sheets and service continuity.

Which entities can access these funding opportunities?
Private and public operators/utilities/concessionaires, governments and subnational governments.

Instruments
- Catastrophe insurance: Traditional insurance for property damage and business interruption which typically covers against multiple hazards during different stages of an infrastructure project from construction (all-risks construction) to implementation (operational property damage and business interruption and catastrophe reinsurance).
- Parametric insurance: Insurance payouts are triggered by climate hazard indicators and so can pay out automatically in real-time. The rapid payout is useful for liquidity needs for service continuity after an event.
- Catastrophe bonds: Natural catastrophe risk transfer that is backed by the capital markets instead of the traditional reinsurance market and therefore provides larger pools of capital.
- Risk pooling: Pools different natural catastrophe risks (e.g. different utilities or operators) together to optimize diversification by geography and hazard. A pool that transfers risk is much more cost efficient than risk transfer on an individual risk basis, given the diversification benefits.

Financial implications
These mechanisms provide liquidity for reconstruction without increasing debt levels. They stabilize post-disaster cash flows, protect fiscal space in the case of public actors, and improve credit ratings by reducing exposure to tail risks.

Examples

- Caribbean Catastrophe Risk Insurance Facility (CCRIF) for Electric Utilities: CCRIF provides parametric insurance for hurricane risk for electric utilities in the Caribbean triggered by hurricane wind speeds and paid within 14 days. The rapid payouts can be used for rapidly reinstating electricity provision.
- California Wildfire Fund: The fund provides financing to utility members that have claims from a wildfire caused by the utility. It therefore pools wildfire liability risk, with state backing.
- Los Angeles Department of Water and Power Catastrophe Bond (2025): The utility transferred USD 100m wildfire risk to capital markets using a type of parametric trigger. This covers both infrastructure damage and potential liability from fires it caused.

6. Programmatic and Policy-Based Approaches

Scaling adaptation requires moving beyond one-off projects. Programmatic and policy-based finance provide multi-year envelopes and embed resilience in reforms. Most multilateral banks have such programmes in place such as the World Bank's Program for Results, IDB's Resilient Infrastructure Facility, EIB's Climate Adaptation Program Loan. The GCF has also shifted to a programmatic approach.

Which entities can access these funding opportunities?
National governments, sectoral ministries, utility programs.

Instruments

- Programmatic financing: Bundles projects under long-term resilience strategies.
- Policy-based finance (PBF): Budget support conditional on reforms (e.g., mandatory risk screening in PPPs).

Financial implications
The main purpose of this type of financing is scalability. Programmatic lending reduces transaction costs, ensures predictable capital flows, and rewards systemic reforms such as mandatory climate risk screening or climate resilience requirements. By embedding resilience conditions into budget support, it creates a self-reinforcing policy-finance loop.

Examples

- World Bank Pro-Roads (Brazil): USD 1.66 billion programmatic financing for resilient state road networks that use performance based contracts to tie financing to achieving resilience metrics.
- Asian Development Bank Policy-Based Loan (Philippines): USD 500 million catastrophe contingent loan that links disbursements to reforms to better integrate disaster resilience in various sectors of the economy. This included improving policy and institutional arrangements for disaster risk management, building resilience of national government assets and Local Government Units to disaster and climate risks, and enhancing disaster risk financing.

7. Other financing sources

Other financing sources to incentivize A&R include land value capture (LVC) and carbon/biodiversity credits or Payment for Ecosystem Services (PES) that could generate additional revenue.

- LVC harnesses property tax/fees on increased land value around resilient infrastructure and is accessible to municipalities or subnational governments. Its financial benefit is to not only stabilize but to add to revenue for a resilient project. However, it only works in specific contexts. For example, it is challenging to put in place for low-income communities and for certain infrastructure sectors.
- Carbon/biodiversity credits or PES monetize co-benefits of Nature-based Solutions (NbS) such as watershed protection. This is accessible to operators or project sponsors and has the financial benefit of adding revenue to a project to partially compensate for the additional resilience costs. However, these instruments have hardly been used so far as the markets are nascent.

Conclusion

Depending on the entity seeking to integrate A&R into a project, there will be a plethora of financing instruments available to incentivize this by lowering the cost of capital, stabilizing or even generating additional revenue, providing liquidity after an extreme event, making projects bankable and allowing scale up. The benefits of each instrument can be combined for example concessional financing or guarantees applied to resilience linked bonds that tie costs to the achievement of resilience metrics could attract private capital markets to robust resilience investments. Or the set-up of utility pools could facilitate programmatic financing for resilience as well as more cost-efficient risk transfer. MDBs and DFIs have already pioneered several innovative resilience financing solutions that could be enhanced by increased private investor participation or be replicated by private investors given that A&R is not just a development objective but has a financial case for improving credit risk, stabilizing returns and protecting underlying assets and their ability to generate value.

