Highway to Hell

Climate Risks will cost hundreds of billions to investors in infrastructure before 2050

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EDHEC
Infrastructure &
Private Assets
Research Institute

About the EDHEC Infrastructure & Private Assets Research Institute

Since 2019, and with the support of the Monetary Authority of Singapore (MAS), the EDHEC Infrastructure & Private Assets Research Institute has been developing ground-breaking research to document the risks and financial performance of investments in unlisted infrastructure equity and debt, as well as the climate impacts and risks of these essential assets. The indices and benchmarks produced by EDHEC are recognised by the European Securities and Markets Authority (ESMA) and used by investors representing USD400bn in infrastructure assets under management. The data produced by the institute is grounded in modern financial theory and the principles of fair value accounting, which are key pillars of sound financial risk management. Through its work, the institute has shown that it is possible to measure market dynamics in private and illiquid markets and produce credible measures of the risk-adjusted performance of private assets that makes them comparable to other asset classes. The same data is used by policy makers and prudential authorities including the G20, the OECD, IAIS, and more. Since 2023, new research efforts have allowed this financial database to be complemented with a unique set of climate data for unlisted infrastructure, which is at the heart of the climate transition, since it represents more than 60% of total Scope 1, 2, and 3 greenhouse gas emissions. Whether it involves a dedicated green taxonomy or measurement of the exposure and quantification of transition and physical risk at the sub-asset level, the granularity, depth, and quality of the EDHEC Infrastructure & Private Assets data make it a unique reference point for public and private decision-makers.

EDHEC Business School's integration of climate change and sustainability issues into financial decisions is not limited to the infrastructure asset class. As a leading academic institution committed to future generations, EDHEC is deeply engaged in producing research that can contribute to the fight against climate change. While the work of the EDHEC Infrastructure & Private Assets Institute aims to make the future consequences of climate change fathomable for investors in private markets, EDHEC-Risk Climate Impact Institute is advancing modelling of climate-related financial risks and extending climate scenario analysis to serve investors across asset classes as well as non-financial corporations. It is also seeking to apply financial innovation to the facilitation of mitigation and adaptation investments.

The two research institutes are also cooperating to develop a deep knowledge base on climate change vulnerabilities affecting real assets, the role of technology in mitigating climate risks, and current and future technological options for decarbonising economic activities. This knowledge base bridges a key gap between extremely granular technical knowledge and high-level policy and investment views that often remain oblivious to what low-carbon alignment can or cannot achieve. This work provides a reality check on claims of net zero.

Authors

Noël Amenc is an Associate Professor of Finance at EDHEC Business School and the founding Chief Executive Officer of Scientific Beta. Prior to joining EDHEC Business School as founding director of EDHEC-Risk Institute, he was the Director of Research of Misys Asset Management Systems. He has published extensively in finance journals and contributed to four books on quantitative equity management, portfolio management, and alternative investments. He is a member of the editorial board of the Journal of Portfolio Management, associate editor of the Journal of Alternative Investments, and member of the advisory board of the Journal of Index Investing. He is also a member of the Finance Research Council of the Monetary Authority of Singapore. He was formerly a member of the Consultative Working Group of the European Securities and Markets Authority (ESMA) Financial Innovation Standing Committee and of the Scientific Advisory Council of the AMF (French financial regulatory authority). He holds graduate degrees in economics, finance and management and a PhD in finance.

Frédéric Blanc-Brude is the Director of EDHEC Infrastructure Institute, a dedicated research unit developing a unique body of applied research on infrastructure investment from the perspective of large asset owners. He is also the CEO of Scientific Infra, a provider of unlisted infrastructure equity and debt index data and analytics. He is a member of the editorial board of the *Journal of Alternative Investments*. He holds a PhD in Finance (King's College London) and degrees from the London School of Economics, the Sorbonne, and Sciences Po Paris. He is a regular contributor to the G20 working group on long-term infrastructure investment, has advised the European Insurance and Occupational Pensions Authority (EIOPA) on the prudential treatment of infrastructure investments and also represents EDHEC on the Advisory Board of the Global Infrastructure Facility of the World Bank. EDHEC*infra* was founded in 2016.

Abhishek Gupta is an Associate Director at the EDHEC Infrastructure Institute and the Head of infraMetrics Product Development. He has more than 10 years of experience in asset management and alternative investments including stints at Goldman Sachs and Partners Group. He holds a Masters of Science in Financial Engineering from Nanyang Business School and a Bachelor of Technology from the Indian Institute of Technology.

Bertrand Jayles Bertrand Jayles is a Senior Sustainability Data Scientist at the EDHEC Infrastructure Institute. He earned a Master's degree in Theoretical Physics from Aix-Marseille University and a PhD in Social Physics from Toulouse University. With experience working in renowned research institutions such as the National Center for Scientific Research (CNRS), the Max Planck Institute, and the Singapore-ETH Zürich Center, his research has focused on various fields including collective behavior and decision-making, social psychology, resilience, complex networks, and behavioral economics.

Jeanette Orminski is a Senior ESG Researcher focused on public opinion and social impact factors in the infrastructure sector. Her experience spans the fields of public opinion, sustainability, and social network analyses. She received her PhD degree in Communication Science from the Nanyang Technological University, Singapore. Focusing on the sustainability discourse on Twitter, Jeanette applied network analysis and machine learning approaches to identify opinion leaders on Twitter. Prior to joining EDHEC*infra*, she worked as a Data Scientist at the Munich Science Communication Lab analysing the topic of Planetary Health.

Darwin Marcelo is Project Director at the EDHEC Infrastructure Institute. He is currently in charge of an ambitious initiative aiming at building a unique, worldwide reference database including ESG impact and risk exposure data and indicators for physical infrastructure *'hard'* assets. Prior to joining EDHEC*infra*, Darwin Marcelo spent 14 years at the World Bank Group as a Senior Economist in the Infrastructure Finance, PPPs, and Guarantees Group (IPG). During this time, he was the Program Manager of the World Bank Quality Infrastructure Investment Partnership (QII) and Lead of the Global Infrastructure Connectivity Alliance (GICA).

Executive Summary

This paper presents an assessment of transition and physical risks in the privately invested infrastructure sector. Leveraging the NGFS scenarios, we quantify the costs associated with delayed or uncoordinated transition and evaluate the potential portfolio value loss resulting from physical risks in the absence of climate action.

We measure company-level transition risk as the difference in Net Asset Value (NAV) between disorderly and orderly scenarios. First, we analyze the statistical relationship between infrastructure companies' total assets, revenues, operational expenses (OPEX), profits, and countries' GDP and inflation using historical data. Second, we apply the estimated relationship between these variables to a *reference* dataset of about 700 infrastructure companies tracked by EDHEC*infra*'s infraMetrics. Finally, we extrapolate the *reference*-based results to our *universe* dataset of about 9,000 firms to calculate the value of the transition risk faced by infrastructure investors.

Our analysis reveals the importance of transition risk for the infrastructure sectors. A disorderly scenario could result in a substantial loss of value to infrastructure investments of nearly USD600 billion. That sum is equivalent to approximately 30% of the total invested value in infraMetric's 9,000 infrastructure assets. Moreover, the negative effects of transition risk will be felt across all sectors, including low-carbon ones such as Renewables and Social Infrastructure.

In addition, we isolate the physical risk effect by calculating the difference of net asset values between "the hot house world" and an orderly scenario. We also analyse the microeconomic effects of physical risk within the hot house world scenario, as this result is of particular importance to investors with assets that are highly exposed to climate events. And to determine the extent to which an investor may be exposed to physical risk, we generate a random combination of assets to show how risky an infrastructure portfolio could be in terms of physical risk.

Physical risks are also significant at the microeconomic level. We show that the cost of physical risks within the Current Policies scenario represents, on average, 4.4% of the total NAV in our *reference* database by 2050, with large variations across sectors. The effect of extreme climate events is negative across all sectors. In the most extreme cases, when investors are exposed to the riskiest assets in the same portfolio, losses can amount to 54% in the hot house scenario. Moreover, portfolios only need one or two highly exposed assets to be significantly impacted.

Our estimations do not fully capture the transition and physical risk effect. First, the carbon footprint of sectors such as Energy and Water Resources and Network Utilities are underrepresented when considering only Scope 1 and 2 emissions. Second, the transition risk effects go beyond the impact of carbon taxes. Following TICCS® and the EU taxonomy, we show that as countries transition to a low-carbon economy, the market value losses in Europe could reach up to USD9 billion in stranded assets. Finally, the magnitude of physical risk may be underestimated due to the NGFS assumptions.

Based on the evidence presented in this paper, we recommend that investors demand coordinated actions and that governments immediately implement carbon taxes to minimize the adverse financial effects of transition risk. The worst impact comes from failing to react until too late.

Contents

1. Introduction

In this paper, we estimate the value of transition and physical risks for the privately invested infrastructure sector. Over the past few decades, institutional investors have increasingly allocated capital to private, mostly unlisted infrastructure companies such as toll roads, airports, power plants, and pipelines. According to infraMetrics [1], this investment represents nearly USD4.1 trillion of enterprise value today and USD2.2 trillion of market capitalization at current market prices in 25 key markets. Using the standard climate scenarios developed by international organizations and central banks, we estimate the costs for a delayed or uncoordinated transition as well as the potential loss in portfolio value due to physical risks in the case of no climate action.

Human activities rely on fossil fuels, and the resulting greenhouse gas (GHG) emissions cause the rise of average global temperatures above pre-industrial levels in a phenomenon known as "climate change" (IPCC, 2014); (Hansen et al., 2000). Climate change creates so-called physical risks relating to changing climatic conditions: a) chronic physical risks, such as higher average temperatures and more frequent and intense extreme weather events, and b) acute physical risks, such as more intense rainfall and storms leading to severe floods and other disasters (Financial Stability Board, 2017). It is now clear that climate change will make living conditions less benign for humans and other species on Earth (IPCC, 2023). It is also expected to make producing and transporting goods and services more difficult and uncertain, raising costs across the economy (Cho, 2022). The physical impacts will become increasingly material in the event of continued GHG emissions, especially after 2050.

To prevent further climate change and physical risks, policymakers and businesses must undertake a difficult transition to an economy that does not require the continued emission of GHG into the atmosphere. The infrastructure sector is pivotal to achieving this, as it accounts for almost 80% of global GHG emissions (United Nations Office for Project Services (UNOPS), 2023). However, according to the Global Infrastructure Hub [2], the infrastructure sector misses investments of USD18 trillion to reach the Paris Agreement and meet the UN Sustainable Development Goals.

The International Panel on Climate Change (IPCC) estimates that if GHG emissions are significantly reduced by 2050, some of the most serious consequences of climate change can be avoided (Zhai et al., 2018). In the best case scenarios – reaching net zero emissions by 2050 or keeping the global temperature rise below 2° Celsius– climate change would be largely manageable for human activity. On the other hand, continuous or increasing annual emissions will lead to a much greater temperature rise and an increasingly unliveable planet (IPCC, 2023).

Therefore, the transition to a low-carbon economy is valuable not only for humans and the environment but also economically. However, given the extreme reliance on fossil fuels of industrial and post-industrial societies, this transition requires significant changes that will create large economic costs in the short term (IPCC, 2014). For example, since GHG emissions are a form of unpriced pollution (i.e., an economic

1 - EDHEC*infra* launched the infraMetrics® platform in 2020 to provide updated, robust, and granular data to investors representing USD 400 billions of infrastructure assets under management. Since 2023, infraMetrics includes a range of climate risk metrics at the index, segment, and asset level, creating benchmarks and comparables ("comps") of climate exposure and risks of infrastructure companies. This includes carbon intensity by dollar of revenue or dollar invested, physical value at risk estimated at the asset level, and extreme financial loss values based on climate scenarios.

2 - Global Infrastructure Outlook `https://outlook.gihub.org/`

externality), governments can try to engineer this transition by taxing emissions, thus forcing the market to recognize the environmental cost of emissions (Herzog, 2009).

The history of carbon taxation is closely linked to the growing awareness of GHG's environmental and economic consequences from human activities. Early discussions revolved around the need to internalize the external costs of carbon emissions and address the market failure of unpriced GHG pollution through carbon pricing mechanisms like a carbon tax (Goulder, 1995). However, challenges in implementation, such as public resistance and concerns about competitiveness, have shaped the discourse over time. As a result, the design and implementation of carbon taxation policies have been refined, and new mechanisms, like border taxation and emissions rights exchanges, have been introduced to encourage global participation in climate action (Nordhaus, 2007). Despite the challenges, carbon taxes remains the only measure in climate scenarios (see more in Chapter 2).

Besides a carbon tax that could potentially create large costs for businesses and reduce their profits, other transition risks exist: A low-carbon economy may also see certain activities being banned by regulators, like producing electric power using coal, or become increasingly unacceptable to the public because they are perceived as contributing to climate change. Finally, and perhaps most importantly, a low carbon economy requires technological advances in which investments in infrastructure play a key role: Two key sectors where significant progress is needed today are the storage of electricity in large-scale batteries and the capture and sequestration of carbon and other GHGs directly from the air (McKinsey & Company, 2023).

As a result, the economy and humanity find themselves exposed to two types of risks. The first of these are changes in the severity and frequency of extreme weather, especially beyond the 2050 horizon. The second are the unknown costs of a transition to a low-carbon economy, which will most likely be incurred before 2050.

Despite the evolving discourse on carbon taxation and economic studies projecting significant consequences, the infrastructure industry often lags in considering climate risks in their investments. Many investors and asset managers tend to overlook their long-term impacts, driven by short-term financial behavior and a "business as usual" mentality (Bisbey et al. (2022) and (MacDonald and Sanchez, 2022)). Additionally, the 2100 horizon often exceeds the lifespan of infrastructure investments and the tenure of current decision-makers, leading to prioritizing short-term financial returns over long-term climate considerations (Dasgupta, 2008).

However, infrastructure projects with long lifespans must be resilient to climate impacts and aligned with low-carbon objectives to avoid becoming stranded assets. Accordingly, investors' myopic approach poses significant risks for both investors and society, as failure to account for climate risks can lead to substantial economic losses and environmental consequences. The history of the carbon taxation discourse underscores the urgency for the infrastructure industry to integrate climate and transition risks into their investment decisions. By adopting more sustainable practices and investing in climate-resilient infrastructure, the industry can be crucial in accelerating the transition to a low-carbon economy while ensuring long-term viability and value.

