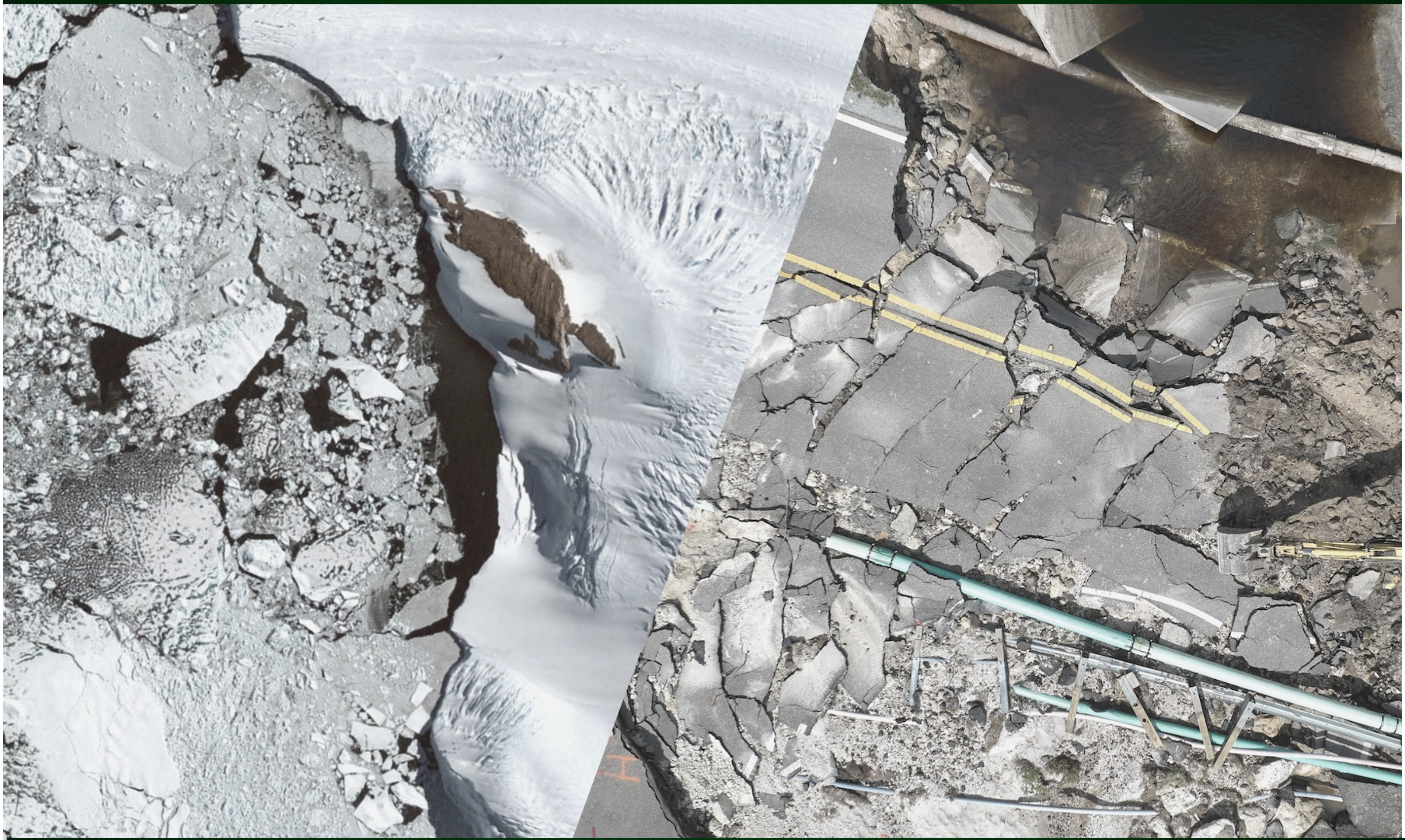
Computing Extreme Climate Value for Infrastructure Investments

Asset Pricing Applied to NGFS Phase 4 and Oxford Economics Scenarios to Measuring Climate Risks at the Asset Level



EDHEC Infrastructure & Private Assets Research Institute

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Authors

Bertrand Jayles is a Senior Sustainability Data Scientist in EDHEC Infrastructure & Private Assets Research Institute, and focuses on climate risks and scenario analyses. He graduated with a Master's degree in Theoretical Physics from Aix-Marseille University. Bertrand went on to pursue a PhD degree at the National Centre for Scientific Research (CNRS) in Toulouse, whereby he specialized in Social Physics, a field of study at the interface of Theoretical Physics, Behavioural Economics, and Social Psychology. After attaining his PhD, Bertrand joined the Max Planck Institute for Human Development in Berlin as a Post-doctoral fellow. He then moved to Singapore when he joined Nanyang Technological University as a Research fellow. His research interests include collective behaviour, social influence, collective intelligence, social resilience, and complex networks.

Jianyong Shen is a Senior Research Engineer and Deputy Lead of Research & Development team at EDHECinfra, where he applies modern machine learning technologies to the development of analytics for infrastructure investment. He has 15-year wide experience of building cutting-edge mathematical models for both the sell- and buy-side of financial institutions for diverse business purposes. He holds a doctorate in Theoretical Physics from Fudan University and is a Financial Risk Manager certified by GARP.

Executive Summary

Climate change poses significant financial risks for infrastructure assets

Investors in infrastructure assets are increasingly concerned by the risks posed by climate change. Indeed, extreme weather events can damage physical assets, leading to direct losses, increased maintenance costs, and lower asset values (e.g., the deadly flood in north-eastern Italy in May 2023). Such risks are referred to as *physical risks*. To mitigate climate change and its associated physical risks, various solutions are being designed, including climate policies and carbon taxes to encourage the shift toward greener technologies as well as changes in consumer preferences. However, such efforts will also come at a cost to companies, in particular those that rely heavily on non-renewable energy. Indeed, transitioning to greener technologies will represent a significant cost, one which many companies may find difficult to bear. Such risks are called *transition risks*.

Estimating climate risks in infrastructure assets is possible

There is thus no perfect solution to tackle the challenge of climate change: acting against climate change will entail transition costs, while not doing so will incur physical damage, the costs of which may exceed transition costs. In this context, understanding the impact of climate risks is critical when making informed decisions in infrastructure investment, and there is a growing need for a quantitative assessment of climate risks and their impact on infrastructure portfolios. However, this is a challenging task, as methods to quantify the consequences of climate change on infrastructure investments are still at an early development stage.

This paper specifically aims to tackle this issue, by describing the novel method that we have developed to measure climate risks. While we here apply this method to infrastructure assets, it paves the way to using similar approaches to enlarge the scope of its application.

We leverage infraMetrics' unique dataset of financial variables for companies across all sectors and over 25 countries worldwide, and develop a methodology to project infrastructure companies' financial indicators (e.g. revenues, dividends, valuation, etc...) by exploiting the latest scientific knowledge on economic and climate scenarios. We use a full Discounted Cash Flow approach to estimate the value of infrastructure companies under various climate scenarios, where macroeconomic quantities (e.g., GDP, inflation, interest rates), carbon emissions and the frequency of hazard-driven physical damages are affected by climate change. Climate change thus influences both the future cash flows and discount rates of companies, and thereby their values under different scenarios and future horizons.

We apply two of the most popular economic and climate scenarios to the infra300 [1] portfolio in this exercise, namely:

- The Network for Greening the Financial System (NGFS) scenarios, a set of plausible future macroeconomic and climate scenarios for each country under various climate mitigation pathways. The NGFS was launched in 2017 by a group of 130+ international entities including central banks and supervisors and is viewed as a reference in the financial industry to perform climate risk analysis.

1 - infra300 is an index calculated by EDHECinfra's, which represents the global infrastructure market well.

• The Oxford Economics Global Climate Scenarios, widely renowned for their credibility and thorough methodology. Oxford Economics, founded in 1981, is a prominent global economic research firm that provides analysis, forecasts, and consulting services to businesses, governments and institutions.

Infrastructure investments are subject to significant climate risks

Our results show that the values of infrastructure portfolios vary significantly across scenarios. Climate risks thus play a very important role when evaluating and managing infrastructure investments. In fact, our approach has demonstrated its strength in estimating the impact of climate risks in different applications. For example, in [Gupta et al. (2023)], we showed that some investors in infrastructure could lose more than half of their portfolio to physical climate risks by 2050, while in [Marcelo et al. (2023)], we showed that transition risks could cost hundreds of billions to investors in infrastructure before 2050.

To quantify the consequences of climate change in a robust way, we define metrics that measure the impact of physical and transition risks independently, and metrics that measure their joint impact on the Net Asset Value (NAV) of infrastructure assets:

• the **Late Alignment Risk** metric measures the joint impact of transition and physical risks if climate policies are implemented late.

• the **No Alignment Risk** metric measures the impact of physical risks if no actions are taken to mitigate climate change.

• the **Extreme Transition Risk** metric measures the transition risks coming from increases in the cost of carbon, which can be very significant in some scenarios.

Besides, we estimate the **Extreme Physical Risk** metric, which measures the potential losses due to physical damages in a world where no climate policies are implemented.

We show that by 2050, if no actions are taken to mitigate climate risks, the potential losses due to climate risks will be about 10 times higher than they would be if climate policies had been implemented. Moreover, we show that **even a delayed implementation of such policies is a far better option than not implementing them at all**. Indeed, the potential losses associated with a late transition are projected to be, by 2050, more than six times smaller than the potential losses of not transitioning at all.