Appendix 2

Illustrative A&R metrics for T&D, Water, and Road projects

Metric Category	Metrics	
	General	Sector-specific
Risk Reduction & Reliability	• Probability-of-failure reduction under specified climate hazard return periods (with/without adaptation). • Share of asset value exposed and protected against multi-hazard climate risks (flood, drought, wildfire, extreme heat, landslides). • Compliance with climate-adjusted engineering standards, including updated design return periods (e.g., 1-in-100-year climate-adjusted event). • Monetized avoided damages, based on ex-ante or ex-post climate impact modelling. • Integration of forward-looking climate analytics (hazard maps, downscaled projections, multi-scenario stress tests) in planning and design. • Redundancy level of climate-critical components, including alternative routing or backup capacity. • Coverage by climate-specific early warning, monitoring, and response protocols across operational sites. • Proportion of new investments incorporating climate-scenario projections into feasibility, design, and budgeting. • Uplift in asset robustness through adoption of climate-resilient materials, technologies, and digital condition-monitoring systems. • Protection coverage through engineered and nature-based solutions, expressed as a share of vulnerable asset segments.	**T&D** • Climate-adjusted SAIDI and SAIFI (System Average Interruption Duration / Frequency Index) for outages attributable to climate hazards. • Share of critical suppliers with climate adaptation plans (e.g., fuel, equipment, and key service providers). • Percentage of climate-exposed line segments and substations with targeted protection measures (e.g., firebreaks, tower footing reinforcement, flood barriers). **Water** • Reduction in Non-Revenue Water (NRW) attributable to resilience measures (leak detection, pressure management, pipe renewal). • Share of raw water sources (intakes, wells, reservoirs) with drought and water-quality protection measures (e.g., minimum environmental flows, backup sources, emergency abstraction rules). • Percentage of treatment plants and pumping stations with climate-resilient design upgrades (e.g., elevated equipment, flood-proof control rooms). **Roads** • Percentage of critical nodes in the road network with functional alternative routes under flood and landslide scenarios. • Average annual hours of road closure avoided on climate-exposed sections (relative to a historical baseline). • Share of high-risk slopes and stream crossings treated with stabilization or protection measures (e.g., retaining structures, rockfall barriers, culvert enlargement).
Service Continuity	• Service hours maintained during acute climate shocks (flood, heatwave, storm, wildfire). • Climate-attributable service outage hours benchmarked pre- and post-resilience investments. • Time-to-recovery performance, measured as the system's ability to return to baseline operational capacity. • Continuity of service for critical users, including emergency, industrial, and essential-service demand. • Network accessibility and operability during hazard events across critical nodes and corridors.	**T&D** • SAIDI and SAIFI improvement during and after climate events, compared with pre-investment baselines. • Percentage of critical load served during extreme events (hospitals, emergency services, key industries). • Maximum duration of controlled load-shedding events under defined climate scenarios.

<table>
<tr><th rowspan="2">Metric Category</th><th colspan="2">Metrics</th></tr>
<tr><th>General</th><th>Sector-specific</th></tr>
<tr><td>Service Continuity</td><td>• Readiness and effectiveness of emergency response protocols, demonstrated through testing and exercises.
• Avoided cascading failures, including downstream network disruptions prevented by resilience measures.
• Maintenance of key quality-of-service parameters (e.g., pressure, voltage, throughput, travel time) under climate stress.
• Operational continuity of climate-critical facilities (e.g., substations, treatment plants, interchanges) during extreme events.
• Performance of contingency and backup systems, including autonomous operation capabilities</td><td>Water
• Hours of continuous water supply maintained during droughts or floods, disaggregated by customer class if possible.
• Number of customers affected per climate-related service disruption avoided (before/after investment).
• Share of wastewater treatment capacity that remains fully operational during heavy rainfall events.
Roads
• Average daily traffic (ADT) maintained on climate-exposed links during extreme events, as a percentage of baseline ADT.
• Time to restore minimum passability for emergency vehicles on affected corridors.
• Accessibility of critical services maintained (e.g., share of hospitals, schools, logistics hubs that remain reachable during climate events).</td></tr>
<tr><td>Economic/ Social Benefits</td><td>• Direct economic losses avoided from reduced downtime, asset damage, and business interruption.
• Gross value added (GVA) preserved through uninterrupted infrastructure service provision.
• Employment safeguarded or generated by climate-resilient operation and investment.
• Public health gains, including reduced exposure to contamination, heat, or disaster-related hazards.
• Continuity of essential public services (water, energy, mobility, sanitation) during climate extremes.
• User cost savings, including avoided travel time, avoided emergency procurement, and reduced service substitution costs.
• Population protected from climate hazards, measured in terms of service reliability and reduced exposure.
• Resilience dividends for enterprises, particularly micro, small, and medium enterprises reliant on uninterrupted service.
• Avoided health expenditures and social protection costs, reflecting reduced climate-induced morbidity and safety risks.
• Reduction in disaster relief and emergency response expenditure.</td><td>T&D
• Monetary value of avoided outage-related penalties and non-supplied energy due to resilience measures.
• Change in electricity quality for key industrial users during climate events (e.g., voltage stability, reduced forced shutdowns).
• Number of jobs preserved in energy-dependent industries thanks to reduced outage duration.
Water
• Reduction in losses from emergency water trucking and temporary supply arrangements.
• Avoided cases of waterborne disease outbreaks linked to resilient water and sanitation operations.
• Economic value of maintained water supply for priority users (e.g., hospitals, major employers, irrigated agriculture).
Roads
• Number of traffic accidents avoided on climate-exposed sections due to improved drainage, slope stabilization, or road safety features.
• Value of freight and passenger delays avoided (time and operating costs) during extreme events.
• Share of regional GDP that remains physically connected to national and export markets during climate shocks.</td></tr>
<tr><td>Regulatory Alignment</td><td>• Alignment with national and subnational climate-resilience standards, codes, and regulatory updates.
• Eligibility for climate-related tariff adjustments and extraordinary regulatory reviews linked to resilience expenditure.
• Compliance with availability-based and performance-based regulatory obligations during climate events.
• Achievement of accredited resilience certifications, such as Climate Bonds Initiative resilience criteria or ICMA-aligned frameworks.</td><td>T&D
• Percentage of T&D assets with resilience requirements explicitly included in concession or license conditions.
• Share of capital expenditure on adaptation that regulators recognize in the Regulated Asset Base (RAB) or equivalent.
• Number of resilience-related non-compliance events (e.g., failure to meet post-event restoration targets).</td></tr>
</table>

Metric Category	Metrics	
	General	Sector-specific
Regulatory Alignment	• Activation of regulatory incentives, including accelerated depreciation, resilience allowances, or regulatory asset base mechanisms. • Conformance with climate-resilient procurement standards, including supplier climate-risk disclosures. • Share of capital investments classified as "resilience-aligned" under regulatory or investor taxonomies. • Reduction in climate-related non-compliance or penalty events. • Eligibility for resilience-linked financial instruments, including green, sustainability-linked, and resilience bonds. • Integration of resilience KPIs in concession agreements, service contracts, and PPP regulatory frameworks.	**Water** • Compliance with drinking-water and effluent quality standards during climate extremes (e.g., share of days in compliance under heavy rainfall or drought). • Percentage of water and sanitation concessions or performance contracts that include explicit climate-resilience KPIs. • Share of tariff reviews that explicitly assess and approve A&R-related CAPEX and OPEX. **Roads** • Service Level Agreement (SLA) compliance for road availability under defined climate thresholds (e.g., maximum days of lane closure per year). • Share of road concessions that include mandatory A&R spending or climate-resilience performance requirements. • Percentage of reconstruction and major rehabilitation projects that apply updated, climate-adjusted design standards.