To address the hesitancy of infrastructure investors, this paper will focus on the materialization of climate risks and consequences within the more tangible and actionable timeframe of 2050. By focusing on concrete consequences within this timeframe, we seek to equip infrastructure investors and policymakers with the knowledge needed to make informed decisions in a rapidly changing climate landscape.

In the first part of the paper, we introduce climate scenarios (see Chapter 2, specifically the six scenarios developed by the Network for Greening the Financial System (NGFS) that describe the consequences from introducing carbon tax policies in different ways (immediately across all sectors and countries to reach net zero by 2050 or to keep the temperature rise below 2° Celsius; later or uncoordinated; never or at country's discretion). Chapter 3 and 4 build the main part of this paper, in which we use those scenarios to estimate future value losses for the privately invested infrastructure sector stemming from transition risks and physical risks, respectively. Both chapters provide details on EDHEC*infra*'s methodology to calculate carbon emissions and damage values on sector and asset level. Paired with infraMetric's extensive financial data and insights from NGFS' climate scenarios, we are able to provide robust predictions of asset value losses (Chapter 3) and portfolio losses (Chapter 4) for infrastructure investors.

2. Climate Scenarios

The IPCC develops climate scenarios to explore the potential impacts of climate change on a global scale. These scenarios are based on a range of different Representative Concentration Pathways (RCPs)[1] and Shared Socioeconomic Pathways (SSPs)[2], which describe different levels of GHG concentration and socioeconomic development. The scenarios by the Network for Greening the Financial System (NGFS) then build upon the IPCC scenarios with a stronger focus on the financial sector, providing a common framework for financial institutions to assess climate-related risks.

2.1 The Network for Greening the Financial System (NGFS)

NGFS developed a set of six reference climate scenarios that serve as a common ground for financial institutions and regulators to assess and manage financial risks and opportunities associated with climate change. All scenarios share a set of basic assumptions, SSP's so-called Middle of the Road narrative, where social, economic, and technological trends do not shift markedly from historical patterns. In short, this narrative assumes that the global population continues to grow at a slower pace, the world's economy continues to grow at a moderate pace, income gaps between regions gradually decrease, and emissions continue to increase until the end of the century. Limited global efforts are foreseen to mitigate climate change.

1 - On demand of the IPCC, the scientific community developed the RCPs to explore scenarios for different possible futures for GHG concentrations in the atmosphere and their associated impacts on the climate (Van Vuuren et al., 2011). The scenarios' names represent the expected radiative forcing values in the year 2100. Radiative forcing is a measure of the imbalance between the amount of energy that enters the Earth's atmosphere from the sun and the amount of energy that is reflected back into space. The higher the radiative forcing, the more warming the Earth will experience.

2 - The SSPs are narratives that combine a range of socio-economic and technological factors with different GHG emissions pathways, thus specifying and standardizing socio-economic foundations that are consistent with the RCPs (Van Vuuren et al., 2017). Because of their greater explanatory power and flexibility, the SSPs are gradually replacing the RCPs in climate change research

The NGFS scenarios complement these assumptions with scenario-specific climate policies. In practice, climate policies are proxied as a carbon tax, of which severity, time of implementation, and coordination across sectors and countries differ across scenarios. In addition to the implementation of a carbon tax, the pace of technological development and levels of carbon dioxide removal technologies also differ across scenarios (see Figure 1). NGFS scenarios are paired into three categories that represent different levels of climate-related risks (transition and physical risks):

- **Orderly scenarios**: Two scenarios assume that climate policies are applied immediately and in a coordinated manner: "Below 2°C" and "Net Zero 2050". In these scenarios, global warming remains limited (low physical risks) while serious transition risks can be avoided

- **Disorderly scenarios**: Two scenarios estimate the effects if policies are applied either too late ("Delayed Transition") or in a disorganised manner ("Divergent Net Zero"). This means to keep global warming below 2° Celsius would require much stronger policies than in orderly scenarios. While such policies would keep physical risks low, these scenarios entail high transition risks and can create significant price shocks.

- **Hot house world scenarios**: Two scenarios describe the effects of climate policies remaining the same as they are today ("Current Policies") or becoming more stringent, but at every country's discretion ("Nationally Determined Contributions" or NDC). In these scenarios, global warming is not contained, and transition risks are low but at the cost of high physical risks.

Figure 1: NGFS scenarios and key assumptions. The color coding indicates whether the characteristic makes the scenario more or less severe from a macro-financial risk perspective: blue being the lower risk, green moderate risk and red higher risk. This chart was taken from Bertram et al. (2021).

Category	Scenario	Policy ambition	Policy reaction	Technology change	Carbon dioxide removal	Regional policy variation
Orderly	Net Zero 2050	1.4°C	Immediate and smooth	Fast change	Medium-high use	Medium variation
	Below 2°C	1.6°C	Immediate and smooth	Moderate change	Medium-high use	Low variation
Disorderly	Divergent Net Zero	1.4°C	Immediate but divergent across sectors	Fast change	Low-medium use	Medium variation
	Delayed Transition	1.6°C	Delayed	Slow/Fast change	Low-medium use	High variation
Hot House World	Nationally Determined Contributions (NDCs)	2.6°C	NDCs	Slow change	Low-medium use	Medium variation
	Current Policies	3°C+	None - current policies	Slow change	Low use	Low variation

3. Transition Risk Could Represent a USD600 Billion Potential Loss in Value

3.1 What are Climate Transition Risks?

Transition risks are the potential adverse impacts on future asset prices of the transition to a low-carbon economy. This transition will likely entail numerous policy, legal, technology, and market changes to prevent climate change. In this process, financial assets may lose revenues, have lower profits, or require higher returns to compensate investors who hold them. Assets may also lose revenue due to lower demand or almost all value if they cannot be aligned with a lower carbon economy.

International organizations and financial institutions aim to quantify transition risks (Jung et al. (2023), Shirono et al. (2023); Alogoskoufis et al. (2021)). Most of these works use carbon emission levels and carbon taxes to proxy the exposure to transition risk. For example, the International Monetary Fund's Framework for Transition Risks a.k.a the Financial Sector Assessment Program (FSAP) focuses on domestic and external carbon taxes as the main source of transition risks. Central banks and the NGFS use carbon taxes to proxy transition risk in their climate scenarios. Moreover, carbon taxes are easier to track and more convenient for modeling purposes (Adrian et al., 2022), contrasting with other sources of transition risk, such as legal, technological, and market changes, which remain understudied. Therefore, any measurement solely based on carbon taxes must be considered a 'conservative' underestimation of the actual transition risk.

Carbon taxes, however, while recognized as one of the main policy tools to mitigate greenhouse gas emissions and combat climate change, have not yet achieved widespread adoption. According to The World Bank[1], 37 countries have implemented carbon taxes. Moreover, NGFS estimates that the current levels would need to be at least four times higher in 2023 and at least 40 times higher by 2050 to put us on track to achieving 1.5°C (Net Zero) before 2050. Several factors contribute to the limited adoption of carbon taxes in various jurisdictions. Firstly, carbon taxes can be politically challenging to implement due to potential opposition from industries and the general public. Second, concerns about the impacts on the industries' competitiveness in the global market and the economy also hinder the widespread adoption of carbon taxes. In fact, countries with higher levels of carbon-intensive industries tend to have weaker carbon pricing policies, suggesting the influence of economic considerations. Finally, the lack of international consensus and cooperation on carbon pricing frameworks further hampers the broader implementation of carbon taxes (Carattini et al., 2018).

These political and economic restraints remain constant, although tax-related transition risks for individual investors only arise if carbon taxes are introduced abruptly or unanticipatedly. In such cases, investors have limited information to assess the adverse financial implications and manage the risk today. Conversely, if carbon taxes were fully anticipated, with timing and levels fully known by investors, the tax-related transition risk would be zero, as they could predict and prepare for its impacts, which would be reflected in increased costs of carbon emissions, higher operation costs, and lower financial performance, especially for carbon-intensive firms (Adrian et al., 2022).

1 - The World Bank Carbon Pricing Dashboard. https://carbonpricingdashboard.worldbank.org/map_data

However, in order to fully anticipate carbon taxes, the industry requires transition risk assessments to estimate carbon emissions reliably. In recent years, companies and third-party organizations have made significant progress in measuring two sources of emissions: the directly owned emissions by companies (**Scope 1**) and the emissions embodied in the energy they buy (**Scope 2**). That said, measuring and disclosing upstream (e.g., from purchased goods, leased assets, or commuting employees) and downstream (e.g., transport and distribution of products, investments, or end-of-life treatment) emissions (**Scope 3**) involves several challenges, including poor data availability, lack of methodologies, and attribution assumptions, among others, that limit the availability and quality of Scope 3 information (Adrian et al., 2022). For this reason, many estimates of carbon emissions only consider Scope 1 and 2 as proxies of carbon footprint.

Despite the limited information about upstream and downstream emissions, transition risks from Scope 3 emissions can significantly affect companies' revenues –especially as Scope 3 emissions are often much higher than Scope 1 and 2 emissions. As climate change awareness grows, stakeholders, including customers, investors, and regulators, are paying more attention to companies' "full" carbon footprint. Failure to address Scope 3 emissions can result in reputational damage, loss of customers, regulatory penalties, and reduced access to capital. Furthermore, companies may face higher operating costs as carbon pricing mechanisms and carbon taxes are implemented. In addition to these financial implications, companies may also face market disruptions as consumer preferences shift towards environment-friendly products and services (see section 3.3.1 for more details on the risks and financial impacts of Scope 3 emissions). To assess transition risks, we use NGFS' disorderly scenarios in our analyses, in which a carbon tax is introduced either rapidly and uncoordinated or delayed. To isolate the systemic transition risk effect, we calculate the difference in asset price (the equity market value) between the disorderly and the orderly scenarios in which immediate and coordinated climate policies, including fully anticipated carbon taxes, are applied.

3.2 The Market Value of Transition Risks for Infrastructure Investors

3.2.1 Approach

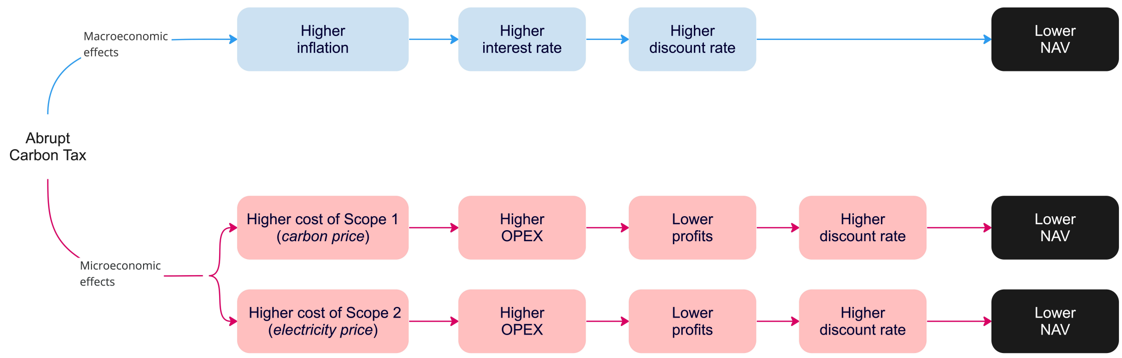
We measure transition risk at the company level as the difference in Net Asset Value (NAV) between disorderly and orderly scenarios as defined by NGFS.

The output of NGFS climate scenarios includes macroeconomic projections to 2050 for GDP, inflation, and interest rates at the country level (see Appendix A.6 for projections of average GDP growth and inflation at different horizons in each NGFS scenario). We use these macroeconomic scenarios to formulate projections of unlisted infrastructure companies' cash flows and discount rates until 2050.

Using historical data, we analyze the statistical relationship between the infrastructure companies' total assets, revenues, operational expenses (OPEX), profits (see Appendix A.4), and countries' GDP and inflation. The analyses include different models for different activities, business models, and company types (following the TICCS® taxonomy[2]). At the microeconomic level, the rapid introduction of a carbon tax in disorderly scenarios negatively impacts the profits, free cash flows, and, ultimately, the value of individual infrastructure companies (see Figure 2). At the macroeconomic level, it would induce higher prices and increase discount rates, also reducing infrastructure companies' value. Furthermore, lower profits increase the risk premia of each company as per the infraMetrics asset pricing model (see Appendix A.2). Moreover, the price

2 - The Infrastructure Company Classification Standard (TICCS®) was created by EDHEC*infra* to provide investors with a frame of reference to approach the infrastructure asset class (TICCS by EDHEC*infra*, 2022).

Figure 2: Macro and micro effects of carbon tax-based transition risk on NAV in the disorderly scenario



shock of new carbon taxes creates inflation and higher interest rates in the general equilibrium of NGFS disorderly scenarios, further impacting the future discount rates of infrastructure companies' dividends.

Similarly, the gradual introduction of a lower carbon tax in orderly scenarios negatively impacts the profits of individual infrastructure companies. However, the effect is significantly lower than in disorderly scenarios. As mentioned above, transition risk is very low in such scenarios because investors can anticipate and price the impact of the carbon tax.

Knowing the historical relationship between GDP and inflation and asset's financial values, as well as understanding the impacts of introducing a carbon tax in the different climate scenarios, provides us with the key information to predict transition risk on the asset level. Based on this information, we can use a discounted cash flow model to reprice unlisted infrastructure equity investments in disorderly and orderly scenarios. For this, we calculate an asset's expected future revenues in each macroeconomic scenario and future dividends and discount rates at different horizons, including the impact of a carbon tax on profits and discount rates. Accordingly, we measure the costs of each scenario (the carbon tax) for investors and the difference in costs between orderly and disorderly scenarios as a systematic measure of transition risk.