In conclusion, our results emphasise the importance for the infrastructure industry of incorporating climate risks into their investment decisions. However, this requires making quantitative estimates of the risks associated with climate change available to investors, which is a challenging task. The method developed in this paper shows that a robust quantitative estimation of climate risks in infrastructure is possible. This method and the robust data based on it, produced by EDHEC*infra*, will help investors in infrastructure make better-informed decisions under the uncertainty inherent to climate change.

1. Introduction

1.1. Climate risks for infrastructure assets

Climate change is one of the most pressing challenges facing humanity today, with potentially severe implications for infrastructure assets. Infrastructure investments such as roads, bridges, ports, airports, and power plants are essential to support people's daily life and the functioning of modern societies. They typically have long lifetimes (e.g. several decades) and are designed to operate under specific climate conditions. However, climate change is causing more frequent and intense extreme weather events, such as floods, droughts, heat waves, and storms, which can damage infrastructure assets and disrupt their operations [Palin et al. (2021); Schweikert et al. (2014); Stewart et al. (2012)]. These risks materialise as physical damage to infrastructure and can lead to direct losses, increased maintenance costs, and lower asset values. Such risks are called **physical risks**. For instance, the recent deadly flood in North-eastern Italy was caused by the Storm Minerva and became one of Italy's "worst floods in a century". It damaged the infrastructure badly, especially the road sector. The cost of rebuilding the road networks in the Ravenna area was estimated at EUR120m-150m [Rizzuti (2023)].

Various solutions have been proposed, and sometimes even implemented, to mitigate climate change and its associated physical risks, including climate policies and carbon taxes. These solutions encourage human society to shift towards greener technologies, which can also upgrade production methods and change consumer preferences. However, such efforts come at a cost to infrastructure companies, in particular those that rely heavily on non-renewable energy sources. For example, new regulations and carbon taxes will weigh heavily on carbon-intensive infrastructure companies, forcing them to accelerate their transition toward greener technologies. As a consequence, these companies will have to bear significantly increased operating costs [Weber et al. (2020); Van der Ploeg and Rezai (2020)]. The risks associated with these costs are called **transition risks**. As we show in this paper, the costs of transition risks are still substantially smaller than the potential costs of physical risks, which could be devastating in a catastrophe future where climate change is not mitigated.

1.2. Coping with climate risks: institutional efforts

To address climate risks, a growing number of organisations have been developing tools and methods to assess their impact on the financial sector in particular. For instance, the Task Force on Climate-related Financial Disclosures (TCFD) has developed a set of recommendations for disclosing climate-related risks and opportunities in financial reporting [TCFD (2017)]. The European Union's Sustainable Finance Disclosure Regulation (SFDR) requires financial market participants to disclose how they integrate sustainability risks, including climate risks, into their investment decisions.

In December 2017, the Network for Greening the Financial System (NGFS) was launched, with the goal of developing a reference set of socio-economic scenarios with different climate developments (climate scenarios), that would serve as a common ground for financial institutions and regulators to assess and manage financial risks and opportunities associated with climate change [NGFS (2023); NGFS documentation (2023)]. These scenarios are based on the latest scientific knowledge on climate change, in particular the reports of the Intergovernmental

Panel on Climate Change (IPCC), a United Nations body that assesses the impacts of and policy responses to climate change [IPCC: Pörtner et al. (2022)].

These climate scenarios developed by NGFS have become a powerful tool for the financial industries to assess the potential financial risks and opportunities associated with climate change. For example, the European Central Bank used the NGFS scenarios to perform an "economy-wide climate stress test, which has been developed to assess the resilience of non-financial corporates (NFCs) and euro area banks to climate risks, under various assumptions in terms of future climate policies" [Alogoskoufis et al. (2021)]. Similar climate stress tests have been carried out by the Dutch National Bank, the Banque de France and the National Bank of Austria [Vermeulen et al. (2018); Allen et al. (2020); Guth et al. (2021)]. These studies demonstrate the usefulness of the NGFS scenarios in providing a common framework for assessing climate-related risks.

Inspired by the success of NGFS scenarios, other entities have since started developing their own climate scenarios, which we see as a perk. Firstly, adding an alternative set of scenarios in our exercise makes our analysis more robust and less dependent on the scenario providers. Secondly, as we will discuss in more detail in the following chapters, there are elements in the climate scenarios provided by NGFS that we found not very convincing. So, we looked into some alternative providers of climate scenarios, and one of them caught our attention: Oxford Economics, one of the world leaders in global forecasting and quantitative economic analysis, offers climate scenarios with characteristics that complement the NGFS scenarios.

Since our aim is to estimate climate risks in infrastructure asset valuation, we will describe and compare the NGFS and Oxford Economics scenarios and their consequences on the valuation of a representative sample of infrastructure assets. Of course, we can repeat the present analysis with any interesting climate scenarios that come to our attention in the future.

1.3. Estimating climate risks in infrastructure assets valuation: our approach

While the above studies provide valuable insights into the potential impacts of climate change on the financial sector and how to address them, comprehensive methodologies for assessing climate risks in infrastructure assets are still limited. This paper, together with former papers by the same team [Marcelo et al. (2023); Gupta et al. (2023)], mark an important step forward in this direction: building on previous work [Alogoskoufis et al. (2021)], we develop a novel and powerful methodology based on a Discounted Cash Flow approach, by which we can estimate both the future cash flows and discount rates of companies, and thereby their value in various climate scenarios. Our method intertwines financial and macro-economic variables to make projections of infrastructure financial indicators (e.g., revenues, dividends) under such scenarios.

We first model the relationship between key financial variables in infrastructure companies (e.g. total assets, revenues) and macroeconomic variables (e.g. GDP, inflation). The calibrated models are able to project financial variables based on macroeconomic projections under different climate scenarios. Importantly, we complement the climate scenario outputs with asset-level measures of emissions and expected physical damage, which are also calculated by EDHEC*infra* [Nugier and Marcelo (2022); Marcelo and Blanc-Brude (2022)]. The emissions and damage will impact infrastructure assets' financial indicators and their future cashflows. Benefiting from EDHEC*infra*'s asset pricing model, we are able to estimate the net asset value (NAV) of infrastructure assets under all these climate scenarios.

Finally, we estimate the potential losses in NAV that companies could incur if the global alignment actions with the Paris agreement were implemented in 2030 rather than earlier, or if they were not implemented at all. We show that the NAV of infrastructure companies is significantly lower in scenarios without any alignment actions than is the case with early- and late-alignment scenarios. We apply our analysis to the infrastructure assets listed in EDHEC*infra*'s infra300[1] index, which is a good representation of the global unlisted infrastructure market.

The preliminary versions of our method (based on previous vintages of NGFS's climate scenarios) have already been exploited to measure the extent of the potential losses that could impact the infrastructure sectors [Marcelo et al. (2023); Gupta et al. (2023)]. Since then, our methodology has been upgraded to better integrate EDHEC*infra*'s industry-leading asset pricing models, which enable us to estimate various key financial indicators of infrastructure companies. Furthermore, we bring in not only the latest climate scenarios from NGFS, but also complementary scenarios from Oxford Economics. Based on these upgrades, we develop a set of metrics to measure climate risks. These enhancements enlarge our views on climate risks and make our conclusions, which reflect the potential financial consequences that investors may soon face, much more robust.

Paper structure and layout

The paper is structured as follows. We first briefly introduce the climate scenarios developed by NGFS and Oxford Economics. Next, we describe the data supporting our analyses and our method for estimating the climate risks that infrastructure assets will face. Finally, we analyse the impact of climate risks on the infra300 index' financial performance and valuations. We then estimate the potential losses associated with these climate risks. We conclude the paper by discussing our findings and their implications for investors and portfolio managers.

1 - infra300 is a representative index constructed by EDHECinfra. It includes 300 companies across all infrastructure sectors and over 20 countries worldwide. It will be presented in more details below.

2. Climate scenarios

2.1. Historical background

In 2017, the NGFS was founded to develop the first set of climate scenarios aimed at quantitatively assessing the impact of climate change on the financial sector. They are usually referred to as "NGFS scenarios" and have become the common reference when analysing the effects of climate change on the financial sector. The NGFS scenarios follow in the steps of a long line of research on climate change and its potential future developments and impact.

First, the Representative Concentration Pathways (RCPs) were developed by the scientific community at the request of the Intergovernmental Panel on Climate Change (IPCC), with the aim of exploring different possible futures for greenhouse gas (GHG) concentrations in the atmosphere and their associated impact on the climate [Moss et al. (2008, 2010); Van Vuuren et al. (2011)]. The RCP scenarios were developed as a set of scenarios that describe different plausible futures based on GHG concentration trajectories. However, they are not specific as to the underlying socio-economic conditions under which these plausible futures may happen. To address these limitations, the Shared Socioeconomic Pathways (SSPs) were developed [Kriegler et al. (2014); O'Neill et al. (2014); Van Vuuren et al. (2014)]. The SSPs are narratives that combine a range of socio-economic and technological factors with different GHG emissions pathways, thus specifying and standardising socio-economic foundations that are consistent with the RCPs [Moss et al. (2010); Van Vuuren et al. (2017)].

Yet, SSPs are *qualitative* descriptions of plausible socio-economic developments, and need to be *quantified* for the IPCC (or other instances) to make assessments and recommendations based on them. This is the role of the Integrated Assessment Models (IAMs), a class of models used to study the complex interactions between human activity and the natural environment [Weyant et al. (1995); Dowlatabadi (1995)]. Developed primarily by economists, climatologists, and energy systems experts, IAMs are designed to integrate information from a variety of disciplines to help policy makers understand the impacts of policy decisions on the environment, the economy, and the society as a whole [Nikas et al. (2019); Hamilton et al. (2015)]. IAMs thus simulate the SSPs with some level of granularity (country and partial sector downscaling) and generate as outputs key variables such as GHG emissions, energy supply and demand (various energy sources), mitigation costs, prices and macroeconomic variables.