Table 3.1 – Example of sectoral Adaptation and Resilience (A&R) Metrics, including metrics from the International Capital Markets Association (ICMA). This table summarizes metrics that can be used to measure the impact of A&R measures across T&D, Water and Roads projects. The metrics are organized by thematic category to align with how infrastructure operators and regulators assess performance. Certain metrics may need to be adjusted by the user to ensure measurability.

Each metric provides a tangible way to quantify and compare resilience outcomes such as technical improvements (e.g. reduced failure probability, improved service continuity) as well as financial and regulatory implications (e.g., avoided losses, tariff adjustments, or compliance with resilience standards).

- Indicators in Risk Reduction and Reliability and Service Continuity categories: could be embedded within performance-based contracts such as Resilience Linked Bonds with payments tied to achieving pre-agreed thresholds or within concession monitoring frameworks to evaluate the effectiveness of A&R interventions. They could also be used in investment appraisals to evaluate a project's climate resilience or in operational performance tracking for operators.
- Indicators in the Economic and Social Co-Benefits category: could be used by public actors to assess the wider co-benefits of certain A&R measures such as economic productivity preserved and jobs preserved.
- Indicators in the Regulatory Alignment category: could be used by operators or investors to assess the probability that A&R measures would be covered by tariffs and therefore more attractive financially.

Appendix 3

Business Case Methodology

1. Data Gathering and Climate Risk Assessment

Hazard

Climate hazards were assessed using a combination of global and regional climate models downscaled and aggregated through Scientific Climate Ratings' model and AXA Climate's Altitude platform for additional insights.

- **Scientific Climate Ratings' model** is able to provide projections for multiple hazards and climate scenarios depending on the project needs. In this case, the analysis focused on floods, storms, and wildfires. These hazards were quantified using downscaled data from CMIP6 (Coupled Model Intercomparison Project Phase 6), which compiles simulations from leading global climate models such as the Geophysical Fluid Dynamics Laboratory model (GFDL-ESM4), Institut Pierre-Simon Laplace model (IPSL-CM6A), Max Planck Institute model (MPI-ESM1-2), Meteorological Research Institute model (MRI-ESM2), and the United Kingdom Earth System Model (UKESM1). Regional climate information was drawn from CORDEX (Coordinated Regional Climate Downscaling Experiment). Exposure was defined as the financial value and service output of each asset, and vulnerability as the sensitivity of asset components to hazard intensity. Additional external datasets were used for specific hazards, including high-resolution flood maps; IBTrACS (International Best Track Archive for Climate Stewardship) for tropical cyclones; and wildfire data from NASA satellite observations.
- **AXA Climate Altitude (Software as a Service platform)** generates hazard projections under three emissions pathways (SSP1-2.6, SSP2-4.5, SSP5-8.5), using validated Global Climate Models (e.g., GFDL (Geophysical Fluid Dynamics Laboratory), MIROC (Model for Interdisciplinary Research on Climate), IPSL (Institut Pierre-Simon Laplace), HadGEM (Hadley Centre Global Environment Model)) and statistical downscaling via the Cumulative Distribution Function transform (CDF-t) against ERA5 reanalysis data. Altitude uses Fathom (flood), WRI (World Resources Institute) Aqueduct 4.0 (water stress), MIT (tropical cyclones), LHASA (Landslide Hazard Assessment for Situational Awareness)/AXA (landslides), IPCC/NASA (sea-level rise) and MODIS/ECMWF ERA5 (Moderate Resolution Imaging Spectroradiometer)/ ECMWF ERA5 (European Centre for Medium-Range Weather Forecasts Reanalysis v5) (wildfires).

For the three climate risk screenings, floods, storms, and wildfires were selected as material hazards for financial modelling, given their relevance to the studied assets and their high potential to erode Net Asset Value (NAV). Other hazards such as extreme heat and landslides were included in additional hazard assessments conducted with Altitude for comprehensiveness but not modelled in the financial analysis.

For the reservoir system case, drought was also selected for financial modelling. Supplementary hydrological modelling was carried out by Suez using a simplified EPA SWMM (United States Environmental Protection Agency Storm Water Management Model) model calibrated with public rainfall records collected by SABESP (São Paulo State Basic Sanitation Company) (2000–2024), outflow records from SABESP, and ERA5 evapotranspiration data. The model was stress-tested under two "worst case" climate scenarios (GFDL 2030 RCP8.5 and ACCESS-CM2 2030 RCP8.5) to capture drought variability and estimate the cost of inaction.

Exposure

Transmission Line:

- Financial value: Free Cash Flow to Equity (FCFE) estimated from regulated revenues (RAP) (2021–2024) as defined in the concession contract, scaled using Índice Setorial de Preços ao Produtor Amplo (SIPA) utility benchmarks; reconstruction cost based on comparable 500 kV transmission and substation projects (e.g., Graça Aranha–Silvânia, CTEEP) and verified against concession contract values. Typical costs range between USD 0.8–1.2 million per km, consistent with regulatory benchmarks.

Reservoir Water System:

- Financial value: Revenues of ≈BRL 3 billion (USD 517 million) were estimated using flow and tariff proxies, based on the reservoir's delivery multiplied by SABESP's 2024 average tariff (BRL 5.03/m³). Fixed assets ≈BRL 8–9 billion (USD 1.38–1.55 billion) were derived from physical replacement proxies, scaling the São Lourenço PPP system (6.4 m³/s, BRL 2.21 bn (USD 381 million)) and adding the Jaguari–Atibainha interconnection ≈BRL 0.8 bn (USD 138 million) to reflect equivalent replacement supply capacity; FCFE derived from SIPA utility benchmarks based on the ratio FCFE-to-revenue.

Sao Paulo Road Concession:

- Financial value: Tariff revenues and FCFE projected to 2055 by the concession agreement; reconstruction costs estimated using World Bank Road Costs Knowledge System benchmarks for South America. This results in an estimated total reconstruction cost of USD 1.05 billion for the entire motorway asset.