It must be considered that our analysis does not include additional costs resulting from alignment efforts. NGFS' orderly and disorderly scenarios assume success in restraining climate change below 1.5˚C or 2˚C, respectively, based on implementing climate policies. However, restraining climate change would only be possible because of fast (in 1.5˚C scenarios) or moderate (in 2˚C scenarios) technological changes that allow the economy to continue growing while generating less emissions. This implicitly means that alignment efforts to achieve Net Zero by 2050 (e.g., Paris Alignment or the UN-convened Net Zero Asset Owner Alliance (NZAOA)) or keep the temperature rise below 2˚C were successful but costly. We will integrate alignment efforts into a future version of our models.

3.2.2 Results

We apply the above mentioned approach to a *reference* dataset of about 700 individual infrastructure companies tracked in infraMetrics. This dataset is representative of a broader *universe* dataset of around 9000 private infrastructure companies in 27 countries covering all TICCS classes by sector, business model, and corporate structure (see Table 1 and Appendix A.1). For each asset in the *reference* dataset, infraMetrics provides detailed data on financials, fair value asset pricing, baseline carbon footprint and intensities (Nugier and Marcelo, 2022)), and baseline physical risk exposures (Marcelo and Blanc-Brude, 2022).

Table 1: Average Difference of Asset-level NAV between Disorderly (Delayed Transition) and Orderly (2˚C) Scenarios for Different TICCS® Segments

TICCS® Code	TICCS® Activity Name	Difference in Market Value
IC40	Energy and Water Resources	-38%
IC50	Data Infrastructure	-32%
IC80	Network Utilities	-33%
IC60	Transport	-30%
IC20	Environmental Services	-30%
IC10	Power Generation x-Renewables	-28%
IC30	Social Infrastructure	-24%
IC70	Renewable Power	-19%
Average		**-30%**

The average difference in value by sector of the discounted cash flow (DCF) valuation conducted between the orderly (Below 2ºC) and the disorderly (Delayed Transition) scenario is presented in Table 1. On average, we observe that the loss of value is 30% of the NAV, with widespread differences between sectors. Whereas a sudden carbon tax regime would generate a loss in value in the renewable power sector of around 19%, the negative effect in the rest of the power generation sector (including coal-, gas-, and oil-fired power generation) would be 46% higher (28% loss) and double in the energy and water resources sector (38% loss), which includes gas pipeline and storage infrastructure.

Remarkably, even sectors such as renewable power and social infrastructure, where the exposures to carbon taxes are very low, would be negatively affected by introducing a sudden carbon taxation regime. Carbon taxes increase prices and interest rates, ultimately affecting investments worldwide. Therefore, even for sectors with low exposure to transition risk, there may be adverse macroeconomic effects derived from abrupt carbon tax policies.

The results above show that the average loss of market value in the event of a disorderly transition could be, on average, 30% of the infraMetrics *reference* dataset of 700 tracked companies. Again, since this loss only considers transition risks in the form of a carbon tax on Scope 1 and 2 emissions, the result should be seen as a conservative underestimation of the adverse effects of transition risk.

3.2.3 Extrapolations

We extrapolate the results above (*reference* database) to our *universe* dataset of about 9000 firms –for which we do not have the full set of climate risk data– to estimate the value of the transition risk faced by infrastructure investors.

First, the NGFS scenarios postulate the application of a carbon tax (see Section 2.1). Since the implementation of the tax is economy-wide, we can consider that its impact will apply to all firms once we control for the average exposure at the sector level.

Second, we use a 'climate comps' approach to extrapolate our results to the universe of infrastructure investments. To this end, we regressed the total emissions (Scope 1 and 2) of the *reference* dataset at the company level against their size –measured by the value of their total assets– and isolate sector-level characteristics using TICCS sector controls as broad proxies of different technologies. This basic model allows us to estimate carbon emissions for the entire infrastructure universe, including aggregate carbon estimations at the sector level (Nugier and Marcelo, 2022). Crucially for the validity of our extrapolation exercise, we observe that the carbon intensities –the ratio of carbon emissions per total assets– of the *reference* and *universe*

Table 2: Carbon intensity in the infraMetrics *Reference* and *Universe* Datasets

	Reference Dataset			Universe Dataset
TICCS®	Scope (1+2) carbon intensity	Median scope (1+2) carbon emissions	Mean scope (1+2) carbon emissions (logs)	Mean scope (1+2) carbon emissions (logs)
IC10	5,357	3,388	12.7	12.5
IC20	7,486	4,852	11.9	11.5
IC30	3,178	247	8.88	8.61
IC40	3,342	924	12.0	11.5
IC50	884	847	11.0	9.31
IC60	90	25	7.5	7.13
IC70	88	0	1.4	1.07
IC80	211	91	10.5	9.46

datasets are statistically the same (see Table 2). Therefore, we can reasonably expect that a carbon tax, on average, will have the same impact on the entire infrastructure universe at the sector level.

Finally, since we established that the *reference* and *universe* datasets exhibit similar sector-level carbon intensities, we can now apply the sector loss coefficients resulting from the difference between the disorderly and orderly scenarios in the *reference* dataset to the entire *universe* dataset (see Table 3). Following this logic, the total infrastructure investment value loss due to transition risk in a disorderly scenario for the 9000 companies listed in infraMetrics is close to USD600 billion.

3.3 Beyond Scope 1 and 2

As discussed above, in these climate scenarios, transition risk is the exposure to the "uncertain" adverse impacts on future asset prices created by a carbon tax. To measure these effects at the company level, we used projections of carbon prices and scopes 1 and 2 emissions. However, this approach does not account for the impact of Scope 3 emissions and other triggers of transition risk beyond carbon taxation. The development and impact of Scope 3 emissions will be included in a future version of our current models. Therefore, our results on transition risk and the loss of USD600 billion should be seen as the minimum effects of disorderly climate scenarios. Nonetheless, this section provides a glimpse of the role and importance of Scope 3 emissions for transition risk assessment.

3.3.1 The impact of Scope 3 emissions

Scope 3 emissions can assess companies' exposure to carbon-intensive activities within value chains and products. Higher Scope 3 emissions might come with higher future transition risks impacting asset values and operating costs if not acknowledged and addressed. For example, companies manufacturing building materials like steel and cement are carbon-intensive and main suppliers of the transport and renewable sectors (Scope 3 emissions –capital goods). Companies mobilizing cargo and passengers are also carbon-intensive and are the main clients of airport and port companies (Scope 3 emissions –downstream transportation and distribution). Carbon pricing regulations could increase upstream costs or reduce downstream revenues. Accordingly, the highest revenue losses from Scope 3-related transition risks will be in industries with sizeable upstream and downstream carbon emissions. This will not only include higher exposure to carbon taxes targeting Scope 3 but also demand risk from changes in consumer preferences, market value loss due to reputational damage, and, in extreme cases, mandatory shutdown.

The lack of primary data, reliance on industry average data, or potential double-counting of

Table 3: Average Difference of Asset-level NAV between Disorderly (Divergent Net Zero) and Orderly (2˚C) Scenarios for different TICCS® segments

TICCS®	Activity Name	Market value difference	Market cap universe US$ billions	Loss US$ billions
IC40	Energy and Water Resources	-38%	227	-86
IC50	Data Infrastructure	-32%	190	-61
IC80	Network Utilities	-33%	314	-104
IC60	Transport	-30%	535	-160
IC20	Environmental Services	-30%	51	-15
IC10	Power Gen. x-Renewables	-28%	178	-50
IC30	Social Infrastructure	-24%	79	-19
IC70	Renewable Power	-19%	553	-105
Average		**-30%**		
TOTAL			**2,126**	**-601**

emissions between reporting entities are some of the factors hindering the development of reliable company-level Scope 3 emissions information (Lloyd et al., 2022). However, estimates at the sector level show that Scope 3 emissions account for around 75% of companies' GHG emissions on average (CDP, 2022). Regulators are weighing on this. For example, in 2022, the US Securities and Exchange Commission (SEC, 2022) proposed a new climate disclosure rule that includes reporting on Scope 3 emissions if deemed material to investors or if the company's emissions targets encompass Scope 3 emissions (SEC, 2022). Hence, companies should prepare for future revenue losses and transition risks from Scope 3 emissions.

The infraMetrics' *reference* dataset includes asset level Scope 3 estimations across all TICCS sectors (see Table 4). We observe that the Scope 3 carbon intensities hugely vary between sectors, with the highest intensities in the energy and water resources sector (including gas, oil, water, and wastewater pipelines, crude oil refinery, LNG, as well as gas and liquid storage) and Network Utilities (including electricity distribution and transmission, district cooling and heating, water and sewerage, and gas distribution).

3.4 Conclusion on Transition Risk

Our calculations show that transition risk in infrastructure is not negligible. The total infrastructure investment value loss due to transition risk in a disorderly scenario is nearly USD600 billion or 30% of the total invested value in infraMetric's 9000 infrastructure assets.

However, the actual magnitude of transition risk is greater than our estimations show. In some sectors, an asset's carbon footprint is underrepresented when only considering Scope 1 and 2 emissions. This is the case in the energy and water resources and the Network Utilities sectors, which are the most exposed to Scope 3-related transition risks. Future versions of our transition risk models will include Scope 3 emissions.

Furthermore, the adverse effects of transition risk go beyond the impact of carbon taxes. For example, following TICCS and the EU taxonomy, we can show that as countries transition to a low-carbon economy, the market value losses in Europe could leave up to USD9 billion in stranded assets. The next section elaborates on this special case.

3.4.1 Infrastructure, sustainability risks, and stranded assets

Governments now demand that financial market participants provide information about their

Table 4: Scope 3-based carbon intensities across all TICCS® sectors in 2022

Scope 3-based carbon intensity			
TICCS®	TICCS® activity name	Per US$ million of revenue	Per US$ million of total asset value
IC40	Energy and Water Resources	288,286	71,329
IC80	Network Utilities	16,761	2,444
IC60	Transport	9,117	863
IC30	Social Infrastructure	5,679	1,380
IC20	Environmental Services	2,604	701
IC10	Power Generation x-Renewables	0[a]	0[a]
IC50	Data Infrastructure	0[a]	0[a]
IC70	Renewable Power	0[a]	0[a]
Average		**14,783**	**3,015**

[a]EDHEC*infra*'s Materiality Profiles show that Scope 3 emissions in these sectors are too low compared to Scope 1 and 2, or do not have enough information to make a reliable measurement. In both cases, they are considered zero.

investments' sustainability level and possible negative impacts on the environment and society. This cannot be done without clearly defining what 'sustainable' is. In this context, the EU taxonomy for sustainable activities (i.e., "green taxonomy") was created as a classification system to clarify which economic activities are environmentally sustainable (European Commission, 2020). This system allows investors to identify potential sustainability risks, including transition risks, arising from investments in unsustainable activities.

We combined TICCS with the EU taxonomy to identify infrastructure companies aligned with the EU taxonomy (i.e., environmentally sustainable companies). We first identified the activities of each infrastructure asset subclass in our *universe* dataset using TICCS, and second, mapped the assets to two out of the six EU taxonomy objectives: "Climate Change Mitigation" and "Climate Change Adaptation". We used the European Nomenclature of Economic Activities (NACE), a classification system that provides codes for products and economic activities, as a bridge between the two. This development allowed us to identify companies exposed to high sustainability risks as those failing to be classified as 'sustainable' under the EU taxonomy (see Table 5).

Companies tagged as 'unsustainable' signal that technical and physical factors, such as their underlying technology or location, prevent them from transitioning to a sustainable economy. This could include the inability to shift technology away from processes that emit GHG into the atmosphere or failure to operate without generating hazardous substances that cannot be mitigated. EU green finance mechanisms and other initiatives will likely exclude unsustainable activities and represent another sustainability risk for investors.

At the extreme, assets that do not align with the EU taxonomy can become 'stranded'. Stranded assets are investments that cannot recoup their investment value and must be written off. The reason assets become stranded may be due to carbon policies (e.g., carbon tax), changing trends in the market (e.g., consumer preference toward clean energy), a technological development that renders them redundant or obsolete (e.g., a shift towards renewable energy), or even legal action (e.g., against high emitters). These factors could deem assets incapable of generating financial value before their economic lifecycle ends.

Using the TICCS mapping to the EU taxonomy (see Table 5), we estimate that 13% of Europe's USD1.8 trillion worth of infrastructure total asset value, or USD244 billion, does not align with

Table 5: Asset value breakdown of infrastructure investments in Europe by TICCS® sector vs. EU taxonomy alignment

		Asset Value in US$ billions			
TICCS®	Activity Name	Total Assets	Qualified	Not qualified	Stranded
IC10	Power Gen. x-Renewables	30.40	24.70	5.70	5.70
IC20	Environmental Services	52.87	51.15	1.72	0
IC30	Social Infrastructure	176.49	102.56	73.94	0
IC40	Energy and Water Resources	100.88	85.52	15.36	4.15
IC50	Data Infrastructure	82.53	82.53	0.00	0
IC60	Transport	427.56	412.82	14.74	0
IC70	Renewable Power	295.28	295.28	0.00	0
IC80	Network Utilities	680.25	546.77	133.48	0
All sectors		**1,846.26**	**1,601.31**	**244.95**	**9.85**

the current EU taxonomy (Arnold and Manocha, forthcoming). However, many of the activities that are not covered by the EU taxonomy could be considered sustainable. The authors' detailed review of technologies included in these activities reveals that only USD10 billion in asset value should be completely excluded and can be expected to be stranded. These losses would be concentrated in the power generation sector (excluding renewable energy) and the energy and water resources sector.

4. Physical Risk Could Lead to 54% Maximum Losses in Portfolio Value

4.1 What are the Physical Risks for Infrastructure Assets?

Physical risks are the uncertain adverse impacts on future asset prices from changes in climate events. Physical risks resulting from climate change can be event-driven (acute) or long-term shifts in climate patterns (chronic). Acute physical risks include increased severity of extreme weather events, such as cyclones, hurricanes, or floods. Chronic physical risks, in contrast, result from long-term shifts in climate patterns (e.g., sustained higher temperatures) and include sea level rise or chronic heat waves (Financial Stability Board, 2017).