2.2. NGFS climate scenarios

All the climate scenarios developed by NGFS share the same socio-economic assumptions (i.e. SSP2[1]), and differ by additional climate policies aimed at reducing (or not) the impact of climate change. The first vintage (or "phase") of NGFS scenarios was released in 2020, and since then a newer, more up-to-date version has been released every year. We use the fourth vintage of NGFS scenarios, released in November 2023, in which seven scenarios were developed [NGFS (2023); NGFS documentation (2023)].

The scenarios are grouped in four categories with different levels of climate risks (see Figure 1):

1 - SSP2 has been selected as the reference pathway for all NGFS scenarios. It is a "middle of the Road" scenario that assumes a future with moderate economic growth, stable population, and technological progress. SSP2 assumes that current policies and trends continue without significant deviation [Fricko et al. (2017)]. The use of BECCS is low, and GHG concentrations roughly correspond to the RCP4.5.

• **Orderly Transition scenarios**[2]: immediate and coordinated climate policies are applied, containing global warming (low physical risks) while avoiding heavy transition risks. The goal of Net Zero 2050 is to reach zero emissions by 2050, while Below 2°C aims to keep the global temperature rise below 2°C by 2100. Carbon taxes are thus higher in the more ambitious Net Zero 2050.

• **Disorderly Transition scenario**: in Delayed Transition, carbon taxes are applied in 2030. To compensate for the the delay, while keeping the same goal of containing physical risks, carbon taxes are introduced as a shock and increase sharply, entailing high transition risks[3].

• **No Transition (hot house world) scenarios**: In Current Policies, climate policies remain the same as they are today. In Nationally Determined Contributions (NDC), the pledged policies are assumed to be implemented, but they are still insufficient and lack coordination across countries. Transition risks are low in these scenarios, but at the cost of high physical risks.

• **Insufficient Transition (too little too late) scenario**: in Fragmented World, efforts to mitigate climate change are made too late (like Delayed Transition) and in an uncoordinated manner (as with NDC). The efforts thus generate important transition risks while failing to limit physical risks.

Note that climate policies are proxied in the IAMs as carbon taxes, of which the severity, time of implementation, and coordination across sectors and countries differ across scenarios. The pace of technological development and levels of Carbon Dioxide Removal technologies also differ across scenarios.

2 - We do not discuss the Low Demand scenario, as its development is still unfinished at the time of writing this paper (some macroeconomic variables are still missing).

3 - It is worth noting that the previous vintages of NGFS included another Disorderly Transition scenario called "Divergent Net Zero", where carbon taxes were introduced immediately but without coordination across sectors. This scenario has now been removed, judged too unlikely.

2.3. Oxford Economics scenarios: complement to NGFS scenarios

In addition to NGFS scenarios, our analysis includes climate scenarios developed by Oxford Economics. Let us briefly present these scenarios (with some quotes taken from their latest quarterly report), the assumptions of some of which are directly aligned with NGFS [Oxford Economics (2023)]:

• **Orderly Transition scenarios**: Net Zero is equivalent to NGFS's Net Zero 2050. Net Zero Transformation is a more optimistic variation of Net Zero, which assumes that "the transition to net zero eliminates prevailing market failures and inefficiencies". Sustainable Development lies in between, assuming that "the policy burden falls mostly on advanced economies, countries with credible net zero pledges and those historically responsible for the largest share of global emissions".

• **Disorderly Transition scenario**: Delayed Transition is equivalent to NGFS's Delayed Transition.

• **No Transition scenarios**: Baseline is equivalent to NGFS's Nationally Determined Contributions (NDC), assuming the implementation of pledged policies. Climate Catastrophe is a more pessimistic version of Current Policies where "governments fail to meet their policy pledges", as a result of which emissions continue to grow and GDP is strongly affected. Energy Disorder lies in between, assuming "a greater focus on energy security through more reliance on domestically available fossil fuels, which intensifies the concentration of greenhouse gases in the atmosphere".

2.4. Limitations of climate scenarios

Despite their interest and importance in evaluating the impact of climate change on the financial sector, current climate scenarios suffer from limitations that reduce their practical utility.

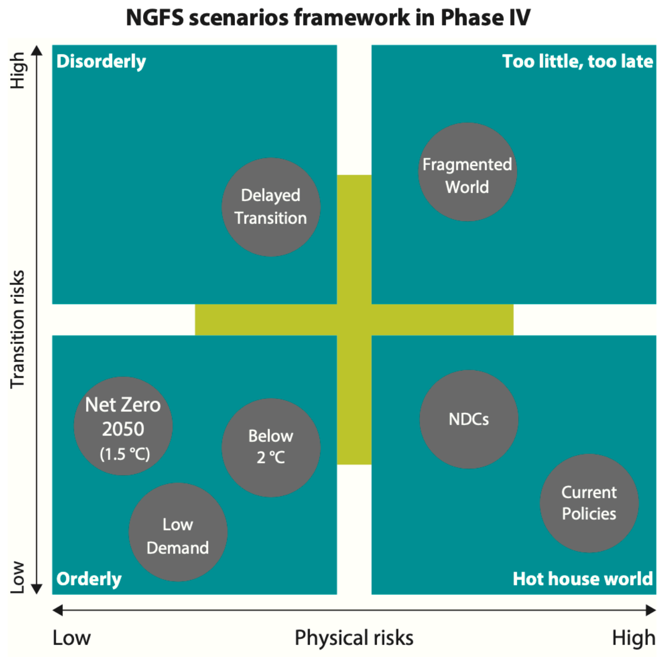

Figure 1: NGFS scenarios positioned according to their transition and physical risks. The diagram is taken from [NGFS documentation (2023)].

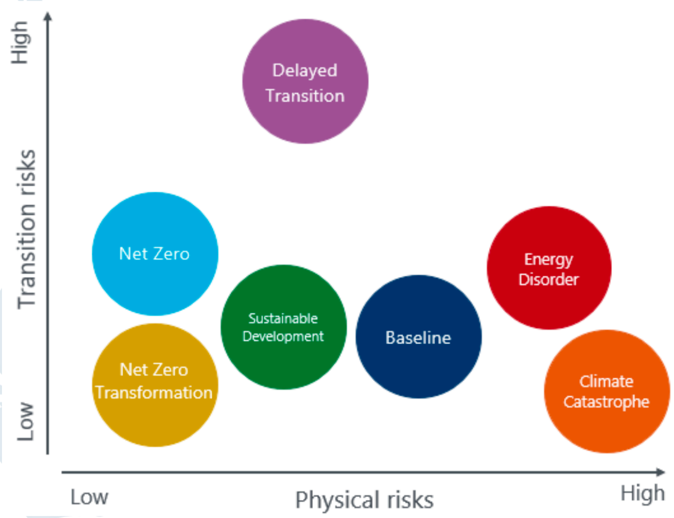

Figure 2: Oxford Economics' scenarios positioned according to their transition and physical risks. The diagram is taken from their latest quarterly report [Oxford Economics (2023)].

The first and foremost limitation is the impossibility to associate probabilities to them. Indeed, climate scenarios are based on a handful of narratives, and lack associated measures of uncertainty or likelihood. This can lead to misinterpretations by giving the (wrong) impression that they are the most likely futures ahead of us, or that they all are equally likely. Moreover, having only a few scenarios, the assumptions of which can sometimes be questionable (see next chapter), is a bit restrictive.

Despite these limitations, climate scenarios still provide a solid foundation to estimate the risks posed by climate change, for the academy as well as for the financial industry. It is to be noted that initiatives within the EDHEC group have started tackling these issues: by introducing variability at different levels (physical and macro-financial), the EDHEC Risk Climate Impact Institute aims to produce distributions of emissions schedules rather than single paths [Rebonato et al. (2024); Kainth (2024)]. In future exercises, we will include the results of their work to estimate uncertainty in climate scenarios. Ultimately, this will allow us to estimate a proper Climate Value-at-Risk.

In the next chapter, we will analyse and compare the projections of NGFS and Oxford Economics.

3. Financial, macroeconomic and climate scenario data

We present the data used in our models, which include i) the historical financial and macroeconomic data used to build the regression model (described in chapter 4); ii) the climate related data, i.e., carbon emissions and physical risk data estimated today; iii) the climate scenario data, i.e., the macroeconomic and emissions projections from NGFS and Oxford Economics climate scenarios.

3.1. Historical data used in the model

As we describe in more detail in the next chapter, our models express the relation between financial variables and macroeconomic variables. We source the financial variables (i.e., total assets and revenue) from EDHEC*infra*'s unique dataset of the unlisted infrastructure assets, which supports infraMetrics in analysing the global unlisted infrastructure market. There are more than 7,500 companies across 25 countries worldwide in the dataset. We use the renowned World Bank data as the source of the historical macroeconomic data involved in the regressions, such as GDP and inflation.

3.2. Climate risk data for infrastructure assets: carbon emissions and physical risks

3.2.1. Infrastructure assets' carbon emissions

As a major driver of climate change, carbon emissions are central to the evaluation of present and future climate risks in the infrastructure sector. Carbon emissions are usually classified according to their different scopes [GHG Protocol (2023)]:

- Scope 1 emissions refer to direct emissions from sources owned or controlled by a company;
- Scope 2 emissions refer to indirect emissions from the generation of purchased electricity;
- Scope 3 emissions refer to all other indirect emissions in a company's value chain, such as emissions from suppliers or customers.