Vulnerability

The financial impacts on assets were modelled as a combination of direct capital losses (CAPEX impacts) and revenue losses from business disruptions.

- **Direct damages:** Impacts on NAV were estimated as the share of NAV eroded by hazard events, using sector-specific damage functions:
    - *Floods:* The flood risk model draws on Gabriels et al. Annual average expected loss is computed from the probability–intensity distribution of events, applying 32 damage functions drawn from the literature. In this case, the damage functions were selected based on their relevance to the asset, considering three types: (1) one corresponding to a water treatment plant in the United States, (2) a global damage function for road assets, and (3) transmission assets specific to the United States. (2021) and Kellermann et al. (2015)
    - *Storms:* Storm impacts use the functions developed by Unanwa et al. (2000), which provide global calibrated curves depending on the relative height and the general use of the assets.
    - *Wildfires:* The wildfire damage function is based on Lüthi et al. (2021). It integrates the probability of fire occurrence (derived from more than 20 years of satellite-based observations), vegetation cover around the asset, and projections of the Fire Weather Index under each climate scenario.
- **Business disruptions:** Service interruptions were modelled following Mandel et al. (2025). The number of interruption days scales proportionally with the degree of capital stock loss, allowing hazard magnitude to be translated into lost business days and revenue shortfalls. Sector-specific coefficients from the US Federal Emergency Management Agency (FEMA) were applied to differentiate impacts across infrastructure types.

2. Resilience Building – Identifying Adaptation Options

Hypothetical adaptation strategies were identified for floods, storms, and wildfires. Measures were parametrized using the Climatech/EDHEC database to ensure consistency in capital and operational expenditure (CAPEX/OPEX) ranges and expected protection levels. Two financing modalities were tested:

- **Debt financing** with CAPEX amortized over ten years.
- **Upfront CAPEX** payment in year one.

Each adaptation measure was integrated into the asset financial modelling to calculate the reduction in asset damage (reconstruction costs) and service disruption (expressed in percent NAV). Results are presented through avoided losses, cost impacts, and the benefit–cost ratio (BCR). Measures that address the same hazard cannot be summed because they protect against the same damages and therefore overlap.

3. Economic and financial analysis

Financial analysis

Damages were estimated as the share of Net Asset Value (NAV) lost due to hazard impacts. Service disruptions were modelled following Mandel et al. (2025), with business-day interruptions proportional to the degree of capital stock loss and sector-specific coefficients from FEMA.

Macroeconomic and financial assumptions were drawn from Oxford Economics' Global Climate Service scenarios, which are derived from the IPCC Shared Socioeconomic Pathways (SSPs). These scenarios incorporate:

- Demographic and socioeconomic foundations (population, income, productivity, emissions).
- Country-level macroeconomic variables (GDP growth, inflation, interest rates, investment).
- Financial market dynamics (capital costs, risk premia).
- Climate damage functions linking physical risks to macroeconomic shocks.
- Policy assumptions reflecting different decarbonization pathways.

The analysis considered seven pathways: Baseline, Slow and Constrained, Net Zero, Net Zero Transformation, Delayed Transition, Climate Distress, Climate Catastrophe (aligned with a high-emissions scenario, roughly >3°C by 2100), and an Expected scenario (weighted average across all). The results from these scenarios are available in the raw data. Only the Baseline and Climate Catastrophe scenarios were considered in the report.

Financial valuation was undertaken through Discounted Cash Flow (DCF) analysis:

- *Time Period:* 2025 as the base year, 2026 as the first operational year, finishing in 2042 for the T&D case, and in 2050 for the other two assets.
- *Discount rates:* The costs of equity have been computed using the Oxford Economics' scenarios risk free rates for Brazil, with an asset-specific risk-premia based on a set of assets in Brazil and in similar sectors, with similar characteristics using Scientific Infra and Private Assets (SIPA) metrics.

Sensitivity analysis

The sensitivity analysis was integrated into the financial modelling and run across all climate scenarios to assess the robustness of adaptation investments under different financial and environmental conditions. Only the Climate Catastrophe (a high-emissions scenario) scenario was considered in the report.

The analysis evaluated how variations in loan maturity and interest rates affect the internal rate of return (IRR) for each bundled option. Sensitivity testing was tailored to the financing profiles of each asset. For the transmission and distribution network and the road infrastructure asset, simulations were run for loan maturities of 6, 10, and 15 years and interest rates of 11.67 percent, 13.17 percent, and 14.67 percent. These assets are treated as project finance structures, whereas the reservoir asset was analyzed as a corporate loan with parent guarantee. The reservoir asset was analyzed under the same range of maturities (6, 10 and 15 years) with different interest rates of 14.05 percent, 15.55 percent and 17.05 percent.

By running the analysis across different financing parameters, the exercise allows to test whether the investments remain viable under multiple financing scenarios and enables to account for economic uncertainty and financial volatility.

4. Analysis of Socio-Economic Co-Benefits

Co-benefits, the additional outcomes from a project (A&R measures) which benefit society more broadly, were estimated using multi-regional input–output (MRIO) data from EXIOBASE. Avoided revenue losses from adaptation were translated into socio-economic effects by applying sector-specific multipliers for Gross Value Added (GVA) and employment (per EUR of output). Each infrastructure asset was mapped to the closest EXIOBASE sector: roads to Land transport, reservoirs to Water supply, and transmission lines to Electricity transmission and distribution. This allowed avoided losses to be expressed as tangible contributions to economic value and jobs.

5. Limitations

The study relies on simplified climate risk, hydrological, and vulnerability models using daily timesteps and benchmark-based financial assumptions. The results should therefore be understood as illustrative, indicating the business-case logic and the general order of magnitude of benefits, rather than as asset-specific risk assessments. Detailed, operator-led modelling would be required to inform actual investment decisions.

The findings should be interpreted with due consideration of several sources of uncertainty. First, significant variability exists in the underlying physical risk data, driven by differences across climate models, emissions pathways, and spatial resolutions. Second, the damage functions used, while tailored to sectoral and geographic contexts, remain generic and not asset-specific, which may affect the accuracy of estimated losses. Third, macroeconomic variables are drawn from Oxford Economics projections, which depend on global assumptions that may change over time. Similarly, the financial parameters rely on a simplified, normative cash flow approach intended to reduce assumptions, but which inevitably introduces approximation. There is also uncertainty related to the risk premium, derived from SIPA data and not calibrated to specific assets, which may influence valuation precision. Finally, the efficiency and cost of adaptation measures can vary widely depending on implementation conditions and technological performance, further contributing to the uncertainty range.