Physical risks may have financial implications for organizations, including infrastructure companies. Adverse effects involve direct damage to assets and indirect impacts from supply chain disruption, both increasing companies' maintenance and repair costs and climate event-related insurance premiums. The financial performance of companies may also be affected by changes in water availability, sourcing, and quality; food security; and extreme temperature changes affecting organizations' premises, operations, supply chain, transport needs, and employee safety (Financial Stability Board, 2017).

Floods and storms are the most common types of climate-related events, accounting for 44% and 28% of all climate events from 2000 to 2019, respectively (United Nations Office for Disaster Risk Reduction (UNDRR), 2020). Furthermore, the UN Office for Disaster Risk Reduction (United Nations Office for Disaster Risk Reduction (UNDRR), 2020) reported that the number of major flood events has more than doubled, while the incidence of storms grew by 40% during the same period. Extreme temperature events accounted for 6% of all climate events during this period, and it was the third most important, by the count of occurrences, climate change-related event. The IPCC confirms that global warming increases the frequency and intensity of weather events. According to their latest report (IPCC, 2023), the frequency and intensity of weather events, such as heavy precipitation and heat waves, have significantly increased since 1950. The frequency of marine heatwaves doubled from 1980, and the proportion of category 3–5 tropical cyclone occurrence has increased over the last four decades (IPCC, 2023).

Even at a 1.5°C global warming, heavy precipitation and flooding events are projected to intensify and become more frequent in most regions. At a temperature rise of 2°C or above, these changes will expand to more regions and become more significant. Table 6 shows the median changes in precipitation, sea level, and temperature between the baseline (i.e., mean precipitation, sea level, and temperature between 1981 and 2010) and the short-, medium-, and long-term (IPCC, 2023). For example, Europe will probably experience a higher change in days above 35°C (between 4-10 more days) and 40°C (between 2-5 more days) in comparison to the worldwide median change (between 3-7 and 1.5-4 more days, respectively). North America will experience a higher change in precipitation levels than Europe in the near (25% higher), medium (33% higher), and long term (32% higher). Other projected changes include the intensification of cyclones and storms and increases in aridity and fire weather.

Table 6: IPCC extreme climate projections. SSP2-4.5 RCP scenario. Comparisons against the 1981-2010 baseline

Variable	Region	Unit (change)	Near Term (2021-2040)	Medium Term (2041-2060)	Long Term (2081-2100)
Maximum 1 day precipitation (RX1day)	World	Median (%)	4.5	7.3	11.9
	Europe	Median (%)	3.2	4.5	7.6
	North America	Median (%)	4	6.7	11.2
Sea Level Rise	World	Median (meters)	0.1	0.2	0.5
	Europe	Median (meters)	0.1	0.2	0.5
	North America	Median (meters)	0.1	0.3	0.5
Days with TX above 35° Celsius	World	Median (days)	2.7	4.4	7
	North America	Median (days)	2.3	4	6.6
	Europe	Median (days)	3.7	6.2	10.2
Days with TX above 40° Celsius	World	Median (days)	1.5	2.5	4
	North America	Median (days)	0.8	1.5	2.6
	Europe	Median (days)	1.9	3.1	5.4

4.1.1 Exposure to physical risks

Physical risks have significant impacts on humans and the environment. And they can have similar effects on the economy with heavy financial implications for organizations, including infrastructure companies. Adverse effects involve direct damage to assets and indirect damage from supply chain disruption, both increasing companies' maintenance and repair costs, time-related costs for delays and disruptions, and climate event-related insurance premiums. The financial performance of companies may also be affected by changes in the availability, sourcing, and quality of water, food security, and extreme temperature changes affecting organizations' premises, operations, supply chain, transport needs, and employee safety (Financial Stability Board, 2017).

Infrastructure assets are the most exposed to the adverse effects of climate-related events. Property and infrastructure damage from natural disasters accounted for two-thirds (estimated at USD220 billion) of all insured natural disaster losses worldwide in 2017 (Morgan Stanley, 2018). In addition, infrastructure investments often include long-lived fixed assets in locations or operations in climate-sensitive regions (e.g., coastal and flood- and fire-prone areas). Moreover, since the frequency and intensity of climate events will increase, future infrastructure exposure to physical risks will do so, too.

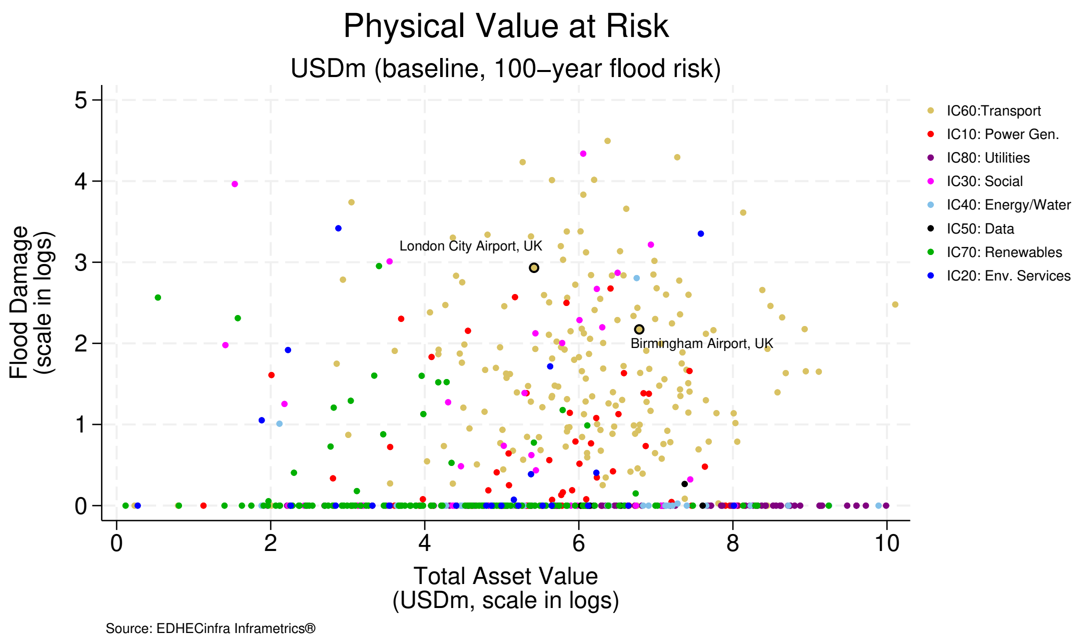
To better understand the current exposure to the effects of climate events, we analyzed the distribution of potential physical risk damages in our infraMetrics *reference* dataset of about 700 tracked companies. We observe large variations in the distribution of damages within and between the three analyzed climate event types (see Table 7 and (Marcelo and Blanc-Brude, 2022) for methodological details). The results show that the consequences of extreme climate events could be significant for highly exposed infrastructure assets (e.g., those in the 90% percentile). Expected damages from floods, cyclones, and storms for the companies most exposed to physical risks (99% percentile) exceeded 52%, 17%, and 9%, respectively. Moreover, the expected damage could have been 86%, 18%, and 27% for the most exposed assets.

To put these results into context, we considered the portfolio of a large Canadian pension fund, including 13 assets. Two of these assets are exposed to severe flood events (see Figure 3), with 18% (London City Airport, UK) and 8% (Birmingham Airport, UK) potential damages that, if materialized, could cost in aggregate USD190 million or 14% of the equity value. That is close to 3% of the value of the Canadian pension fund's

Table 7: Distribution of Physical Risk Damages (Flood, Cyclone, Extratropical Storm)

	Baseline 2020 Climate Events (100-year events)		
Percentile	Flood Damage %	Cyclone Damage %	Extratropical Storm Damage %
25%	0	0	0
50%	0	0	0
75%	0.03	0	0.01
90%	0.09	0	0.02
95%	0.16	0.02	0.04
99%	0.52	0.17	0.09
Min	**0**	**0**	**0**
Mean	**0.034**	**0.01**	**0.01**
Max	**0.86**	**0.18**	**0.27**

Figure 3: Potential Flood Damage vs. Total Asset Value Across all Infrastructure Sectors



portfolio, despite the fact that these two assets weigh only 1% and 7% in the portfolio, respectively.

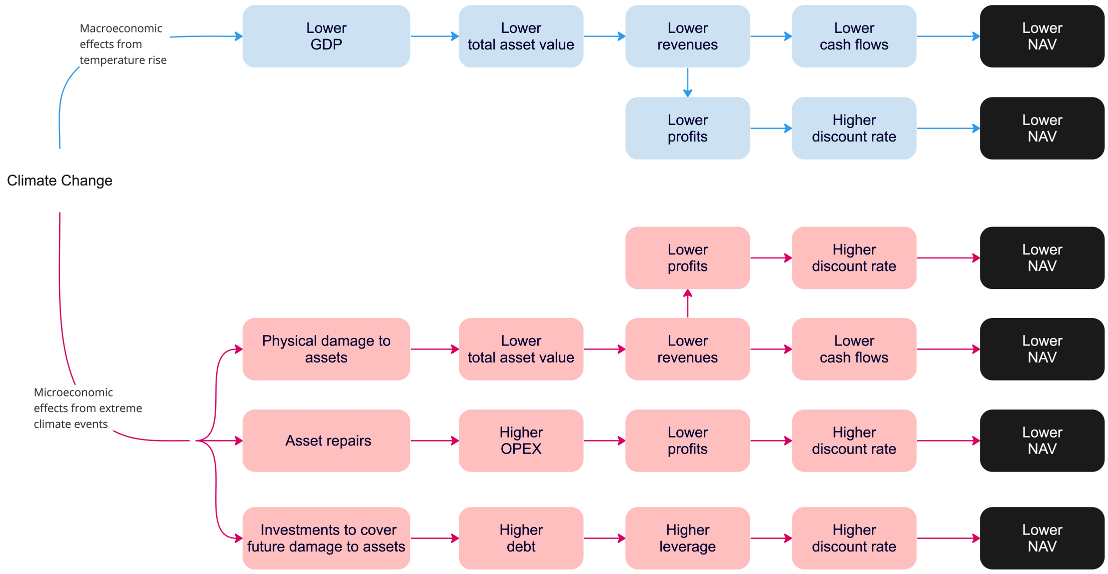
To calculate the impact of physical risks for investors, we assessed the expected physical risks by 2050 and their financial implications. In the calculations below, we use a scenario that does not implement additional climate policies (one of NGFS' hot house world scenarios) and hence, represents the maximum physical risk scenario. To isolate the physical risk effect, we calculate the difference in asset prices (NAV) between the hot house world and an orderly scenario where coordinated actions and policies to minimize climate change are applied. Moreover, we analyze the microeconomic effects of physical risk within the hot house world scenario, as this result is exceptionally important for investors with assets highly exposed to climate events.

4.2 The Market Value of Physical Risks by 2050

4.2.1 Approach

Previously, we used NGFS scenarios to forecast the impact of different climate policies on transition risk. In this section, we use the NGFS scenarios to predict the effects of making no additional efforts to restrain climate change –our main proxy of physical risk. Whereas in orderly scenarios, global warming remains contained, and

Figure 4: Macro and micro effects of extreme climate events on NAV



the physical risks associated with climate change are low, climate policies remain unchanged in hot house world scenarios at the cost of high physical risks, especially after 2050. According to the IPCC (2023), continuing the policies implemented by the end of 2020 will lead to global warming of 3.2°C by the end of the century.

The risk from extreme climate events for companies' NAV manifests through two channels (see Figure 4): At the macroeconomic level, overall productivity and economic output decline due to increases in global temperatures. As a result, the reduction in economic activity (measured using NGFS' GDP projections) impacts the total asset value of companies.

At the macroeconomic level, our approach estimates companies' NAV using the variables described above as inputs of the infraMetrics asset pricing model: First, we calculate cash flows at the infrastructure company level using the projections of revenue and debt. Second, we estimate the discount rates using companies' size (proxied by total assets), profits (as a function of revenues, OPEX, and total assets), and leverage (as a function of total debt and total assets; for more details on our asset pricing model, see Appendix A.2). Since the underlying inputs of this valuation model are physically risk-sensitive, the resulting NAV effectively reflects the effects of extreme climate events under the hot house world and the orderly scenario. These calculations allow us to measure the cost of each scenario to investors and the difference between scenarios as a measure of physical risk.

At the microeconomic level, our calculations refer to asset damage as the portion of the asset that would be destroyed upon the occurrence of extreme weather events (our current models calculate damage from floods, cyclones, and storms, as they are the most destructive and common extreme weather events). Moreover, previous work on the materiality of climate events shows that chronic physical risks (e.g., increasing mean temperatures and sea levels) are not material to infrastructure assets before 2050. Therefore, we measure asset level damage using damage functions specific to each type of climate event and infrastructure asset (Marcelo et al., 2022). Similar to the carbon emission levels to calculate transition risk, this data is part of infraMetrics' *reference* dataset.

4.2.2 results

At the macroeconomic level, the effects of increasing global mean temperatures will only be

Table 8: Average Impact of Physical Risk on NAV within the Hot House Scenario (Current Policies)

TICCS®	Activity Name	Mean	Min	Max
IC10	Power Generation x-Renewables	-1.5%	0.0%	-6.4%
IC20	Environmental Services	-2.2%	-0.1%	-18.2%
IC30	Social Infrastructure	-2.4%	0.0%	-13.1%
IC40	Energy and Water Resources	-7.5%	-0.9%	-40.7%
IC50	Data Infrastructure	-3.7%	-0.4%	-5.7%
IC60	Transport	-10.9%	0.0%	-97.8%
IC70	Renewable Power	-1.5%	-0.1%	-7.2%
IC80	Network Utilities	-5.4%	-0.5%	-26.1%
Average		**-4.4%**	**-0.3%**	**-26.9%**

significant in terms of reduced global productivity and lower GDP after 2050. This means that the macroeconomic effects of increased temperatures on asset values, revenues, and profits and, ultimately, on cash flows and discount rates, through the economic output channel (Figure 4) will only compound after 2050. When applying the approach to our *reference* dataset of 700 infrastructure companies, we observe that the loss of value between the hot house world and the orderly scenario is very close to zero. However, this result is conservative for two reasons: First, the GDP growths fast under the NGFS' orderly and hot house world scenarios until 2050. Second, the NGFS assumes that carbon emissions stabilize in the hot house world scenario. These assumptions are arguably too optimistic.