As of today, most countries apply carbon taxes only to Scope 1 and 2 emissions, so we focus on and estimate today's Scope 1 and 2 emissions at the company level using the methodology described in Appendix A and in [Nugier and Marcelo (2022)].

3.2.2. Physical risks data

We also estimate the impact of various hazards on infrastructure assets, based on their geographic specification (e.g., location, area...) and sector features [Marcelo and Blanc-Brude (2022)]. In short, this impact of physical risks on infrastructure assets is quantified by a damage factor which represents the portion of the infrastructure asset that would be damaged upon the occurrence of a given hazard, and by a return period which indicates the likelihood of such hazard event.

According to the United Nations' Office for Disaster Risk Reduction, the most common extreme weather events are floods (44%) and storms (28%). Flood events have doubled in the past 20 years, while the frequency of storms has increased by 40% [CRED (2020)]. Our calculations therefore focus on floods and storms as climate events. We will include more hazard types such as heat waves and more in future exercises. Details can be found in Appendix B.

3.3. Projections of macroeconomic variables in climate scenarios

As described in chapter 4, the projections of macroeconomic variables in NGFS and Oxford Economics climate scenarios are at the heart of our modelling approach: i) scenario projections of GDP and inflation are used to project financials based on the coefficients of the regression model; ii) projections of carbon emissions and taxes are used to calculate the cost of carbon; iii) projections of interest rates are used as risk factors for the discount rates in our asset pricing models.

We compare the projections of these variables in NGFS and Oxford Economics to help the readers understand the climate scenarios better. For spacing reason, we show figures for the US only, but the patterns are highly similar in all major economies. For NGFS, we use the projections of the REMIND-MAgPIE (which we will abbreviate as Remind) integrated assessment model (IAM, see section 2.1), which are the most comparable to the projections of Oxford Economics.

3.3.1. GDP and inflation

Figures 3 and 4 show the projections of GDP and its growth in the US until 2050, in every scenario of NGFS (left) and Oxford Economics (right). The green, blue and red colours are used for Orderly, Disorderly and No Transition scenarios, respectively. The purple colour is used for NGFS's Inefficient Transition scenario (Fragmented World), which we present here even though it will be excluded from our analyses in chapters 4 and 5 (because Oxford Economics does not include such a scenario).

Oxford Economics projects significant differences between scenarios. In particular, GDP in the Climate Catastrophe scenario (light red) is dramatically affected. The Baseline scenario has an obvious slower GDP growth as compared to the three orderly scenarios. Besides, the Delayed Transition scenario (blue) shows the impact of carbon taxes in 2030 in a clearer way than in NGFS. On the contrary, GDP grows relatively fast in all NGFS's scenarios, with small differences. In fact, we struggle to understand why the NGFS scenarios project so little differences between scenarios, including in the Current Policies scenario, which stands for "inaction" against climate change.

Figure 5 shows the projections of inflation in all scenarios. In NGFS, inflation starts high (about 6.5%) in Net Zero 2050, and then drops below the levels of other scenarios (about 1.5%) until about 2045 when it catches up (about 2.5%). Inflation follows a roughly similar path in all other scenarios, with Delayed Transition being marked by a "bump" reflecting the introduction of a carbon tax.

In Oxford Economics, the patterns show more differences across scenarios. In particular, the Climate Catastrophe scenario projects a continuously increasing inflation until at least 2050. Together with the decrease of GDP, this scenario depicts a catastrophic future of the USA's macroeconomy with high inflation and negative GDP growth. Other scenarios show a reasonable inflation range and timing.

3.3.2. Carbon tax and carbon emissions

As already mentioned, carbon taxes are meant to discourage carbon emissions by making carbon-based activities less economically viable. An increase in carbon tax is thus expected to induce a decrease in carbon emissions. Figure 6 shows projections of the carbon tax in the USA until 2050, in all scenarios of NGFS and Oxford Economics.

In Oxford Economics, the pattern is very clear: no carbon tax in the No Transition scenarios (red), a delayed (introduced in 2030) but high carbon tax in the Disorderly Transition scenario (blue), an immediate but milder carbon tax in the Orderly Transition scenarios (green). In NGFS, the pattern is similar if one considers Net Zero as the Orderly

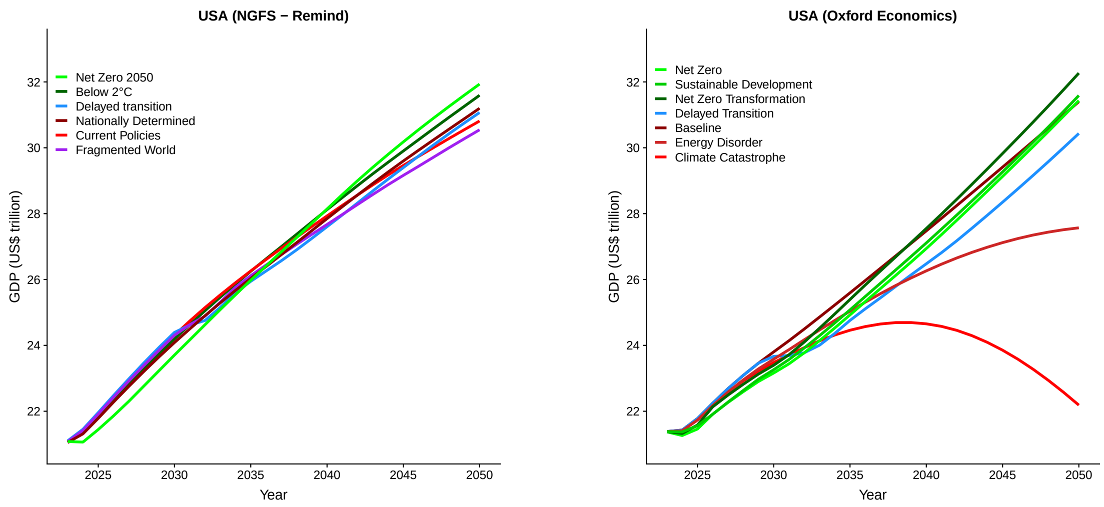

Figure 3: Projections of GDP in the US, for all scenarios of both NGFS and Oxford Economics. Green, blue, purple and red colours refer to Orderly, Disorderly, Inefficient and No Transition scenarios, respectively. We use different shades to distinguish between scenarios within the same colour category.

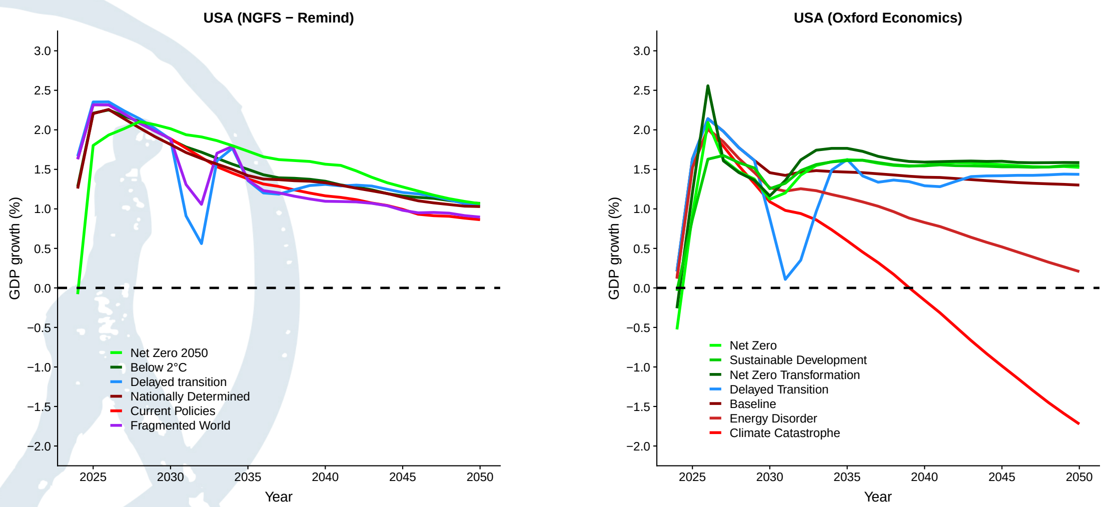

Figure 4: Projections of GDP growth in the US, for all scenarios of both NGFS and Oxford Economics. Green, blue, purple and red colours refer to Orderly, Disorderly, Inefficient and No Transition scenarios, respectively.

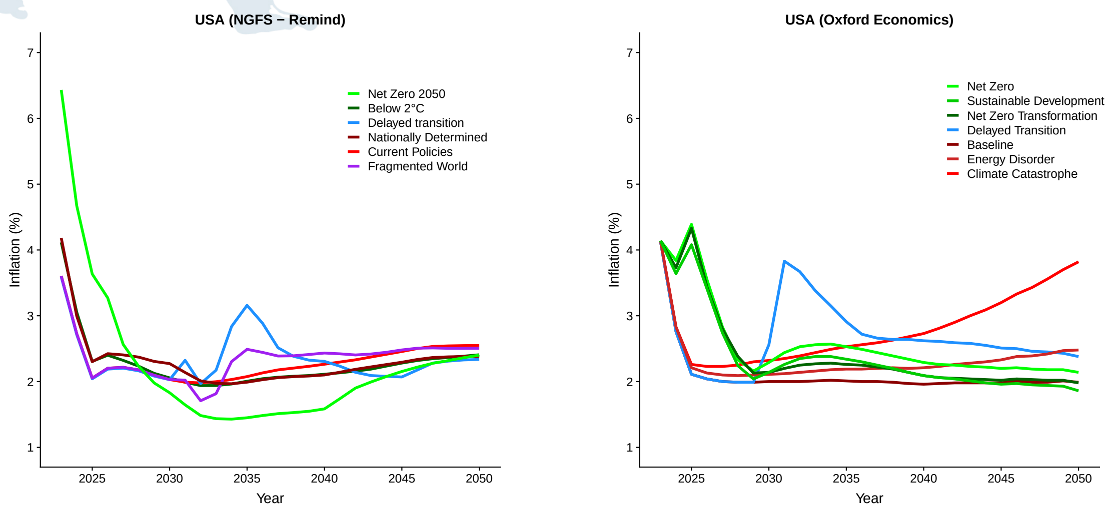

Figure 5: Projections of inflation in the US, for all scenarios of both NGFS and Oxford Economics. Green, blue, purple and red colours refer to Orderly, Disorderly, Inefficient and No Transition scenarios, respectively.