6. Comparison to other case studies and methodologies

The methodology underpinning the Business Case Studies converts current and projected climate-exposure and loss impact data into quantified avoided-loss estimates and indicative benefit–cost ratios for every A&R measure for a given asset. It does not replace on-the-ground, detailed engineering analysis but rather identifies where this should be targeted. The model is a decision-support instrument that identifies at a high level where deeper site-specific feasibility analyses should be conducted:

- It supports portfolio screening - identifying measures that could be technically feasible and financially attractive enough to warrant deeper design.
- It produces finance-ready outputs (NPV, IRR, BCR, payback, cost per avoided-loss unit) that can open a dialogue with lenders and regulators on the value for money of adaptation measures. These baseline metrics can then be refined through site-specific cost and performance data.
- It can guide regulatory dialogue on which measures may justify public co-investment, tariff recognition, or blended-finance support.

How does this methodology differ from PCRAM? PCRAM is a framework for conducting in-depth climate risk assessments of infrastructure. It requires extensive local data and customized analysis for each site. In contrast, this study's methodology offers a streamlined approach for faster screening across multiple assets. Both can be applied to individual assets or portfolios, but PCRAM is more detailed and resource-intensive while this methodology enables quicker and broader analysis. Organizations can use this approach first to identify priorities, then apply PCRAM for deeper analysis of selected asset.

How can stakeholders use these results?

- **Investors and lenders:** use the relative ranking of measures to prioritize which actions to test further in due diligence, and to inform the design of sustainability-linked KPIs or blue-loan eligibility criteria. High future risk could also signal that the lender/investor should require more insurance to be purchased.
- **Operators and concessionaires:** integrate the most cost-efficient measures into medium-term CAPEX planning, then commission engineering analysis and local cost validation to confirm feasibility. Increased insurance would also be a consideration for high future risk.
- **Regulators and policymakers:** identify high-benefit but lower-commercial-return measures that may justify co-financing or tariff incentives, ensuring that resilience investments with strong social spillovers can proceed.

The model's results are indicative and should be interpreted as providing a high-level understanding of potential risks and priorities. They are not a substitute for detailed, site-specific analysis and must always be refined and validated through comprehensive engineering, hydrological, and reliability studies before implementation.

A growing body of research has sought to quantify the financial and economic value of resilient infrastructure. These studies differ markedly in their data needs, analytical depth, and type of outputs, and therefore complement the methodology applied in this report. The most relevant studies are grouped into three categories: (A) project-level case studies, (B) methodological frameworks, and (C) macro- and scenario-based analyses:

A. Project-Level Case Studies

These studies provide quantified evidence of avoided losses and economic returns from resilience investments, similar in intent to this report.

- **U.S. Chamber of Commerce (2025). Beyond the Payoff: How Investments in Resilience and Disaster Preparedness Protect Communities.** Demonstrates measurable economic benefits from infrastructure resilience, including preservation of over 70,000 jobs following hurricane events in the U.S. Highlights local case studies showing benefit–cost ratios above 4:1. The methodology requires community-level employment data, regional economic indicators, and disaster impact assessments as inputs, and produces job preservation metrics, community-wide economic impacts, and aggregate benefit-cost ratios as outputs. This differs from the present report by measuring community-level socioeconomic impacts rather than asset-level financial returns, producing economic multipliers rather than infrastructure cash flow projections.
- **U.S. Environmental Protection Agency (EPA) (2025). Case Studies for Preparedness and Resilience (ARC-X).** Features multi-sector, place-based adaptation projects with documented operational outcomes. The case studies require site-specific hazard data, adaptation measure specifications, and implementation timelines and costs as inputs. They produce qualitative performance narratives, implementation lessons, and operational outcomes (e.g., reduced flooding frequency, improved service continuity) as outputs. This differs from the present report by producing implementation guidance and operational metrics rather than standardized financial valuations, focusing on lessons learned rather than investor decision-making metrics like NPV or IRR.
- **Zurich Flood Resilience Alliance (2024). Compendium of Green Infrastructure Case Studies.** Presents financial and operational outcomes from flood management projects combining gray and green infrastructure. The analysis requires hydrological data, ecosystem service valuations, and project construction and maintenance costs as inputs, producing flood damage reduction estimates, ecosystem co-benefits quantification, and project-specific ROI calculations as outputs. This differs from the present report by emphasizing nature-based solution co-benefits (e.g., biodiversity, water quality) alongside avoided flood losses, whereas this report focuses on engineered infrastructure across multiple hazard types with standardized financial metrics.
- **European Environment Agency (EEA) (2024). Climate-ADAPT Case Studies Database.** Documents adaptation actions implemented across Europe, with qualitative assessment of performance and replicability. The database compilation requires policy documents, implementation reports, and stakeholder interviews as inputs, and produces qualitative effectiveness assessments, replicability scores, and policy recommendations as outputs. This differs from the present report by producing policy-oriented qualitative evaluations rather than quantitative financial valuations, designed for knowledge sharing among policymakers rather than investment analysis.

B. Methodological Frameworks and Tools

These references describe structured approaches for assessing climate risk and adaptation value, complementing the applied methodology used in this report.

- **IIGCC (2025). Physical Climate Risk Assessment Methodology (PCRAM) 2.0.** Provides the most advanced investor-focused framework for asset-level climate risk appraisal. The methodology requires high-resolution climate projections (≤10km grid), asset-level engineering specifications, detailed exposure inventories, vulnerability functions calibrated to specific asset types, and operational continuity data as inputs. It produces probabilistic damage estimates by return period, expected annual losses, value-at-risk metrics, and time-series projections of climate impacts under multiple scenarios as outputs. This differs from the present report in that PCRAM requires site-specific, engineering-grade data that may not be available at portfolio screening stage and produces probabilistic risk distributions. The present report uses standardized hazard-vulnerability relationships and produces simplified avoided-loss estimates suitable for initial portfolio screening—identifying which assets warrant deeper PCRAM-style assessment.