However, at the microeconomic level, the cost of physical risks within the Current Policies scenario represents, on average, 4.4% of the total NAV of the assets in our *reference* database by 2050, with important variations across sectors, as shown in Table 8. The effect of extreme climate events is negative across all sectors, with a maximum average loss of -27%, impacting the NAV of the Transport (-11% on average with a maximum of -98%) and the Energy and Water Resources sector (-7% on average, with a maximum of -41%) the most. For example, the negative impact of physical risk on NAV in the transport sector would be four times greater than in the renewable power sector (at a -5.4% loss).

These results confirm that certain sectors, like transport assets, are ultimately more exposed to climate hazards. Still, we see that all sectors are impacted by physical risks even before 2050. In other words, before the impact of physical risk at the macro level starts reducing asset values through the main business channel: the demand for infrastructure services.

Moreover, whereas the average loss of value due to physical risk alone reached 11% on average for transport assets, individual cases can be much larger, as shown in Table 8 above. Therefore, it is possible for some investors to be highly exposed to climate risks despite these being considered limited in aggregate before 2050.

To determine the extent to which an investor may be exposed to such risk, we analyze infrastructure portfolios. We first review the number of assets held by investors in infrastructure companies to determine a typical portfolio profile in terms of the number of assets and sector exposures. Second, we use a random combination of assets to show how risky an infrastructure portfolio can be when it comes to physical climate risk.

4.2.3 The concentration of physical risks

Infrastructure investors tend to hold only a few assets in their portfolios. While some investors may invest through funds and increase the number of underlying assets they are exposed to, most individual managers or direct investors have only a few assets in a portfolio. Accord-

Table 9: Average number of directly held assets in portfolios of different investor peer groups

Row Labels	Mean number of direct stakes in infrastructure assets per investor	Mean Allocation to Infrastructure Equity	Number of Investors surveyed
Insurers	5	3%	30
Pension funds	8	7%	66
Sovereign Wealth Funds	12	4%	14
Infra-only Managers	29	100%	107
Multi-Alts Managers	17	23%	187
Total	**17**	**45%**	**404**

Source: infraMetrics Investor Peer Group Research, 2023

ingly, infrastructure portfolios are generally not very diversified, with a limited average number of assets directly held per investor.

Our review of the data (see Table 9 suggests that asset managers hold only a few assets (23 infrastructure assets on average) across multiple funds. By contrast, asset owners directly hold even fewer assets (8 on average). We see that asset owners typically have a dozen assets or less. In contrast, managers who invest through one or multiple funds have more assets in their global portfolio (all funds combined) but still not many assets.

This suggests that even if assets had equal weights in the portfolio, which is unlikely, directly held individual assets in an asset owner portfolio would typically make up at least 12.5% of the portfolio's value (assuming eight assets on average). Therefore, portfolios would only need one or two assets highly exposed to physical risk to be significantly impacted. In practice, assets are usually not weighted equally in a portfolio. Instead, infrastructure portfolios can be highly concentrated in a very small number of large assets (e.g., utilities) and some much smaller ones (e.g., wind farms). If the large assets are prone to physical risks, this could jeopardize the portfolio even more.

This suggests that even if assets had equal weights in the portfolio, which is unlikely, directly held individual assets in an asset owner portfolio would typically make up at least 12.5% of the portfolio's value (assuming 8 assets on average). Therefore, portfolios would only need one or two assets highly exposed to physical risk to be significantly impacted. In practice, assets are usually not weighted equally in a portfolio. Instead, infrastructure portfolios can be highly concentrated in a very small number of large assets (e.g., utilities) and some much smaller ones (e.g., wind farms). If the large assets are prone to physical risks, this could jeopardize the portfolio even more.

To capture this low diversification profile, we build thousands of random portfolios of the 500+ assets we priced in the hot house world and the orderly scenario and examine the degree of extreme risk (max portfolio loss) in the two scenarios depending on the number of assets in the portfolio. The methodology to create random portfolios is derived from the infraMetrics fund benchmark and is described in Appendix A.3.

Table 10 and Figure 5 show the range of maximum losses due to physical risk: The difference in value by 2050 between the same portfolios with and without asset-level physical risks. For a given portfolio size which varies between 5 and 20 assets, the level of losses solely due to physical risk factors is twice as large in the hot house world scenario due to the increase in the intensity and frequency of weather-related damages. In the most extreme cases, when investors are exposed to the riskiest assets in the same portfolio, losses can amount to 27% in the orderly transition scenario and to 54% in the hot house world

Figure 5: Histogram of portfolio losses due to physical risk by or before 2050

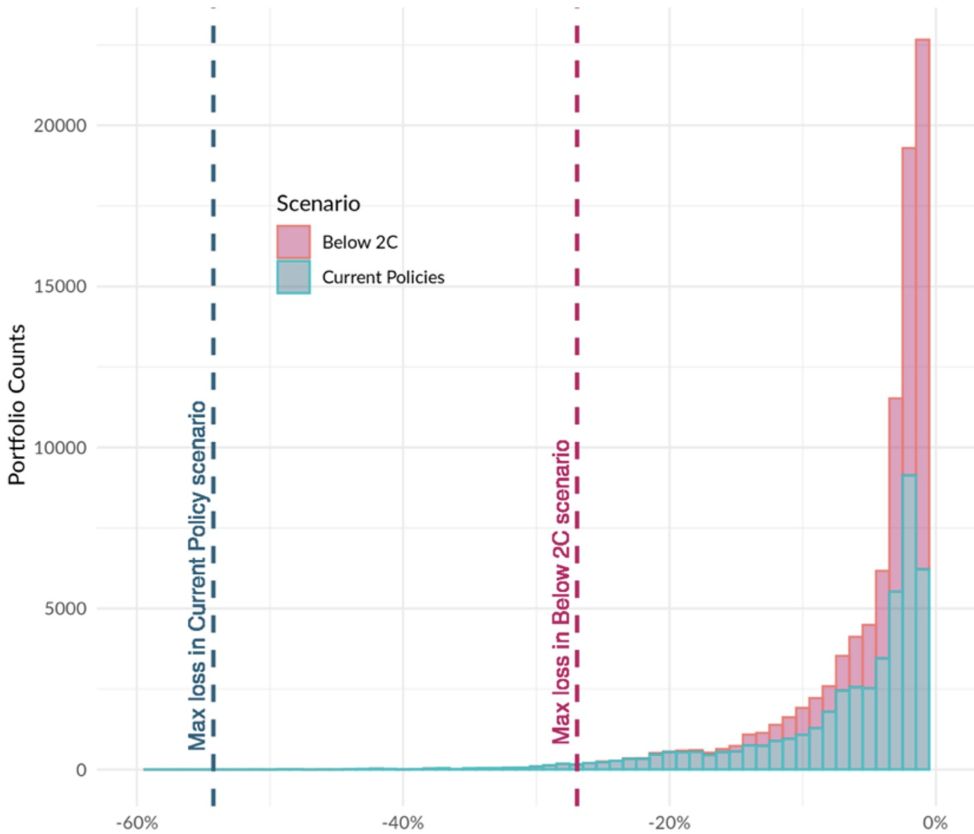


Figure 6: Extreme portfolio loss due to physical risk by or before 2050

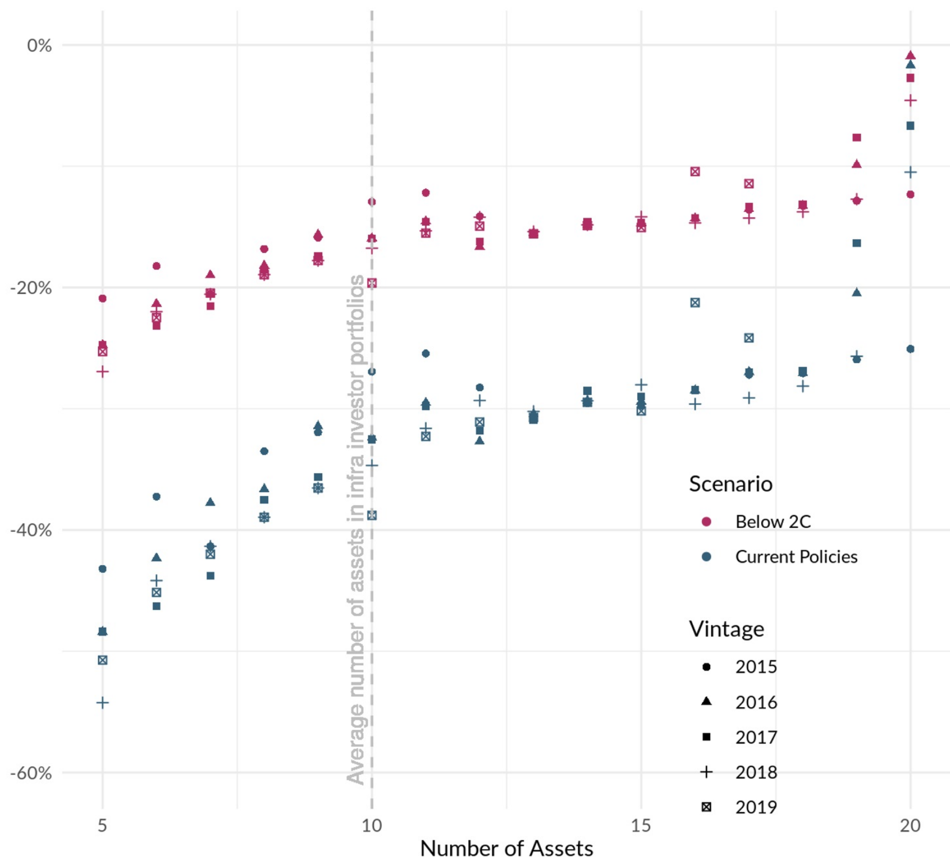


Table 10: Maximum, mean, and minimum portfolio loss in simulations (5 vintages)

Scenario	Extreme Loss	Mean Loss	Min Loss	N
Below 2C	-27%	-3%	-0.2%	45,413
Current Policies	-54%	-7%	-0.3%	45,413

scenario. Figure 6 illustrates these results for simulations using different portfolio vintages that would be fully invested by 2022.

In other words, an investor that started to build a portfolio or a fund in 2018 and would be fully invested by 2022 and planning to keep assets for another 30 years would be exposed to losses solely due to physical risks ranging from approximately 10-50% depending on the number of assets in the portfolio.

4.3 Conclusion on Physical Risk

Our calculations show that the effects of physical risks in infrastructure in 2050 will be significantly high on the microeconomic level for individual investments, with some assets and portfolios facing high exposure to physical risks. Furthermore, the potential effects of climate events are based on historical climate data and are expected as of today. As temperatures continue to rise, the impacts of physical risks will become more severe as climate events become more intense and frequent.

Additionally, we argue that the real magnitude of physical risk may be underestimated due to the NGFS assumptions at the macroeconomic level. However, at the microeconomic level, we show that some sectors would be impacted more severely than others in a hot house world scenario and that, given the configuration of most infrastructure portfolios, large exposure of a few assets could significantly increase portfolio-level exposure to physical risks.

Of course, 2050 is still 30 years away and past the investment horizon of many investors, especially the ubiquitous 10-year investment funds. However, many investors are now exposed to longer-term investments over 20 to 25 years, as well as evergreen funds and direct investments that are meant to be held to maturity. Moreover, the same Limited Partners currently invested in 10-year funds will be exposed to the same assets in the next generation of infrastructure funds, be they follow-on funds or under new management.

The Task Force on Climate-related Financial Disclosures (TCFD) requires reporting material physical risks precisely because these can be material and will necessarily increase in a hot house world scenario. We show that such risks are already material for many investors in infrastructure assets, even if these are located in developed economies.

Finally, our estimate can be considered very conservative in light of the very limited impact of physical risk on the economy implied by the NGFS scenario. A 'too little, too late' scenario by which emissions keep rising and climate change happens faster does not currently exist in the NGFS data but would show a rapidly decreasing value of infrastructure assets due to their loss of future revenues, itself the result of a less active economy, mostly due to chronic heat.

5. Conclusion

In this paper, we measured the value of transition and physical risks for the privately invested infrastructure sector. Using the NGFS scenarios, we estimated the costs of a delayed or uncoordinated transition and the potential loss in portfolio value due to physical risks in the case of no climate action.

Our calculations show that transition risk in infrastructure is not negligible. The total infrastructure investment value loss due to transition risk in a disorderly scenario is nearly USD600 billion or 30% of the total invested value in infraMetric's 9000 infrastructure assets. Whereas the highest negative effect would be experienced by the Energy and Water resources sectors with a 38% reduction of the NAV on average, the negative effects of transition risk would impact all sectors, including low-carbon ones like the Renewables and Social Infrastructure sectors.

Moreover, we estimate the effects of physical risks in infrastructure investments in 2050 to be significantly high at the microeconomic level, with some assets and portfolios facing high exposure to physical risks. Indeed, extreme climate events could impact the assets' NAV to a maximum of -98% in the transport sector and to a maximum of -41% in the Energy and Water Resources sector. In the most extreme cases, when investors are exposed to the riskiest assets, losses can amount to 54% in the hot house world scenario. Infrastructure investors tend to hold only a few assets in their portfolios. Therefore, it would only take one or two highly exposed assets to physical risk to significantly expose an entire portfolio.

However, the magnitude of the transition and physical risks is greater than our estimations show. First, in some sectors, the asset's carbon footprint is underrepresented when only considering Scope 1 and 2 emissions. This is the case in the Energy and Water Resources and the Network Utilities sectors, which are the most exposed to Scope 3-related transition risks. Future versions of our transition risk models will overcome this limitation. Second, the effects of transition risk go beyond the impact of carbon taxes. Following TICCS® and the EU taxonomy, we show that as countries transition to a low-carbon economy, the market value losses in Europe could leave up to USD9 billion in stranded assets. Finally, the real magnitude of physical risk may be underestimated due to the NGFS assumptions. For example, NGFS assumes that carbon emissions stabilize in the current policy scenario today, and the effects of increasing global temperatures on productivity and GDP are only noticeable after 2050, an assumption that could be deemed too optimistic.