Transition scenario and Current Policies as the No Transition scenario.

However, the projections of NDC (Nationally Determined Contributions) and Below 2°C are confusing when considering their respective

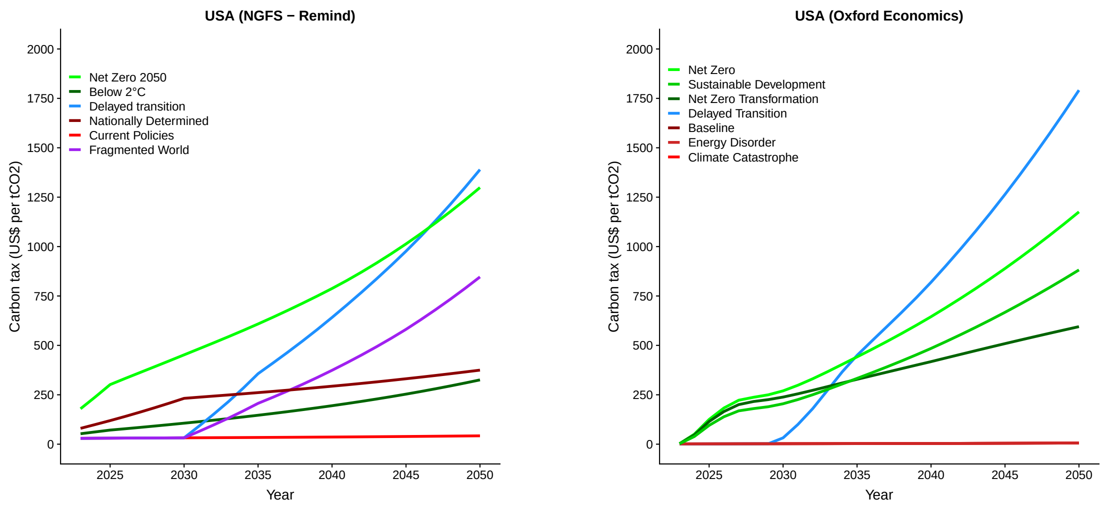

Figure 6: Projections of the carbon tax in the US, for all scenarios of both NGFS and Oxford Economics. Green, blue, purple and red colours refer to Orderly, Disorderly, Inefficient and No Transition scenarios, respectively.

narrative: can NDC really be called a No Transition scenario when it projects a higher carbon tax and lower emissions (see Figure 7 below) than an Orderly Scenario (Below 2°C), and vice versa? Below 2°C and NDC are too close to each other, such that they are not good representatives of Orderly Transition and No Transition scenarios, respectively.

Figure 7 shows the corresponding projections of carbon emissions at the country level. In NGFS, emissions decrease in all scenarios, but not at the same pace: emissions decrease the fastest in Net Zero 2050 (light green), and the slowest in Current Policies (light red). In line with the introduction of a carbon tax in 2030, emissions in the Delayed Transition scenario first decrease at the same pace as in Current Policies, and then decrease faster than in Net Zero 2050, for a similar result in 2050.

We observe two surprising points in the NGFS scenarios: i) all the projections indicate decreasing carbon emissions at country level, including in Current Policies and ii) negative emissions are expected in the future in all scenarios except in Current Policies. We think that these projections are very optimistic, even if considering the feasibility of Carbon Capture and Storage technologies.

The different patterns of country level carbon emissions look better in Oxford Economics. In Climate Catastrophe, the emission slightly increase until 2040, thus better reflecting a world where no more efforts are made to fight against climate change. The decrease after 2040 is only due to the sinking macroeconomy under this scenario. Meanwhile, the Baseline scenario projects a slow decrease of carbon emissions, in agreement with the expected implementation of climate policies pledge by countries. In the Orderly and Disorderly Transition scenarios, carbon emissions decrease steadily, but without ever becoming negative, reflecting more realistic assumptions in our opinion.

3.3.3. Interest rates

Interest rates play a significant role in our asset pricing models, being related to risk premia and discount rates. Figure 8 shows the projections of long- and short-term interest rates in all scenarios.

In NGFS, both short- and long- term interest rates start at a very high level in the Net Zero 2050 scenario. In particular, the short-term rate before 2025 reminds us of the situation of the US economy in the 1980s. Such levels are not very likely given the recent global macroeconomic developments.

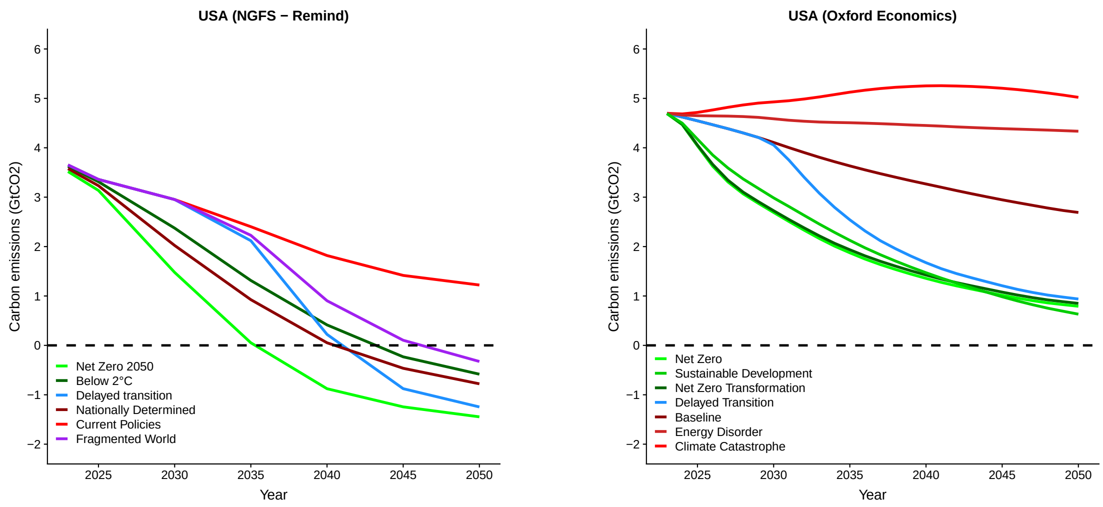

Figure 7: Projections of carbon emissions in the US, for all scenarios of both NGFS and Oxford Economics. Green, blue, purple and red colours refer to Orderly, Disorderly, Inefficient and No Transition scenarios, respectively.