- **OECD (2023). Integrating Climate Change in Infrastructure Project Appraisal.** Offers detailed guidance on embedding climate adaptation into cost–benefit analysis (CBA) and multi-criteria decision-making. The framework requires climate scenarios, project design specifications, monetized impacts across all cost and benefit categories (market and non-market), discount rates, and distributional weights as inputs. It produces net present social value, benefit-cost ratios, multi-criteria scorecards, and sensitivity analyses across climate scenarios as outputs. This differs from the present report in that the OECD approach requires comprehensive economic valuation of all project impacts (including externalities like carbon, health, and equity) and produces social welfare metrics. The present report applies a narrower financial lens focused on avoided infrastructure losses and revenue preservation, producing investor-oriented financial returns (NPV, IRR) rather than social CBA metrics.
- **European Commission – JASPERS (2014). Guide to Cost-Benefit Analysis of Investment Projects.** Remains the primary EU reference for infrastructure CBA. Adaptation valuation is one element within a broader appraisal framework. This report builds on it by explicitly quantifying resilience benefits and avoided losses in financial terms. Remains the primary EU reference for infrastructure CBA. The guide requires detailed project engineering and cost data, traffic/demand forecasts, shadow prices for economic resources, and monetized environmental and social impacts as inputs. It produces economic NPV, financial NPV, economic rate of return, distributional impact tables, and sensitivity and risk analyses as outputs. This differs from the present report as a comprehensive socioeconomic appraisal tool requiring extensive data inputs for all project impacts, where adaptation is one component within broader project justification.

C. Macro- and Scenario-Based Analyses

These studies quantify resilience benefits at national or global scales, providing the macroeconomic context for project-level results.

- **World Bank (2019). Lifelines: The Resilient Infrastructure Opportunity.** Demonstrates that resilient infrastructure yields average benefit–cost ratios above 4:1 globally, using macroeconomic modeling. The analysis requires national infrastructure inventories, macroeconomic input-output tables, historical disaster loss databases, and climate projections at country/regional scale as inputs. It produces aggregate national/global benefit-cost ratios, GDP impact estimates from infrastructure disruption, and infrastructure investment needs by country as outputs. This differs from the present report by using computable general equilibrium (CGE) and input-output models to estimate economy-wide impacts and producing country-level aggregates. The present report conducts bottom-up asset-level financial analysis producing project-specific returns rather than macroeconomic multipliers.
- **World Bank (2019). Strengthening New Infrastructure Assets: The Economic Case for Resilience.** Quantifies macroeconomic impacts of infrastructure disruption and the economic returns to resilience investments. Provides a foundation for the avoided-loss modeling applied here. Quantifies macroeconomic impacts of infrastructure disruption and the economic returns to resilience investments. The methodology requires infrastructure service disruption scenarios, economic dependency matrices, historical disaster databases, and population and economic activity distributions as inputs. It produces estimates of GDP losses from infrastructure failure, economic returns to

resilience at national scale, and infrastructure risk indices as outputs. This differs from the present report by modeling indirect economic losses through supply chain and service interruptions using macroeconomic frameworks, producing economy-wide impact estimates. The present report focuses on direct infrastructure asset losses and revenue impacts, producing financial returns from the asset owner/investor perspective rather than societal economic welfare measures.

Endnotes

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11 L'Her, Guillaume et al. 2024. Transport Resilience and Adaptation to Climate Impacts: A Case Study on Agricultural Transport in Brazil. Complex Networks and Their Applications XII. pp 243–50, doi.org/10.1007/978-3-031-53503-1_20.

12 World Bank Group and IMF Development Committee. Foundations for Growth and Jobs. September 26, 2025. https://www.devcommittee.org/content/dam/sites/devcommittee/doc/documents/2025/Final_DC2025-0004.pdf

13 See: United Nations Environment Programme. 2025. Adaptation Gap Report 2025. www.unep.org/resources/adaptation-gap-report-2025. Also note that these numbers likely understate actual investment, as many private and project-level resilience measures are not tagged as adaptation. Moreover, differences between adaptation and mitigation finance tracking methodologies limit direct comparability and mean that aggregate adaptation flows may not fully capture the breadth of activity underway. Going forward, it will be important to enhance data collection and tracking to better understand the investment landscape.

14 Investor Group on Climate Change (IGCC). 2025. Physical Climate Risk Assessments of Infrastructure Assets: Synthesis Report, May–December 2024. https://igcc.org.au/wp-content/uploads/2025/06/IGCC-Physical-Climate-Risks-Assessments-of-Infrastructure-Assets.pdf.

15 Climate Policy Initiative. 2025. The Cost of Inaction. www.climatepolicyinitiative.org/the-cost-of-inaction/

16 The analysis uses forward-looking climate modeling to assess infrastructure performance under future climate scenarios.Net asset value (NAV) impact: NAV—the projection of future cashflows actualized with a discount rate—was calculated both without A&R measures, where NAV declines due to physical damage (CAPEX reconstruction costs) and service interruptions (revenue shortfalls or regulatory penalties), and with A&R measures, where NAV is preserved. The analysis quantifies both the reduction in NAV from climate impacts and the increase of NAV from implementing A&R measures. Internal rate of return (IRR): The IRR was calculated specifically for each individual A&R measure by comparing the measure's implementation cost against the discounted stream of

avoided losses over the asset's operational life. Flood risk was quantified by overlaying asset boundaries on global fluvial, pluvial, and coastal flood-depth maps (current and Aqueduct scenario horizons), converting pixel-level depths to relative damage via asset-specific fragility functions, aggregating by zonal statistics to obtain asset damage for each return period, and then combining across return periods—and multiplying by asset values—to derive expected annual loss. Wildfire risk was quantified by overlaying the asset footprints on satellite-derived burn-date probability maps (MODIS), adjusting probabilities for local vegetation density and Fire Weather Index–based climate projections, converting pixel-level burn probabilities to relative damage using a conservative function (damage = 1 for any burn event), aggregating via zonal statistics to asset level, and multiplying by asset value to derive expected annual loss.