Carbon taxes, probably the main policy tool to mitigate greenhouse gas emissions and combat climate change, have not achieved widespread adoption. Today only a few countries have implemented carbon taxes and at levels that would need to be at least 40 times higher by 2050 to put us on track to achieving 1.5°C (Net Zero) before 2050. However, carbon taxes can be politically challenging to implement due to potential opposition from industries and the general public, and governments' concerns. Moreover, the lack of international consensus and cooperation on carbon pricing frameworks further hampers the broader implementation of carbon taxes.

And yet, based on the evidence presented in this paper, we recommend that investors demand coordinated actions and that governments immediately implement carbon taxes to minimize the adverse financial effects of transition risk. The worst impact comes from reacting too late.

Finally, managing climate risks is only possible with reliable climate risk and financial measurements at the asset level. This paper shows the huge potential of consistent measurements that accurately portray the impact of climate risks on infrastructure investments. Armed with this knowledge, investors can make informed decisions, proactively respond to potential challenges, and capitalize on opportunities arising from climate-related changes.

A. Appendix

A.1 EDHEC*infra*'s Unlisted Infrastructure Universe and TICCS

EDHEC*infra* documented around 9,000 unique infrastructure companies in the 25 most active national markets for infrastructure investors to define an investible universe of unlisted infrastructure companies. These companies have a minimum of USD 1 million in total asset book value, are privately owned, and can be categorized using The Infrastructure Company Classification Standard (TICCS) of infrastructure companies. EDHEC*infra* maintains and updates this universe on an annual basis. However, the fair market value of individual firms is only calculated for a subset of this universe (circa 700 companies) as it requires an in-depth analysis of the company's financials, future cash flows, and market cost of equity (discount rate).

The TICCS taxonomy is a four-pillar classification system based on consensual, objective criteria and distinguishes between the business model (pillar 1), asset-level activities (pillar 2), geo-economic exposures (pillar 3), and the corporate structure (pillar 4) of infrastructure companies. Thus, an infrastructure company can be a global airport set up as a regulated corporation, a merchant, a combined-cycle gas turbine power generator connected to a national grid, or a project financed special purpose entity providing light rail services with contracted revenues and a sub-national client (e.g., a city). TICCS refers to an infrastructure entity not only as a physical asset but understands it as a business providing a service from which it derives its value. Created in 2018, TICCS is reviewed biennially by the market and an independent review committee, including some of the largest investors in the world. Today, it is a universally recognized standard for classifying investments and constructing benchmarks or comparable segments.

To determine the size of the exposure to climate risk for investors in infrastructure, we need to estimate the *aggregate* market value of equity for all 9,000+ companies. To do this, we use the available market price data to build comparables ("comps") by TICCS segment for the ratio of equity price (NAV) to total asset book value (TA). Table 11 shows the breakdown of the identified universe and the comps for different TICCS pillars using monthly pricing for the years 2021 to 2022.

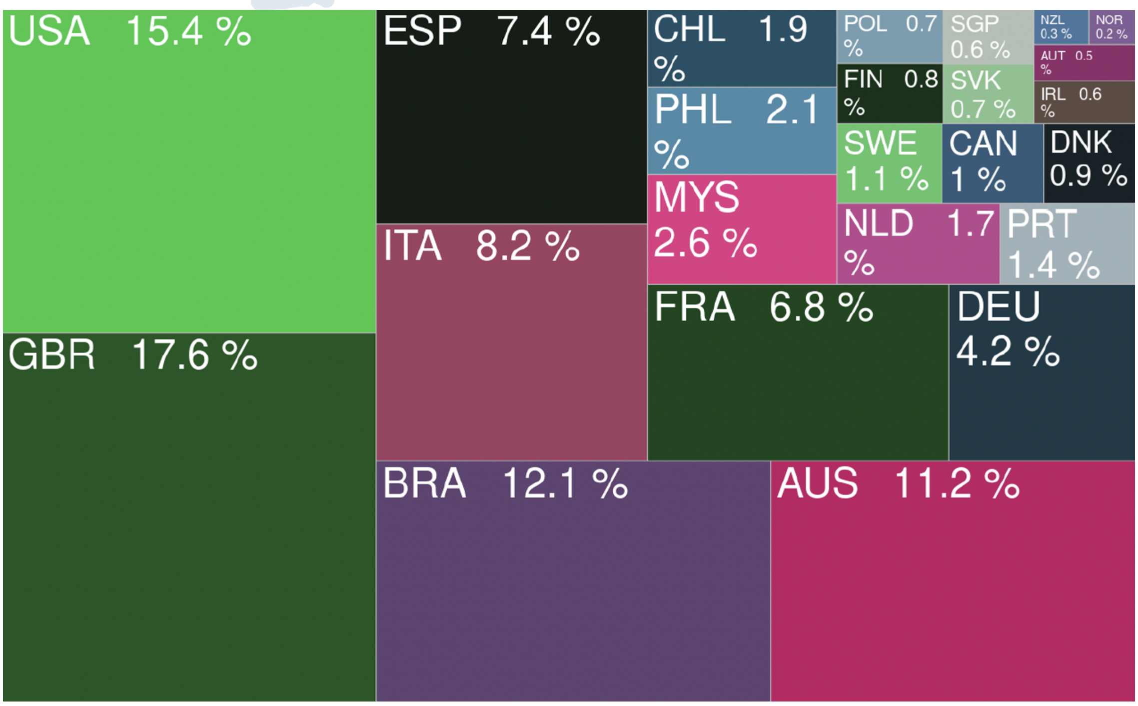
To estimate company-level NAV to TA ratios for all assets in the universe, we regress this data against several control variables, namely, TA, age, a country risk effect proxied by the term spread, and all TICCS pillars, including interactions between industrial activities and business models. The regression results obtained allow for predicting the NAV/TA ratio for all assets in the universe and, from there, using each company's TA book value to derive a typical NAV for these firms at the end of 2022, given its characteristics. Of course, this NAV is less precise but enables us to compute an aggregated market size. Accordingly, combining average values and actual values provides us with a reasonable estimate of the total size and an order of magnitude to consider the size of expected climate losses.

The final market cap for the companies in the *universe* dataset is close to USD2 trillion at the end of 2022, split between countries, as shown in Figure 7. Note that larger markets are either large economies like the US (where most infrastructure remains state- or city-owned and -financed) but also countries that have chosen to privatize infrastructure more than others, like the United Kingdom or Australia.

Table 11: TICCS® universe and comps for asset's ratio of NAV to total asset value (infraMetrics, 2023)

TICCS® Code	Universe Breakdown in %	Mean NAV/TA	Median NAV/TA	Obs.
Business Model Class				
Contracted	58.9	0.499	0.359	2,355
Merchant	23.1	0.736	0.506	859
Regulated	18.0	0.449	0.349	705
Industrial Activity Superclass				
Power (IC10)	12.1	0.711	0.464	272
Env. Service (IC20)	3.8	0.446	0.357	141
Social Infra. (IC30)	14.6	0.352	0.275	584
Nat. Res. (IC40)	4.1	0.736	0.637	107
Data (IC50)	1.7	0.639	0.481	99
Transport (IC60)	35.4	0.564	0.366	1,435
Renewables (IC70)	16.0	0.667	0.543	832
Network Utilities (IC80)	12.5	0.346	0.305	449
Geo-Economic Exposure				
Global		0.589	0.570	90
Regional		0.587	0.437	1,670
National		0.804	0.482	384
Subnational		0.440	0.337	1,775
Corporate Structure				
Project Finance Vehicle	74.0	0.526	0.374	2,942
Corporate	26.0	0.589	0.409	977

Figure 7: Breakdown of the USD 1.8 trillion market capitalisation for companies in the unlisted infrastructure universe (YE 2022)



A.2 EDHEC*infra*'s Asset Pricing Model

This section explains how we use the outputs of the climate risk model (total assets, revenues, OPEX, total debt, leverage, profitability) in infraMetrics's asset pricing approach to project the value of infrastructure assets under all NGFS scenarios.

InfraMetrics asset pricing approach is a two-stage process to forecast the cash flows and estimate an equity risk premium of infrastructure companies, built upon the insights from the modern financial theory. It is used to estimate the mark-to-market valuations of privately-held infrastructure companies on a monthly basis.

When dealing with infrastructure assets privately held in institutional portfolios, the market prices are not readily available. This model solves the problem of paucity of data available on transaction prices, and makes it possible to assess the fair market value of illiquid assets accurately[1]. As a result, the valuation of unlisted infrastructure equity investments relies on the guiding principles and modern asset pricing theory of the International Financial Reporting Standards (IFRS) 13 –a framework for fair value measurements (IFRS Foundation, 2011).

One of the most commonly used methods for this purpose is the income or discounted cash flow (DCF) approach:

$$\mathrm{NAV}_{i,t} = \sum_{\tau=1}^{T} \frac{\mathrm{Div}_{i,t+\tau}}{(1 + r_{t+\tau})^{t+\tau-1}} \quad \text{(A.1)}$$

where $NAV_{(i,T)}$ is the Net Asset Value at time t of asset i, $DIV_{(i,t+\tau)}$ is the cash flow of asset i at time $t+\tau$, $r_{(t+\tau)}$ is the discount rate at time t, and T is the maturity date of the project contract.

In turn, we have:

$$r_{t+\tau} = \mathrm{Rf}^{C}_{t+\tau} + \gamma_{i,t} \quad \text{(A.2)}$$

with $Rf^{C}_{(t+\tau)}$ being the yield curve at time t in country C, at the horizon T of asset I, and $\gamma_{(t,i)}$, being the risk premium of asset i reflecting the market price at time t of the risk of future dividends.

Finally, the risk premium is a function of a limited number of systematic risk factors found in every infrastructure company:

$$\gamma_{t,i} = \sum_{k=1}^{K} \beta_{i,k,t} \cdot \lambda_{k,t} \quad \text{(A.3)}$$

Common factors determine the risk premium level of a given investment in two ways: 1) Risk that the investment is exposed to (e.g., the amount of leverage). We can call beta β the amount of risk or exposure. 2) Price (return) that the market is willing to bear to take this risk. The market price of this risk or risk premium, we can call lambda λ. If companies are exposed to multiple common risk factors, their cost of equity (discount rate) is just a combination of betas and lambdas.

Our valuation methodology involves the following steps:

- Arrive at a **cash flow forecast** at the valuation time (i.e., the gross cash flows that are expected to accrue to the asset owners).
- Estimate the market price of risk (**risk premium**) for the relevant investment at the time of valuation. This is the equity risk premium that is relevant to each infrastructure company.
- Determine the relevant term structure of **interest rates** with an equivalent duration (i.e., horizon) to the investment.
- Finally, compute an asset price. Given the estimates of each of these three components in the different climate scenarios, we can compute the valuations of all the infrastructure companies in the respective scenario.

A.2.1 Cash flow forecast

We use infraMetrics' methodology to forecast cash flows in unlisted infrastructure companies. It aims to minimize the multiplication of estimation

1 - see infraMetrics Asset Pricing Methodology for more details at `https://docs.edhecinfra.com/display/AP`

errors by using the smallest number of variables possible. Infrastructure companies' free cash flow to equity is modeled as a stochastic process described as a two-dimensional state vector (mean and variance). The future free cash flow to equity of each firm is defined as:

$$\text{FCFE}_t = \text{CFADS}_t - \text{DS}_t \qquad \text{(A.4)}$$

where DS_t is the senior debt service owned at time t and $CFADS_t$ is the cash flow available for debt service at time t. This free cash flow process results from the firm's business model and risk, the choice and evolution of its financial structure, and it ultimately determines the ability of the firm to repay its senior creditors and equity investors. Crucially, infrastructure companies are characterized by limited growth opportunities and numerous long-term commitments (to invest only in their core business, to deliver service, etc.); thus, making future debt service and equity payouts a direct function of the firm's free cash flow which cannot be used for other purposes.

While we cannot model the payouts to equity investors directly, we can use the following indirect, multi-step approach:

- Estimate CFADS:
  CFADS of a company follows a well-defined pattern over its life which can be explained using revenues, debt service, revenue growth, and control variables for business risk and sector effects, along with the idiosyncratic effect in each company based on historical trends. The result, combined with the forecasts of revenue and outstanding debt in the different NGFS scenarios, allows us to estimate CFADS of each infrastructure company in the NGFS scenarios.
- Estimate Retention Rate:
  Similarly, the retention rate of a company, its tendency to retain the free cash, also follows a pattern over its life which can be explained using revenues and control variables for business risk and sector effects, along with the idiosyncratic effect in each company based on historical trends.
- Estimate dividend forecast:
  The dividend forecast is simply the result of the other estimated variables combined as below:

$$\text{Payout}_t = (\text{CFADS}_t - \text{DS}_t) \cdot (1 - \text{RR}_t) \quad \text{(A.5)}$$

where DS_t is the senior debt service owned at time t, $CFADS_t$ is the cash flow available for debt service at time t, and RR_t is the retention rate at time t.

This approach is accurate when forecasting infrastructure companies' free cash and future dividends (CFADS' in-sample median error = 3%; dividend growth' out-sample mean error = 3%; dividend growth' out-sample median error = 0.5%).