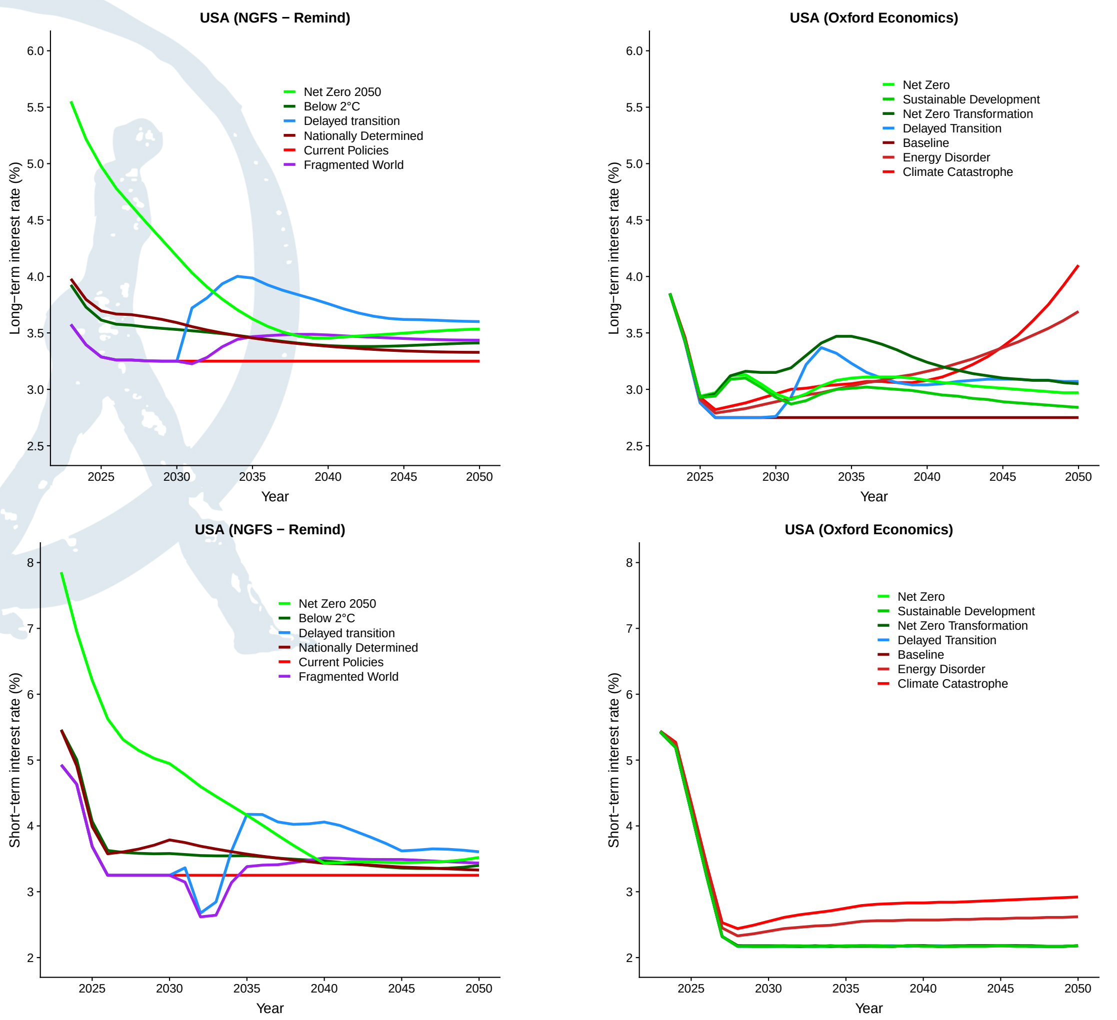

Figure 8: Projections of long- and short-term interest rates in the US, for all scenarios of both NGFS and Oxford Economics. Green, blue, purple and red colours refer to Orderly, Disorderly, Inefficient and No Transition scenarios, respectively.

In Figure 9, we show the term spread, which is the difference between the long-term and the short-term interest rates. NGFS scenarios have significantly more chances to get a negative term spread over the 2023-2050 period, while the term spread in Oxford Economic scenarios become and remain positive quickly. The Climate Catastrophe scenario has the lowest term spread values. A low or negative term spread is generally viewed as a sign of macroeconomic anomaly. Oxford

Economics projections of interest rates and term spread appear more realistic to us.

3.3.4. Conclusions on climate scenario data

In summary, the Oxford Economics projections look more intuitive and reasonable than those of NGFS. In particular, Current Policies in NGFS appears too optimistic for a "No Transition" scenario, i.e., one supposed to represent the risks of inaction. Climate Catastrophe in Oxford Economics strikes us as a better candidate for such a scenario, and thus as a better reference point from which to evaluate the potential gains and losses of transitioning to a low carbon economy. In chapter 5 we will present the results in comparative figures between NGFS and Oxford Economics. To avoid overloading the figures (with information that may be redundant or unnecessary), we will select three scenarios from NGFS and Oxford Economics respectively:

- one Orderly Transition scenario, where the world starts aligning immediately with the Paris Agreement in order to mitigate climate change without abrupt transition shocks.
- one Disorderly Transition scenario, where the world starts aligning in the next decade (2030), thereby applying heavy tax shocks but still mitigating climate change.
- one No Transition scenario, where no actions are taken to mitigate climate change, and where the climate thus becomes much wilder.

In NGFS, we have seen above that Below 2°C and NDC appear almost contradictory with their own assumptions. We will thus select Net Zero as the Orderly Transition scenario, and Current Policies as the No Transition scenario. We select Delayed Transition as the Disorderly Transition scenario, since it is the only one. Moreover, since Oxford Economics does not provide an "Inefficient Transition scenario", we will also exclude NGFS' Fragmented World from our analyses. In Oxford Economics, we select Net Zero and Delayed Transition as Orderly and Disorderly Transition scenarios, respectively, as they are the most comparable to the NGFS ones. As for the No Transition scenario, we select Climate Catastrophe, which shares the feature with Current Policies of being the worst-case scenario. However, they do not share the same assumptions, and we have shown that Climate Catastrophe offers a more realistic representation where no actions are taken to mitigate climate change.

3.4. infra300 index: representative sample of infrastructure companies

We have mentioned in the introduction that we will apply our exercise to EDHEC*infra*'s infra300 index, a representative index of the infrastructure sector. The infrastructure companies within infra300 are selected among ∼6,000 firms in 22 countries to represent the global unlisted infrastructure market according to the TICCS categories [TICCS (2022)]. The infra300 index has been certified by the European Securities and Markets Authority (ESMA) and is becoming a widely recognised benchmark of the unlisted infrastructure investment market. Figure 10 shows the profile of this index per region and sector. More details about its construction and validity can be found [here] and [here].

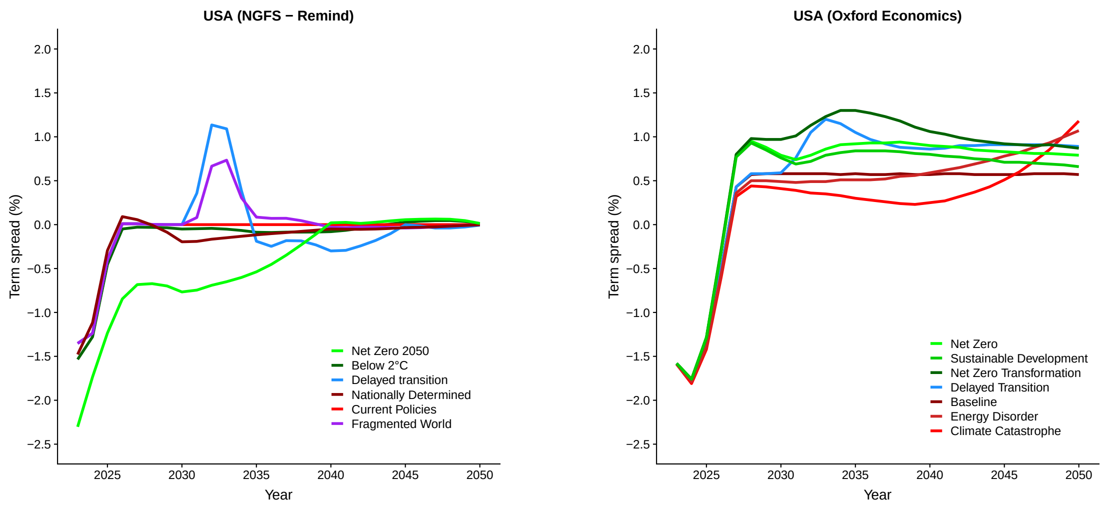

Figure 9: Projections of the term spread in the US, for all scenarios of both NGFS and Oxford Economics. Green, blue, purple and red colours refer to Orderly, Disorderly, Inefficient and No Transition scenarios, respectively.

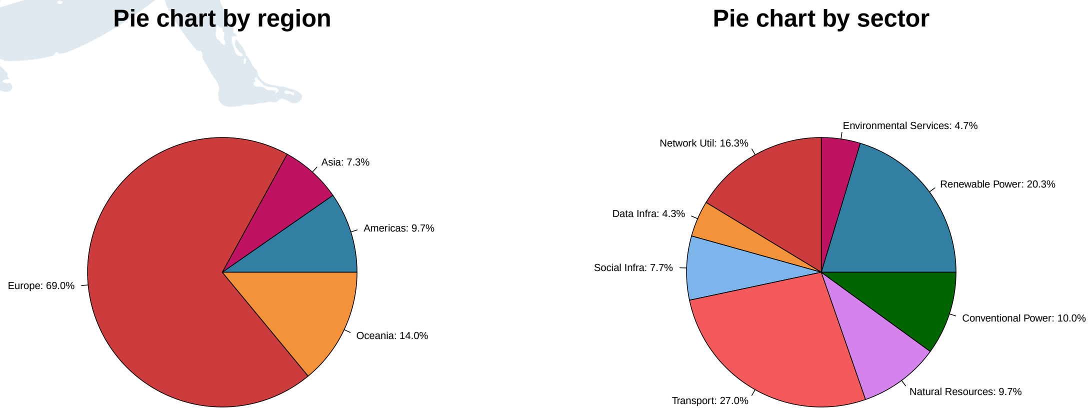

Figure 10: Pie charts showing the distribution of the infra300 companies per region and sector.

4. Climate risk model

Our goal is to quantify climate risks in infrastructure assets at different future horizons. For this, we need to estimate the prices of assets in different climate scenarios and then to compare these prices between scenarios. We use EDHEC*infra*'s well established asset valuation approach, briefly introduced below. Then, we present the models describing the relation between infrastructure financials and macroeconomic variables. Finally, we explain how the carbon taxes and physical risks can be integrated into the projected financials to estimate infrastructure asset values in any given climate scenario.

4.1. Infrastructure asset valuation approach

When dealing with infrastructure assets privately held in institutional portfolios, the market prices are not readily available. Therefore, we follow the guiding principles of the International Financial Reporting Standards (IFRS) 13 – a framework for fair value measurements – and of the modern asset pricing theory to value unlisted infrastructure equity investments.

One of the most commonly used methods for this purpose is the discounted cash flow (DCF) approach, which equates the value of an investment at any time t to the sum of all the future cash flows (i.e., the dividends) that this investment generates from $t+1$ until the investment's end (usually called "maturity"). To account for the fact that the value of money is different (and usually higher) today than tomorrow, the future dividends are discounted by a factor called discount rate.