17 For example, in response to wildfires, upgrades have included remote monitoring systems, weather forecasting tools and stakeholder and community engagement to enhance early detection and coordinated responses.

18 Independent Authority for Fiscal Responsibility (AIReF). Economic Implications of Climate Change: Oxford Economics Climate Scenarios, Main Impact Channels and Results. Supporting document 5/25. March 31, 2025. https://www.airef.es/wp-content/uploads/2025/04/Documentos-tecnicos-segunda-opinion-sostenibilidad-a-largo-plazo-AAPP/250324.-ECONOMIC-IMPLICATIONS-OF-CLIMATE-CHANGE.pdf

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20 Empresa de Pesquisa Energética (EPE). 2025. Fact Sheet on Impacts of Climate Change on the Brazilian Transmission Grid. www.epe.gov.br/en/press-room/news/epe-publishes-fact-sheet-about-impacts-of-climate-change-on-the-brazilian-transmission-grid

21 IPCC, 2021-2023, Sixth Assessment Report, Working Group 1, Regional Fact Sheet – Central and South America, https://www.ipcc.ch/report/ar6/wg1/downloads/factsheets/IPCC_AR6_WGI_Regional_Fact_Sheet_Central_and_South_America.pdf

22 World Bank. 2023. Brazil Country Climate and Development Report. https://openknowledge.worldbank.org/server/api/core/bitstreams/fd36997e-3890-456b-b6f0-d0cee5fc191e/content

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24 Rodrigues, Robeson. "Power Outages Highlight Vulnerabilities in Brazil's Energy Sector." Valor International. November 21, 2024. https://valorinternational.globo.com/business/news/2024/11/21/power-outages-highlight-vulnerabilities-in-brazils-energy-sector.ghtml

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26 A complementary assessment using AXA Climate's Altitude tool also identified extreme heat as a high-risk hazard that could significantly reduce line performance. In addition, changing air temperature, and landslides are projected as a medium risk by 2050, due to intense precipitation and terrain susceptibility. For the actual financial analysis, only three hazards were modeled while landslides, extreme heat and changing air temperature were excluded.

27 Although modeling results rate storms as a low risk, operational evidence shows otherwise. Since 2012, the operator has recorded five major thunderstorm events linked to downbursts: localized convective winds that damaged guyed and self-supporting towers. These events, often undetected by Brazil's sparse meteorological network, impose loads exceeding design standards by over 50 percent and complicate regulatory recognition of exceptional damage. The operator is already taking this risk into account. This suggests storm risks are underestimated in current models and should be treated more conservatively in resilience planning.

28 Damage functions used in the analysis are drawn from peer-reviewed sources: Gabriels et al. (2021) and Kellermann et al. (2015) for floods, Unanwa et al. (2000) for storms, and Lüthi et al. (2021) for wildfires.

29 The cost of equity was estimated using Oxford Economics' scenario-based risk-free rates for Brazil, combined with asset-specific risk premia derived from comparable assets in Brazil and similar sectors identified in the SIPA metrics database. 2025. https://sipametrics.com/

30 The discount rate is built as the sum of the risk-free rate (given by the climate scenario considered) and of risk premia. For this asset, under the SSP2-4.5 scenario, the risk-free rate is expected to be 13.8%, vs 13.9% under the SSP5-8.5. Macroeconomic conditions linked to GDP growth and emissions trajectory could impact this metric, explaining the slight difference in rates here.

31 The cost of equity was estimated using Oxford Economics' scenario-based risk-free rates for Brazil, combined with asset-specific risk premia derived from comparable assets in Brazil and similar sectors identified in the 2025 SIPA metrics database. https://sipametrics.com/

32 Sensitivity analysis examined how loan maturity and interest rates affect the Internal Rate of Return (IRR).

33 Sensitivity testing examined nine combinations: loan maturities of 6, 10, and 15 years against interest rates of 11.67 percent, 13.17 percent, and 14.67 percent. Firebreaks achieve IRRs of 445-886 percent, exceptionally high because the IRR compares only the specific measure's modest investment cost against substantial avoided climate-related losses over the asset's lifetime, not full project economics including revenues, debt amortization and operating costs. Longer loan maturities dramatically improve returns by spreading repayment while avoided-loss benefits compound, whereas interest rate variations have minimal impact. This confirms that when financing climate retrofits, securing longer loan tenors matters far more than marginal rate reductions. These exceptionally high IRRs reflect the relatively modest investment cost, compared with substantial, avoided climate-related losses. Not that they do not reflect full project economics, including revenues, debt amortization and operating costs.

34 The cost of each measure is expressed both in terms of percent of total asset CAPEX and in percent of impact on final net asset value, considering an internal cashflow payment of the measure cost. The benefit-to-cost ratio (BCR) is presented for an internal cashflow payment of the measure cost, for the high-emissions scenario.

35 Adaptation's socioeconomic benefits are substantial but only partially quantifiable. Multi-regional input-output modelling translates avoided losses into preserved economic value across economic sectors.

36 Daily economic activity equals 8.8 million users times Mato Grosso's 74,620 Brazilian reais per capita (~USD 12,869 at 5.80 BRL/USD), divided by 365; annual safeguarded activity equals that daily figure times 9.2 days avoided.

37 Disruption days are calculated using FEMA sector- and country-specific coefficients (representing business interruption days from complete capital stock destruction) scaled proportionally to partial damage levels, per Mandel et al. (2025).

38 Reuters. "Brazil Urges Regulator to Consider Terminating Enel's Power Contract in Sao Paulo." December 17, 2025.

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41 See: Plano Nacional de Recursos Hidricos, PNRH 2022-2040, https://www.gov.br/mdr/pt-br/assuntos/seguranca-hidrica/plano-nacional-de-recursos-hidricos-1/pnrh_2022_para_baixar_e_imprimir.pdf. Also note that utilities in São Paulo and Ceará have invested in diversifying water sources, including new reservoirs, inter-basin transfers, and groundwater wells. Several municipalities have upgraded stormwater drainage and elevated pumping equipment after repeated flooding. A few pilots of nature-based solutions exist: reforestation programs in water catchments (notably by SABESP in São Paulo's Atlantic Forest), green infrastructure in urban stormwater systems, and constructed wetlands for wastewater treatment.