A.2.2 Equity risk premium

We rely on the infraMetrics' asset pricing methodology to estimate the equity risk premium for infrastructure companies in each climate scenario. The following key risk factors explain observed transaction prices and their implied expected returns:

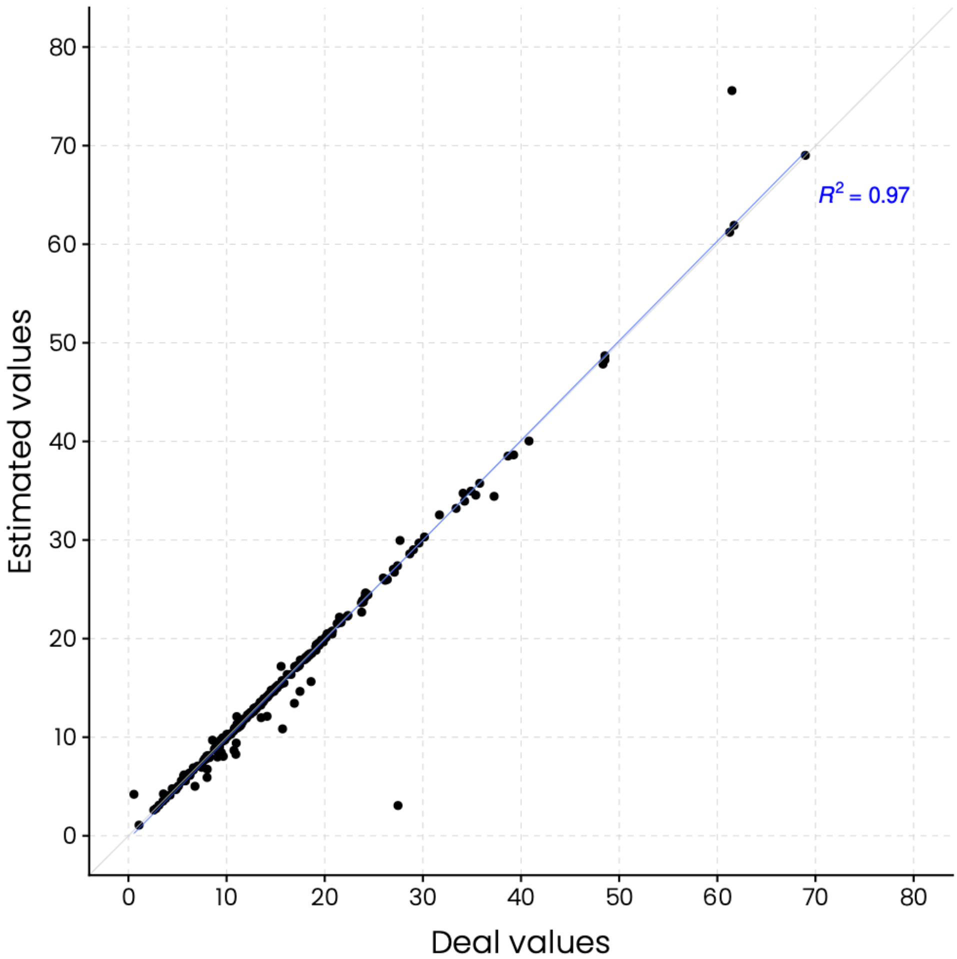
- Leverage (senior liabilities over total assets)
- Size (total assets)
- Profitability (return on assets before tax)
- Investment (CAPEX over total assets)
- Country risk (term spread)
- A range of control variables, including business model and industrial activities, based on TICCS

The model determines the market price or premium of each of these factors over a more than 20 years period. To forecast the equity risk premium of infrastructure companies, we assume that these factor prices are mean-reverting, and their long-term (15-year) averages will serve as a good proxy of the prices in the future. As shown in Table 12 and Figure 8, this approach can produce very accurate valuations compared to realized transaction prices with an estimation error within 5% of the transacted price.

Table 12: Estimated (Est.) vs. reported valuation ratios and model's goodness-of-fit.

Ratio	Reported Mean	Est. Mean	Reported Median	Est. Median	R^2	RMSE
EV/EBITDA	15.54	15.34	12.98	12.61	0.97	2.27
P/Book	2.37	2.28	1.65	1.59	0.87	0.90
P/Sales	3.35	3.21	2.52	2.32	0.85	1.43

Figure 8: Reported vs estimated EV to EBITDA ratios"



To test the results of this valuation approach, including the estimates of cash flows and equity risk premium, we conduct robustness tests of more than 250 reported transactions from a diverse set of sectors and countries. Figure 8 presents the results of this robustness test.

- We compare the mean and median of the valuation ratios of the observed market transactions against the infraMetrics estimates. We find that on an aggregated basis, the estimates are fairly close.
- We also present a distribution of the estimated errors of the individual reported deals. The median and mean errors are less than 1%. However, the extreme percentile values can reflect up to 5% estimation error.
- We also show a linear regression chart of the estimated and reported EV/EBITDA ratios. It shows a very high R-squared value, and the dots are well-aligned with the diagonal line (a perfect match between model and predicted prices would line up all dots on these plots on the 45º line).

By forecasting the key risk factors, we also have the loadings (or betas) for each of these factors for each company and their different values in different NGFS scenarios. As a result, we compute a different estimate of equity risk premium in each scenario that considers the drivers of the firm's risk premium. For instance, in an orderly transition scenario, an infrastructure company could be less profitable initially due to higher upfront costs but generate more profits later. However, the reverse might be true in the delayed transition scenario. The loadings and price estimates of these risk factors allow us to forecast the equity risk premium of each infrastructure company in the NGFS scenarios at each point in time.

A.2.3 Interest rates

EDHEC*infra*'s asset pricing model uses the scenario-dependent forecasts of interest rates provided by the National Institute Global Econometric Model (NiGEM), a global economic model used by NGFS, to assess the impact of climate change on various macroeconomic variables, including interest rates. NiGEM takes NGFS data as input, and its predictions thus depend on the scenario and model considered. Together, interest rates and equity risk premia determine the appropriate discount rate (yield) estimate for any given climate scenario.

A.3 Random Portfolio Generation

We follow the methodology described in Gupta and Blanc-Brude (2021) to build random portfolios of infrastructure assets. The approach mimics the portfolio development process of an investor in illiquid assets like infrastructure. It starts from a pre-defined universe and allows thousands of theoretical investors to buy assets each year, considering the size of the fund, the likelihood of deploying the capital in that year, and the number of investments the fund targets. This reproduces the J-curve effect[2] by building portfolios over several years.

The calibration of the approach includes the following aspects:

- **Portfolio size**: With the ever-growing investor interest in the unlisted infrastructure asset class, average fund and portfolio sizes have increased from about USD200 million in 2000 to more than USD1 billion in 2020. We have assumed the fund size to be distributed between USD100 million to USD2 billion, with probabilities that follow the historical average.
- **Number of investments**: The typical number of investments in a closed-end private infrastructure fund range from five to 20. Therefore in these fund calibrations, we assume a normal distribution over this range of investments. The final number of deals is also impacted by the market activity in any given investment year.
- **Deal success rate**: We assume a deal success probability depending on market activity for any given investment year. This determines which funds are eligible to make an investment at any given time. This data is calibrated based on the historical number of deals divided by the number of active investors.
- **Investment size**: We assume that capital is equally deployed (at the price given by the prevailing NAV) to all the randomly selected companies in the fund.

For a given universe, companies eligible for investment are shortlisted. If the investors are eligible to make a deal on that investment date based on a deal success rate assumption, a random company is invested, which becomes unavailable for investment for the rest of the investment period. This process is followed until the fund has invested up to the investment ratio or the fund is abandoned (if its TVPI multiple, total value divided by paid in capital, is less than 1 after four years).

2 - J-curve reflects the net cash flows of a private equity where the investment has negative returns at first, for a period of time due to the impact of manager fees, before then entering a period of recovery as the underlying investments start to gain in value

A.4 Calibration of the Climate Scenario Model Equations

We introduce a climate risk model inspired by Alogoskoufis et al. (2021). The model consists of two parts: The calibration part regresses historical financial and macroeconomic variables (GDP and inflation), and the projection part integrates climate risks into the calibrated equations to make scenario-dependent projections of the financial variables.

The calibration consists of three regressions involving GDP and inflation for total assets, revenues and OPEX. To ensure stationarity and avoid spurious correlations, we consider the growth rates of all variables rather than their raw values, except for inflation which is already a growth rate. The variables are then log-transformed to estimate elasticities better after they are topped by 1 to limit the occurrence of negative numbers.

Infrastructure companies belong to two main categories: Corporate companies are multi-project firms akin to corporate-governance structures found in other industrial sectors, while project companies are single-project or project-financed firms with a limited lifetime. Because corporate and project companies can exhibit fundamental differences in behavior, we perform separate regression analyses for each. While the same model structure applies to both, there are critical differences in the equation for total assets. Relevant differences also exist in the regression coefficients for both categories and in the projections of financial variables.

A.4.1 Total assets

Based on Alogoskoufis et al. (2021), total assets follow an auto-regressive pattern, and their growth correlates with GDP growth and inflation. Regression analysis supports these assumptions (see Table 13). For corporate companies, the equation for total assets reads:

$$\begin{aligned}\text{Total Assets}^{(i,t)} = \alpha &+ \beta_1 \cdot \text{Total Assets}^{(i,t-1)} \\ &+ \beta_2 \cdot \text{GDP}^{(i,t-1)} \\ &+ \beta_3 \cdot \text{Inflation}^{(i,t-1)}\end{aligned} \tag{A.6}$$

where i and t are indices for a specific company and year (time), respectively. Note that GDP and inflation are taken at the country level and thus do not have an i index.

To account for devaluation, a term is added to the equation that gives each year's percentage of a company's lifetime. This term, coined "Percent Lifetime", captures the expected decrease in total assets for project companies, and its regression coefficient is negative.

$$\begin{aligned}\text{Total Assets}^{(i,t)} = \alpha &+ \beta_1 \cdot \text{Total Assets}^{(i,t-1)} \\ &+ \beta_2 \cdot \text{GDP}^{(i,t-1)} \\ &+ \beta_3 \cdot \text{Inflation}^{(i,t-1)} \\ &+ \beta_4 \cdot \text{Percent Lifetime}^{(i,t)}\end{aligned} \tag{A.7}$$

A.4.2 Revenues

In the infrastructure sector, we expect the revenues of corporate companies to be correlated with total assets. The regression coefficient of total assets growth is highly significant, while the coefficient of lagged revenue growth, when added, is not significant. This suggests that revenue growth is well and sufficiently explained by growth in total assets.

$$\text{Revenues}_s^{(i,t)} = \beta \cdot \text{Total Assets}_s^{(i,t)} \tag{A.8}$$

The effects of GDP and inflation on revenues are reflected through their effect on total assets.

A.4.3 Operating expenses (OPEX)

Likewise, we expect OPEX to grow with the size (total assets) of the business, and the correlation coefficient of total assets growth with OPEX is highly significant:

$$\text{Opex}_s^{(i,t)} = \beta \cdot \text{Total Assets}_s^{(i,t)} \tag{A.9}$$

Table 13: Overview of relationships between projected and explanatory variables

Projected variable	Explanatory variable (expected positive or negative impact)
Total Assets	Lagged total assets (> 0) Lagged GDP (> 0) Lagged inflation (> 0) Percentage of Lifetime (< 0) *for projects only* Physical risks (< 0): fraction of total assets lost
Revenues	Total assets (> 0) Physical risks (< 0): fraction of revenues lost
OPEX	Total assets growth (> 0) Physical risks (> 0): replacement/repair of total assets lost Carbon price (> 0): price of Scope 1 emissions Electricity price (> 0): price of Scope 2 emissions
Total Debt	Total assets (> 0): same growth Physical risks (> 0): investments to cover future total assets losses
Leverage	Total assets (< 0) Total debt (> 0)
Profitability	Total assets (< 0) Revenues (> 0) OPEX (< 0)

Note: The table reads from right to left and presents which variables explain each of the projected variable. We report the direction of the impact of each regressor in parentheses. For instance, the higher the lagged inflation, the higher the total assets ("> 0" sign) or the higher physical risks. the lower the revenues ("< 0" sign).

Similarly to revenues, we include the effects of GDP and/or inflation on OPEX in the total assets term. We excluded intercepts in the revenues and OPEX regressions since there are no revenues or expenses in the absence of total assets.

A.4.4 Regression results

Table 14 presents the results of the regression analyses performed for both corporate and project companies. The regression coefficients are all highly significant. The R^2 of both companies are relatively small but of the order of what is usually expected when dealing with growth rates. Residuals are distributed close to normal, around 0, with very low autocorrelation levels.

Table 14: Regression results for corporate and project companies

Regressor	Corporate companies			Project companies		
	Total assets	Revenues	OPEX	Total assets	Revenues	OPEX
Total assets L1	0.078*** (0.016)			0.043*** (0.013)		
GDP L1	0.344*** (0.076)			0.163*** (0.046)		
Inflation L1	1.274*** (0.157)			0.631*** (0.087)		
Percent Lifetime				-0.038*** (0.003)		
Total asset		0.236*** (0.024)	0.322*** (0.025)		0.243*** (0.018)	0.334*** (0.021)
Constant	-0.006*** (0.002)			-0.006*** (0.002)		
Observations	3,486	1,107	2,631	5,195	1,871	5,401
Adjusted R^2	0.032	0.077	0.058	0.042	0.085	0.043

Note: L1 denotes the first lag (i.e., value in the previous year) of a variable.
$^{*}p < .1$; $^{**}p < .05$; $^{***}p < .01$

A.5 Scenario-Dependent Projections of Financial Variables

We assume that the relationships between financial and macroeconomic variables described above hold in the future (until 2050, at least). The calibrated equations to forecast total assets, revenues, and OPEX can thus be used, provided that forecasts of GDP and inflation are available. NGFS provides such forecasts for six distinct climate scenarios with different levels of expected climate risks. We added the index s to the equations to denote scenarios. On top of macroeconomic forecasts, we include expected damages (physical risks) and additional costs related to the price of carbon and energy (transition risks) in the estimated forecasts of financial variables.

In regards to **physical risk**, Marcelo and Blanc-Brude (2022) estimate the impact of climate-change-driven hazards on physical assets quantified by a damage value D that represents the portion of the asset that would be destroyed upon the occurrence of a given hazard. We include damage values for 100-year flood, cyclone, and extratropical storm hazards. A 100-year hazard event means that its probability of occurrence is $\rho = 1\%$. Importantly, D and ρ are not scenario- or time-dependent. However, we expect physical risk to change (and likely to increase) in scenarios where efforts to mitigate climate change are insufficient.

NGFS' orderly and disorderly scenarios assume that climate goals are met (i.e., physical risks are mitigated, and the temperature rise remains below 2°C). Accordingly, we assume that D and ρ remain constant in those scenarios. However, in the hot house world scenarios, climate goals are not met, and the global mean temperature increase is expected to exceed 3° Celsius in the Current Policies scenario and to be about 2.6° Celsius in the NDC scenario. Following IPCC's[3] estimations that physical risks double by 2050, and multiply by 4 to 6 by the end of the century, we assume that D and ρ grow by 2% per year in the NDC scenario and by 2.5 percent in the Current Policies scenario.