The Net Asset Value (NAV) of the asset i at time t under climate scenario s can be calculated as:

$$\text{Net Asset Value}_s^{i,t} = \sum_{\tau=1}^{T} \frac{\text{Dividends}_s^{i,t+\tau}}{\left(1 + \text{Discount Rate}_s^{i,t}\right)^{\tau}} \quad (4.1)$$

where i, t and s are indexes for assets, time (year) and scenario, respectively, and T is the number of years until maturity (i.e. the investment end). We calculate the dividends (i.e. equity payout) as:

$$\text{Dividends}_s^{i,t} = \text{FCFE}_s^{i,t} * \left(1 - \text{Retention Rate}_s^{i,t}\right) \quad (4.2)$$

where the retention rate represents companies' tendency to retain free cash (e.g., for investment opportunities, debt reduction, etc), and FCFE stands for Free Cash Flow to Equity. FCFE is calculated as:

$$\text{FCFE}_s^{i,t} = \text{CFADS}_s^{i,t} - \text{Debt Service}_s^{i,t} \quad (4.3)$$

where CFADS is the Cash Flow Available for Debt Service.

The discount rate in eq. 4.1 is the sum of the risk free rate and the equity risk premium:

$$\text{Discount Rate}_s^{i,t} = \text{Risk Free Rate}_s^{t} + \text{Risk Premium}_s^{i,t} \quad (4.4)$$

where the risk free rate is interpolated from the government bond yield curves, provided by NGFS and Oxford Economics in each climate scenario at the country level (no index i).

Following eq. 4.1 to eq. 4.4, the infrastructure assets' NAV is determined in each climate scenario by i) the country's risk-free rate sourced from each scenario's projections, and ii) the company's CFADS, debt service, retention rate and risk premium, which are well modelled by EDHEC*infra*'s asset pricing models.

Our asset pricing models estimate these key financial variables by using factor models. We identify the major risk factors and estimate their coefficients (factor prices), using Kalman filters based on the observed transaction prices (actively updated) in the global unlisted infrastructure market. In particular, we find that revenue is a key risk factor common to CFADS, debt service and retention rate, while total assets (size) and term spread are important risk factors of equity risk premium. These key risk factors are impacted by the specific macroeconomy of each climate scenarios, as described in the next section.

Our asset pricing models can thus estimate these risk factors and thereby the NAV of infrastructure assets in any of the NGFS and Oxford Economics climate scenarios. Appendix C shows examples of our model information and supports the robustness of our asset pricing modelling approach. More details about the EDHEC*infra* Asset Pricing Methodology can be found in the EDHEC*infra*'s documentation[1].

4.2. Impact of climate risks through the macroeconomy

We first construct and calibrate regressions for total assets and revenues, inspired by [Alogoskoufis et al. (2021)], based on recursive equations which involve GDP and inflation. We can then inject the climate scenario projections of GDP and inflation into the regression models to project total assets and revenues in each scenario. This accounts for the macroeconomic channels by which climate risks impact infrastructure assets' financials.

4.2.1. Total assets

Following [Alogoskoufis et al. (2021)], we assume that total asset values follow an auto-regressive pattern, and that their growth is correlated with GDP growth and inflation. There are two main types of infrastructure companies: corporate- and project-type companies. The project-type companies are single-project or project-financed firms with a planned investment end. These companies are in the form of Special Purpose Vehicles. The corporate-type companies are firms holding multiple projects without a pre-defined investment end. They operate like normal firms in the other industries. Because both types of infrastructure companies can exhibit fundamental differences in behaviour, we modelled them separately. For corporate companies, the equation for total assets reads:

$$\text{Total Assets Growth}^{i,t} = \alpha + \beta_1 \text{ Total Assets Growth}^{i,t-1} + \beta_2 \text{ GDP Growth}^{t-1} + \beta_3 \text{ Inflation}^{t-1} \tag{4.5}$$

where i and t are indexes for company and year (time), respectively. Note that GDP and inflation are taken at country level, and thus do not have an i index. The regression analysis supports this equation, and its robustness is shown in Table 3 in Appendix D.

This equation misses a key property of project companies, which is the devaluation of assets. Indeed, at the investment end, projects will be decommissioned and their total assets will thus decrease significantly. We add a term in the equation to account for this effect. This additional term, coined "Percent Lifetime", captures the expected decrease in total assets for project companies, and its regression coefficient is negative (see Table 4 in Appendix D). Without this term, the other coefficients would wrongly capture the decrease in total assets and thus be biased, and their interpretation would be flawed:

$$\text{Total Assets Growth}^{i,t} = \alpha + \beta_1 \text{ Total Assets Growth}^{i,t-1} + \beta_2 \text{ GDP Growth}^{t-1} + \beta_3 \text{ Inflation}^{t-1} + \beta_4 \text{ Percent Lifetime}^{i,t} \tag{4.6}$$

We log-transform these variables to better estimate elasticities, and top them by 1 to avoid too many occurrences of negative numbers. We omit the log transformation part in the equations above to facilitate readability while keeping the general logic.

4.2.2. Revenues

The revenues of infrastructure companies are correlated with the total assets and are expected to be impacted by the macroeconomic variables. We indeed find that revenue growth is well and

1 - https://docs.edhecinfra.com/

sufficiently explained by the growth of total assets, as supported by Table 3 in Appendix D:

$$\text{Revenues Growth}^{i,t} = \beta \text{ Total Assets Growth}^{i,t} \qquad (4.7)$$

The effects of GDP and inflation on revenues are reflected through their effect on total assets. Note that we did not add an intercept since there are no revenues in the absence of total assets.

Assuming that these relationships between financials and macroeconomic variables hold in the future in all climate scenarios, we can project the total assets and revenues of companies based on the projections of the GDP and inflation under these scenarios.

4.2.3. Integrating company specific views on revenue forecasts

The above models of total assets and revenues reflect their global cross-sectional relation with the macroeconomic variables. However, each infrastructure sector and company has its own unique characteristics. To address such company-level specificities, we integrate EDHEC*infra*'s company-level revenue forecasts into the above projections. EDHEC*infra* makes revenue forecasts for every company in the index universe (the infra300 index in particular) and routinely updates these forecasts to reflect the latest developments affecting the company and its sector. However, these revenue forecasts do not incorporate climate risks; rather they try to capture the trends shown in the current economic and sector environment. We therefore align our scenario projections of the revenue growth of each company to EDHEC*infra*'s revenue forecasts by assuming that their forecasts correspond to the NDC scenario in NGFS and the Baseline scenario in Oxford Economics (which are equivalent). We then keep the differences between each scenario and NDC or Baseline as given by the regression model above.

The projected values of total assets and revenues can then be used in the factor models for CFADS, debt service, retention rate and risk premium for different climate scenarios. We have thus shown how to integrate the macro-level climate risks channelled through the macroeconomy. However, companies also have their own sensitivities to climate risks (such as their geolocation, industrial sector and carbon emissions), which will translate into additional costs, affecting their cash flows. The next subsection describes these asset-level climate risks and the further adjustments made on CFADS to reflect their future impact on assets under the various climate scenarios.

4.3. Direct impact of climate risks on companies' cash flows

In addition to the risks coming from the macroeconomic developments, infrastructure companies will suffer losses due to physical risks (potential physical damage) and transition risks (carbon emissions), which depend on the climate scenario considered. When a hazard event occurs, physical damage to assets will affect their production capacities (i.e., their capacity to generate revenue) and increase the repairment costs. Another burden to the operating costs of infrastructure companies will be the introduction of carbon taxes, which will increase the cost of carbon emissions. We estimate both risks here and describe how they further impact the infrastructure financials.

4.3.1. Projection of physical risks

As mentioned in section 3.2.2, physical risks are measured by a damage factor D, which indicates the percentage of the infrastructure asset that will be damaged if a hazard event occurs, and by the frequency ρ of this hazard (details in Appendix B). For instance, a hazard of severity D and return period of 100 years means that a hazard of equal or higher severity than D is expected to occur within the next 100 years. We define the frequency ρ of the hazard as its annualised probability of occurrence, namely 1% per year in this example. Because of climate change, we expect the frequency ρ and severity

D of hazard events to increase in the future, if no efforts are made to mitigate climate risks.

In the Orderly and Disorderly Transition scenarios, where climate goals are met (i.e., physical risks are mitigated and the temperature rise remains below 2ºC), the frequency ρ and damage factor D of hazard events can be assumed to keep the same levels as today, i.e., the "baseline" values (chapter 3). In the No Transition scenarios, however, climate goals are not met and the global mean temperature increase by end-of-century is expected to reach about 2.8ºC in Current Policies (NGFS) [NGFS (2023)] and about 3.6ºC in Climate Catastrophe (Oxford Economics) [Oxford Economics (2023)]. We therefore expect ρ and D to increase with time in these scenarios.

Recent research showed that river flood damage in Europe could rise by a factor of about 6 ± 2 by the end of the century, in the absence of climate mitigation (i.e., an expected about 3ºC GMT increase) [Dottori et al. (2023)]. This is consistent with a growth of about $2.3 \pm 0.5\%$ per year until 2100. Consistently with these numbers, we thus assume that D and ρ grow by 2.5% per year in the Current Policies scenario, and 3.5% in the Climate Catastrophe scenario.

As an example, consider the M5 South West Motorway in Sydney, Australia. In the Current Policies scenario, this project company has $\rho = 1.05\%$ chance of losing $D = 11.6\%$ of its total assets in 2023, and $\rho = 2.1\%$ chance of losing $D = 23.1\%$ of its total assets in 2050. Likewise, the George Best Belfast City Airport (corporate company) has $\rho = 1.05\%$ chance of losing $D = 15.6\%$ of its total assets in 2023, and $\rho = 2.1\%$ chance of losing $D = 31.1\%$ of its total assets in 2050.