42 Availability payments and tariffs occur in PPP modalities known as concessão patrocinada/administrative while tariff -only structures occur in modalities known as concessão comum (source: (source: JusBrasil. Lei nº 11.079/2004 – Parcerias Público-Privadas. December 2004. www.jusbrasil.com.br/topicos/10646343/lei-n-11079-de-30-de-dezembro-de-2004)

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49 A complementary assessment using AXA Climate's Altitude tool identified four high-risk hazards for the reservoir—extreme heat, landslides, water stress, and wildfire—and three medium-risk hazards: changing air temperature, extreme precipitation, and flooding. Landslide risk, though not modeled in the NAV calculations, is projected to be high under a high-emissions scenario, potentially increasing sedimentation and threatening critical reservoir structures. Extreme heat and water stress are not modeled in this analysis, although drought risk can proxy these risks.

50 Drought risk was evaluated through two analyses: prospective hydrological modeling, which simulated future operational impacts and financial losses and the aqueduct model, which provided a broader climate risk screening showing low-medium risk by 2050. The national climate risk platform (AdaptaBrasil) also indicates high risk of water stress. Due to modeling uncertainties, drought conditions are not systematically shown to evolve similarly across all climate models, as several scenarios indicate stable or even improved water availability.

51 Damage functions are drawn from peer-reviewed sources: Gabriels et al. 2021 and Kellermann et al. 2015 for floods; Unanwa et al. 2000 for storms; and Lüthi et al. 2021 for wildfires.

52 The cost of equity was estimated using Oxford Economics' scenario-based risk-free rates for Brazil, combined with asset-specific risk premia derived from comparable assets in Brazil and similar sectors identified in the 2025 SIPA metrics database. https://sipametrics.com/

53 The same process was used to estimate the cost of equity for the loan calculations.

54 As noted earlier, adaptation measures are typically far more cost-effective when integrated by design at the planning stage, avoiding expensive retrofits later. However, in practice, such early investments may not present a compelling business case for concessionaires, as they can affect project competitiveness and rely on uncertain future climate projections. For this reason, the analysis looked at the impact of A&R investments on assets that are already operational.

55 As with the modeling for the transmission line, the high IRRs are the result of computations that only measure the adaptation investment against avoided losses, not full project economics.

56 The cost of each measure is expressed both in terms of percent of total asset CAPEX and in percent of impact on final net asset value, considering an internal cashflow payment of the measure cost. The benefit-to-cost ratio (BCR) is presented for an internal cashflow payment of the measure cost, for the high-emissions scenario.

57 Avoided losses calculated using multi-regional input-output modeling to track value-added preservation across economic sectors.

58 Daily economic activity equals 9 million users times São Paulo's 77,566 Brazilian reais per capita (~USD 13,392 at 5.80 BRL/USD), divided by 365; annual safeguarded activity equals that daily figure times 0.12 days avoided.

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60 World Bank. 2022.

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65 The scope of this study does not extend to quantifying constraints on regional productivity.

66 Climate models remain divergent: some project worsening flood risks, while others indicate potential improvements.

67 A complementary climate risk analysis was conducted using AXA Climate's Altitude platform. This separate risk assessment identifies floods, landslides, and wildfires as high-risk hazards for the corridor, and does not identify any medium-level risks. Under a high-emissions scenario, wildfires pose high risks across 91 percent of the corridor, landslides pose high risks across 83 percent, floods across 57 percent, and storms remain low risk. Landslides present localized but severe risks to embankments, tunnels, and bridges, with the potential for sudden service interruptions. However, they were not modeled quantitatively for this case study since high-resolution landslide susceptibility maps were not available for the full corridor.

68 The decrease of total losses when shifting from an intermediate emissions scenario to a high-emissions scenario is due to certain global climate models projecting a reduction in flood risk in the pessimistic climate scenario: from 9.4 percent of NAV in an intermediate emissions scenario to 8.3 percent of NAV in a high-emissions scenario. This explains why flood-focused adaptation measures are less cost efficient in the pessimistic climate scenario in terms of avoided loss and co-benefits.

69 Damage functions are drawn from peer-reviewed sources: Gabriels et al and Kellermann et al for floods, Unanwa et al for storms, and Lüthi et al for wildfires.

70 The cost of each measure is expressed both in terms of % of total asset CAPEX and in % of impact on final net asset value, considering an upfront payment of the measure cost. The benefit-to-cost ratio (BCR) is presented for an upfront payment of the measure cost, for a high-emissions scenario.

71 As noted earlier, adaptation measures are typically far more cost-effective when integrated by design at the planning stage, avoiding expensive retrofits later. However, in practice, such early investments may not present a compelling business case for concessionaires, as they can affect project competitiveness and rely on uncertain future climate projections. For this reason, the analysis looked at the impact of A&R investments on assets that are already operational.

72 The sensitivity testing examined nine combinations: loan maturities of 6, 10, and 15 years against interest rates of 11.67 percent, 13.17 percent, and 14.67 percent — consistent with the project finance structure of the concession.

73 The cost of each measure is expressed both in terms of percent of total asset CAPEX and in percent of impact on final net asset value, considering an internal cashflow payment of the measure cost. The benefit-to-cost ratio (BCR) is presented for an internal cashflow payment of the measure cost, for the high-emissions scenario.

74 Adaptation's socioeconomic benefits are substantial but only partially quantifiable. Multi-regional input-output modelling translates avoided losses into preserved economic value across economic sectors.

75 Daily economic activity equals 75,500 daily travelers times São Paulo's 77,566 Brazilian reais per capita (~USD 13,392 at 5.80 BRL/USD), divided by 365; annual safeguarded activity equals that daily figure times 1.65 days avoided.

76 These figures—calculated using multi-regional input-output modeling—capture direct and indirect employment results across supply chains. Health improvements, community resilience, and ecosystem services add further job preservation value beyond what these numbers show.

77 European Union. Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment. *Official Journal of the European Union*, April 25, 2014. L 124, pp. 1–18.

78 Use of these tools should include revised NPV/IRR calculations to reflect avoided losses and extended asset life, modified probability of default models to account for how climate exposure increases default risk and updated loss-given-default models to capture asset damage and business interruption from climate events.

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