Our model assumes that climate risks affect corporate and project companies in the same way. Since the goal is to make projections at the industry and sector levels, long-term projections on projects and corporates are needed. Hence, we disregard the limited lifetime of firms in the projection part (i.e., the Percent Lifetime term is excluded). This is equivalent to assuming that projects are replaced or renewed when completed or evergreen.

A.5.1 Total assets and physical risk

Physical risks imply that assets may be damaged in the future by climate-driven hazards. If we assume hazard events to be independent and mutually exclusive (i.e., they cannot occur at the same time), then the expected value of Total Assets TA can be expressed as:

$$\mathrm{TA}^{(i,t)}_{reduced_s} = \mathrm{TA}^{(i,t)}_s \left(1 - \rho^t_s D^{(i,t)}_s\right) \qquad \text{(A.10)}$$

where TA are the total assets growth as forecast using the regression coefficients, and $D^{(i,t)}_s$ is the sum of the damage values by each hazard (currently floods, storms, and cyclones). Note that the mutual exclusivity assumption can also be seen as neglecting the probability that two or three events occur in the same year since these would be two or fours orders of magnitude less likely than the occurrence of a single event.

A.5.2 Revenues and physical risk

The fraction D of total assets that are impaired represents a loss of production capacity which should be proportionally reflected in the expected value of Revenues Rev:

$$\mathrm{Rev}^{(i,t)}_{reduced_s} = \mathrm{Rev}^{(i,t)}_s \left(1 - \rho^t_s D^{(i,t)}_s\right) \qquad \text{(A.11)}$$

where $Rev^{(i,t)}_s$ is the revenue growth as extracted from the regression.

3 - IPCC WGI Interactive Atlas at https://interactive-atlas.ipcc.ch/

A.5.3 Operating Expenses (OPEX)

On the contrary, impaired total assets must be repaired or replaced and thus contribute to the overall costs. Moreover, costs associated with transition risks need to be added:

- Introducing a carbon tax directly impacts the price of Scope 1 emissions through increases in the carbon price.
- Increasing the carbon price and other policies affect the mix and price of energy and thus the price of Scope 2 emissions through the price of electricity.

Hence, we project OPEX using the following equation:

$$\begin{aligned}\text{Opex}^{(i,t)}_{\text{augmented}_s} = \text{Opex}^{(i,t)}_s &+ \rho_s D^{t}_s{}^{(i,t)} \text{Total Assets}^{(i,t)}_s \\ &+ \Delta(\text{Carbon})^{(i,t)}_s \\ &+ \Delta(\text{Electricity})^{(i,t)}_s\end{aligned} \quad (A.12)$$

where $Opex^{(i,t)}_s$ is the OPEX growth as extracted from the regression and:

$$\begin{aligned}\Delta(\text{Carbon})^{(i,t)}_s = &(\text{Scope1} \times \text{Carbon Price})^{(i,t)}_s \\ &- (\text{Scope1} \times \text{Carbon Price})^{(i,t-1)}_s\end{aligned} \quad (A.13)$$

$$\begin{aligned}\Delta(\text{Electricity})^{(i,t)}_s = &(\text{Scope2} \times \text{ElectricityPrice})^{(i,t)}_s \\ &- (\text{Scope2} \times \text{ElectricityPrice})^{(i,t-1)}_s\end{aligned} \quad (A.14)$$

Carbon and electricity price projections come from NGFS. Scope 1 and 2 emissions are assumed to grow at the global emissions rate per country, which also come from NGFS.

A.5.4 Total dept and physical risk

Based on the assumption that corporate companies keep the same capital structure over time, the total debt follows the total assets growth rate (as impacted by physical risks). Further, companies raise funds to cover potential damages to total assets. We expect these funds to equal the expected damage to total assets and cover extra costs (see OPEX above):

$$\text{Total Debt}^{(i,t)}_s = \text{Total Debt}^{(i,t-1)}_s \times \frac{\text{TA}^{(i,t)}_s}{\text{TA}^{(i,t-1)}_s} \quad (A.15)$$

Investments are added to cover potential future damages:

$$\text{Total Debt}^{(i,t)}_{augmented_s} = \text{Total Debt}^{(i,t)}_s + \rho^{t}_s D^{(i,t)}_s \cdot \text{TA}^{(i,t)}_s \quad (A.16)$$

A.5.5 Leverage and profitability

From the projections of total assets, revenues, OPEX, and total debt, we can estimate projections of leverage and profitability – two important financial variables needed as inputs of our asset pricing models:

$$\text{Leverage}^{(i,t)}_s = \frac{\text{Total Debt}^{(i,t)}_s}{\text{TA}^{(i,t)}_s} \quad (A.17)$$

$$\text{Profitability}^{(i,t)}_s = \frac{\text{Revenues}^{(i,t)}_s - \text{Opex}^{(i,t)}_s}{\text{TA}^{(i,t)}_s} \quad (A.18)$$

Note that these two equations are not recursive, such that leverage and profitability depend directly on the four key underlying financial variables. The impact of climate risks on leverage and profitability is a direct consequence of the impact of climate risks on the four other variables.

Table 15: Projection of the average GDP growth and inflation at different horizons in each NGFS scenario

Scenario	Horizon 2030	Horizon 2040	Horizon 2050
Below 2°C	GDP: 1.95; Inflation: 2.88	GDP: 1.7; Inflation: 2.44	GDP: 1.53; Inflation: 2.33
Net Zero 2050	GDP: 1.47; Inflation: 3.55	GDP: 1.57; Inflation: 2.62	GDP: 1.5; Inflation: 2.33
Divergent Net Zero	GDP: 0.75; Inflation: 5.51	GDP: 1.05; Inflation: 3.72	GDP: 1.14; Inflation: 3.04
Delayed Transition	GDP: 1.82; Inflation: 2.62	GDP: 0.89; Inflation: 3.47	GDP: 0.91; Inflation: 3.1
NDC	GDP: 1.97; Inflation: 2.68	GDP: 1.59; Inflation: 2.45	GDP: 1.39; Inflation: 2.4
Current Policies	GDP: 2.11; Inflation: 2.56	GDP: 1.71; Inflation: 2.3	GDP: 1.46; Inflation: 2.3

Note: * NDC stands for Nationally Determined Contribution.

A.6 Projection of Average GDP Growth and Inflation at Different Horizons in each NGFS Scenario

Table 15 above shows the various projection paths for inflation and GDP according to the NGFS scenarios.

About Us

The EDHEC Infrastructure & Private Assets Research Institute is a research centre of the EDHEC Business School, one of the best ranked business schools for its programs and research in finance. The institute was created in 2016 with the support of the business school and several key seed partners, including the government of Singapore, Natixis and Meridiam, to spearhead new research in the asset pricing and credit risk of private infrastructure investments.

Thanks to this work, an industry initiative was created in 2019 to contribute even more actively to the development of the infrastructure asset class. Our corporate entity, Scientific Infra and Private Assets Ltd is an ESMA-regulated provider of market indices, benchmarks and valuation analytics for investors in unlisted infrastructure equity and private debt, including the widely used infra300® index. The infraMetrics® platform already provides robust and granular data to investors representing USD400bn of infrastructure AUM (YE2022) as well as prudential regulators and public policy bodies.

In 2020, the institute launched a major new project on the measurement and benchmarking of climate risks and the social acceptability of infrastructure investments. After three years of development, several key research results a major data collection effort, we now publish climate and social risk data in infraMetrics®, alongside our indices and analytics since Q1 2023.

Having achieved market recognition for infrastructure investment benchmarks, EDHEC*infra* was also renamed "EDHEC Infrastructure & Private Assets Research Institute" to reflect a new ambition for our work, with a focus on private equity and debt. privateMetrics, a new platform, will launch in 2023 and provide asset valuation tools and market indices for investors in private companies worldwide.

While developing an indexing and benchmarking business, the institute continues to develop new research, including new work on the uses of machine learning to process text, accounting and geographic data and create new data on private markets. We are also regularly involved in regulatory and policy matters by providing free access to our unique data to prudential regulators and policy-setting bodies or government departments needing information on the procurement of infrastructure projects, in particular the cost of capital of private investors and the financial risks they face.

The EDHEC Infrastructure and Private Assets Research Institute is also supported in its endeavours by an international advisory board consisting of senior executives from the investment world. Since its creation, EDHEC Infrastructure and Private Assets Institute has published more than 50 academic research papers. Our data is also frequently used by the industry to produce research including by the Boston Consulting Group, BlackRock, Ares Management, PGIM, CBRE and many more. Research at EDHEC is both "for business" and "for good": it has both commercial and social value.

- Adrian, M. T., P. Grippa, M. M. Gross, M. V. Haksar, M. I. Krznar, C. Lepore, M. F. Lipinsky, M. H. Oura, S. Lamichhane, and M. A. Panagiotopoulos (2022). *Approaches to climate risk analysis in FSAPs.* International Monetary Fund.
- Alogoskoufis, S., N. Dunz, T. Emambakhsh, T. Hennig, M. Kaijser, C. Kouratzoglou, M. A. Muñoz, L. Parisi, and C. Salleo (2021). *ECB economy-wide climate stress test: Methodology and results.* Number 281. ECB Occasional Paper.
- Bertram, C., J. Hilaire, E. Kriegler, T. Beck, D. Bresch, L. Clarke, R. Cui, J. Edmonds, M. Charles, A. Zhao, et al. (2021). Ngfs climate scenario database: technical documentation v2. 2.
- Bisbey, J., C. Lee, and P. Ryan (2022). Ignoring climate risks in infrastructure drives down social and economic value for future generations.
- Carattini, S., M. Carvalho, and S. Fankhauser (2018). Overcoming public resistance to carbon taxes. *Wiley Interdisciplinary Reviews: Climate Change 9*(5), e531.
- CDP (2022). Cdp technical note: Relevance of scope 3 categories by sector.
- Cho, R. (2022). The Economics of Climate Change in 8 Minutes.
- Dasgupta, P. (2008). Discounting climate change. *Journal of risk and uncertainty 37*, 141–169.
- Financial Stability Board (2017). Recommendations of the task force on climate-related financial disclosures.
- Goulder, L. H. (1995). Environmental taxation and the double dividend: a reader's guide. *International tax and public finance 2*, 157–183.
- Gupta, A. and F. Blanc-Brude (2021). Robust benchmarks for investors in private infrastructure funds. *EDHECinfra Research Publication.*
- Hansen, J., M. Sato, R. Ruedy, A. Lacis, and V. Oinas (2000). Global warming in the twenty-first century: An alternative scenario. *Proceedings of the National Academy of Sciences 97*(18), 9875–9880.
- Herzog, T. (2009). World greenhouse gas emissions in 2005. *World Resources Institute 7*, 2009.
- IFRS Foundation (2011). IFRS 13 Fair Value Measurement.
- IPCC (2014). *Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press.
- IPCC (2023). IPCC AR6 WGII: Overaching Outreach FAQ2.
- Jung, H., J. A. Santos, and L. Seltzer (2023). Us banks' exposures to climate transition risks. *FRB of New York Staff Report* (1058).

References

- Lloyd, S. M., M. Hadziosmanovic, K. Rahimi, and P. Bhatia (2022). Trends show companies are ready for scope 3 reporting with us climate disclosure rule.
- MacDonald, M. and C. Sanchez (2022). Flying blind: The threat to infra from ignoring physical climate risks.
- Marcelo, D. and F. Blanc-Brude (2022). Assessing Physical Risks of Infrastructure Assets. *EDHECinfra Research Publication*.
- Marcelo, D., T. Whittaker, and F. Blanc-Brude (2022, December). Physical risks & the cost of capital of infrastructure investments. Technical report, EDHEC*infra*.
- McKinsey & Company (2023). Leveraging infrastructure investment to meet net-zero goals.
- Morgan Stanley (2018). Weathering the storm: Integrating climate resilience into real assets investing, 1-16.
- Nordhaus, W. D. (2007). To tax or not to tax: Alternative approaches to slowing global warming. *Review of Environmental Economics and policy*.
- Nugier, F. and D. Marcelo (2022). Estimating Carbon Footprints of Transport Infrastructures Globally: the Case of Airports. *EDHECinfra Research Publication*.
- SEC (2022). The enhancement and standardization of climate-related disclosures for investors.
- Shirono, K., A. Prasad, and D. Seneviratne (2023). Carbon footprint of bank loans—a measure of transition risks for the financial sector. In *Data for a Greener World: A Guide for Practitioners and Policymakers*. International Monetary Fund.
- TICCS by EDHEC*infra* (2022). The Infrastructure Company Classification Standard (TICCS®). *2022 Edition – includes NACE, EU Taxonomy and CPRS Mappings*.
- United Nations Office for Disaster Risk Reduction (UNDRR) (2020). *Human Cost of Disasters: An Overview of the Last 20 Years 2000-2019*. New York: United Nations.
- United Nations Office for Project Services (UNOPS) (2023). Infrastructure for climate action.
- Van Vuuren, D. P., J. Edmonds, M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, et al. (2011). The representative concentration pathways: an overview. *Climatic change 109*, 5–31.
- Van Vuuren, D. P., K. Riahi, K. Calvin, R. Dellink, J. Emmerling, S. Fujimori, S. Kc, E. Kriegler, B. O'Neill, et al. (2017). The shared socio-economic pathways: Trajectories for human development and global environmental change.
- Zhai, P., H. Pörtner, D. Roberts, J. Skea, P. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, et al. (2018). Global warming of 1.5⊠ c. *an IPCC Special Report on the impacts of global warming of 1.*

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For more information, please contact:
Nataliia Gaidarenko
e-mail: nataliia.gaidarenko@edhec.edu

EDHEC Infrastructure & Private Assets Research Institute
EDHEC Asia-Pacific
One George Street - #15-02
Singapore 049145
Tel.: +65 6653 8575

EDHEC Europe
10 Fleet Place
London EC4M 7RB
Tel.: +44 20 7332 5601

edhec.infrastructure.institute