4.3.2. Projection of carbon emissions and carbon taxes

As mentioned above, most countries in the world only tax companies' direct carbon emissions (Scope 1 and 2). We thus only consider Scope 1 and 2 emissions in our calculations and assume that both grow at the same rate as the country level emissions in each scenario provided by NGFS and Oxford Economics. The country level carbon taxes per scenario are also taken from NGFS and Oxford Economics. However, since NGFS projects negative emissions in the near future, we floor the carbon cost paid by the companies to zero.

4.3.3. Impact of climate risks on CFADS

These extra costs due to potential damage and carbon taxes are not counted in the factor model, which is calibrated on the current economic and financial trends. Yet, they affect the cash flows of companies directly, in ways that are specific to each company and depend on the scenario. We thus reduce the CFADS calculated from the factor model (with the fm label), as follows:

$$\text{CFADS}_s^{i,t} = \text{CFADS}_{fm}{}_s^{i,t} - \text{Expected Damage}_s^{i,t} - \Delta\text{Carbon Cost}_s^{i,t}$$

$$\text{Expected Damage}_s^{i,t} = \rho_s^t \times D_s^{i,t} \times \text{Total Assets}_s^{i,t}$$

$$\Delta\text{Carbon Cost}_s^{i,t} = \text{Carbon Cost}_s^{i,t} - \text{Carbon Cost}_s^{i,\text{today}}$$

$$\text{Carbon Cost}_s^{i,t} = (\text{Scope 1} + \text{Scope 2})_s^{i,t} \times \text{Carbon Tax}_s^{i,t}$$

The use of ΔCarbon Cost avoids double counting the potential effects of carbon taxes already included in the calculation of CFADS (in the factor model), since some countries have already started charging carbon taxes in recent years. Figure 11 illustrates the functioning of the climate risk model, showing the dependencies between the key variables.

We now have complete models for the use of risk factors in estimating infrastructure assets' NAV in all climate scenarios, incorporating physical and transition risks at both macroeconomic and company level (eq. 4.1). To estimate the impact of climate risks on infrastructure assets, we then calculate the relative difference between the NAV estimated in different conditions, as shown in the next chapter.

As a final remark to conclude this chapter, note that during the calculation of NAV at different

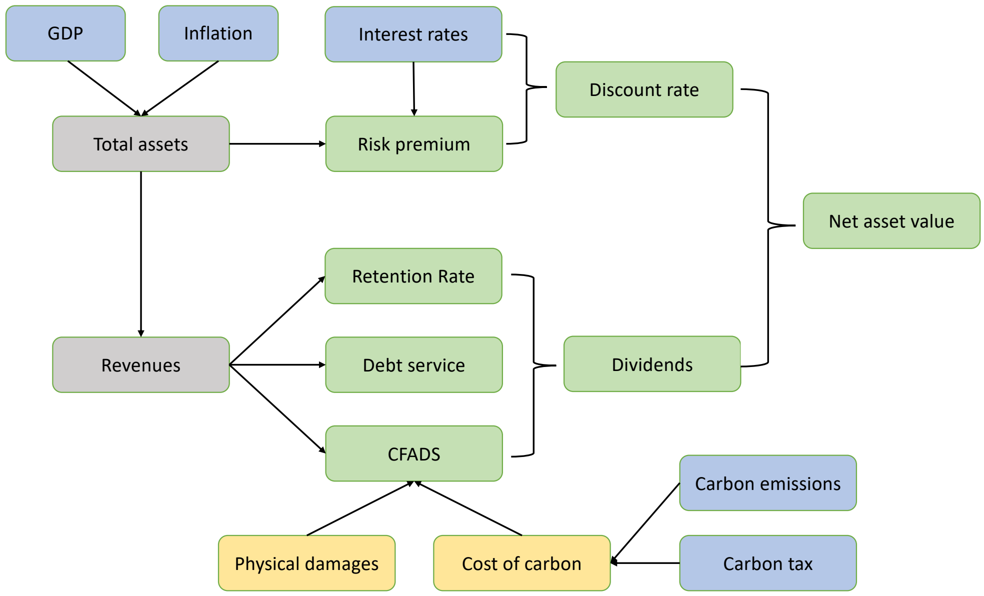

Figure 11: Schematic illustration of the climate risk model. The macroeconomic variables taken from NGFS and Oxford Economics are highlighted in blue, while asset level variables (carbon cost and physical damage) are highlighted in yellow. The financial variables that are used as inputs of EDHECinfra's asset pricing model are highlighted in grey, while the output variables of the asset pricing model are highlighted in green.

horizons, we use the "constant maturity" assumption to freeze the companies' maturities and their financial status (e.g., the starting values of revenue and size) at every future horizon. This is a common technique used in the analysis of fixed income portfolios. Without this assumption, project companies would disappear when their maturity is reached, which could significantly alter the portfolio's composition.

5. Results: impact and cost of climate risks

Our model makes it possible to calculate metrics that can be used to explore the impact of climate risks on companies' performance and value. We compare our model estimations for various metrics in the Orderly, Disorderly and No Transition scenarios for both NGFS and Oxford Economics. We apply the exercise to the infrastructure companies listed in EDHEC*infra*'s infra300 index.

5.1. Impact of climate risks on companies' performances

5.1.1. Climate cost

We call "climate cost" the sum of (i) the expected losses from potential physical damage and (ii) the cost of carbon due to carbon taxes. This quantity measures the typical costs induced by physical and transition risks in each climate scenario. Figure 12 shows the climate cost normalised by the size (total assets) of companies, averaged over the infra300 index in all three scenarios.

The climate cost is the highest in the No Transition scenario (red lines) in both NGFS and Oxford Economics and the lowest in the Orderly Transition scenario (green lines). With a higher initial growth, climate cost in the Disorderly Transition scenario (blue lines) catches up later (after 2040) with the orderly scenario. The costs are much higher in Climate Catastrophe than in Current Policies.

5.1.2. EBITDA-at-risk

EBITDA is the Earnings Before Interest, Tax, Depreciation and Amortisation. We call "EBITDA-at-risk" the ratio of carbon cost (i.e., carbon emissions times carbon tax) to EBITDA. It measures a company's cost in carbon emissions during the transition to a greener economy. Higher values indicate an extra burden of operating the infrastructure due to the introduction of a carbon tax. EBITDA-at-risk is thus a measure of transition risks.

Figure 13 shows the average EBITDA-at-risk across the infra300 companies under different climate scenarios. The EBITDA-at-risk remains low and more or less constant in the No Transition scenario where the carbon tax is negligible. The immediate introduction of a carbon tax implies a sharp initial increase in the Orderly Transition scenario, while the sharp increase starts around 2030 in the Disorderly Transition scenario due to the later introduction of carbon tax. The carbon tax in turn forces companies to reduce their emissions and leads to a decrease in the cost of carbon and thereby in EBITDA-at-risk.

5.1.3. Carbon intensity per revenue

Carbon intensity gives the profile of a company or a sector's carbon footprint. It is usually measured as the ratio of carbon emissions to an operation related financials, e.g. production, revenues, etc. It measures how "green" the economic activity of the infrastructure company is, or in other words, how reliant this infrastructure's operations are on carbon emissions. A higher carbon intensity implies a higher reliance of an asset on carbon emissions in its operations, and thereby a higher sensitivity to carbon taxes and a higher exposure to transition risks.

Figure 14 shows the average carbon intensity per revenue over the Infra300 companies. The general pattern is the same in both NGFS and Oxford Economics: the carbon intensity decreases swiftly in the Orderly and Disorderly Transition scenarios, following a similar decrease in carbon emissions (Figure 7). In the No Transition scenario, Oxford Economics predicts that the carbon intensity remains more or less constant, while it decreases

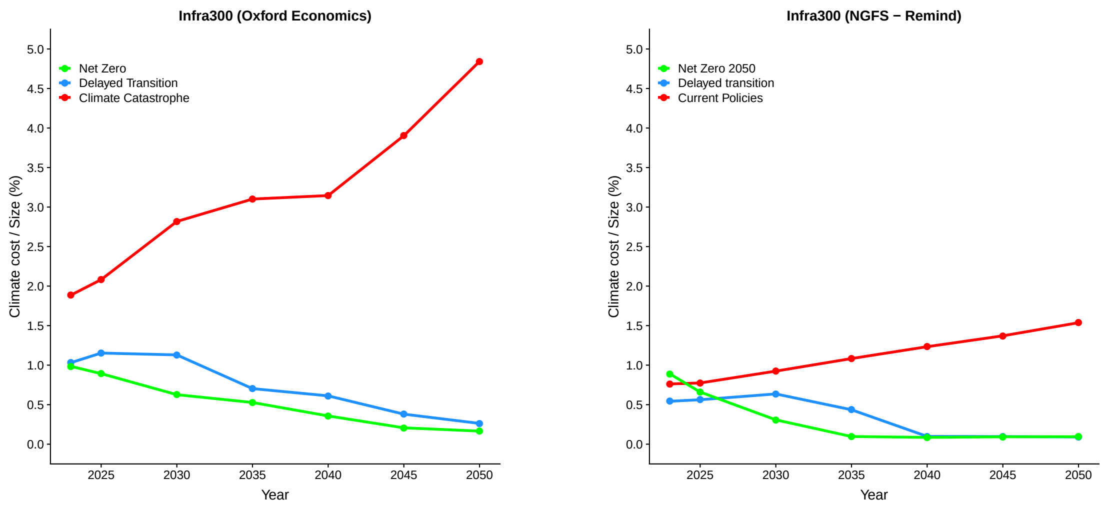

Figure 12: Estimations until 2050 of the climate cost (average over the infra300 index) in the Orderly Transition scenario (green), Disorderly Transition scenario (blue) and No Transition scenario (red) of both NGFS and Oxford Economics.

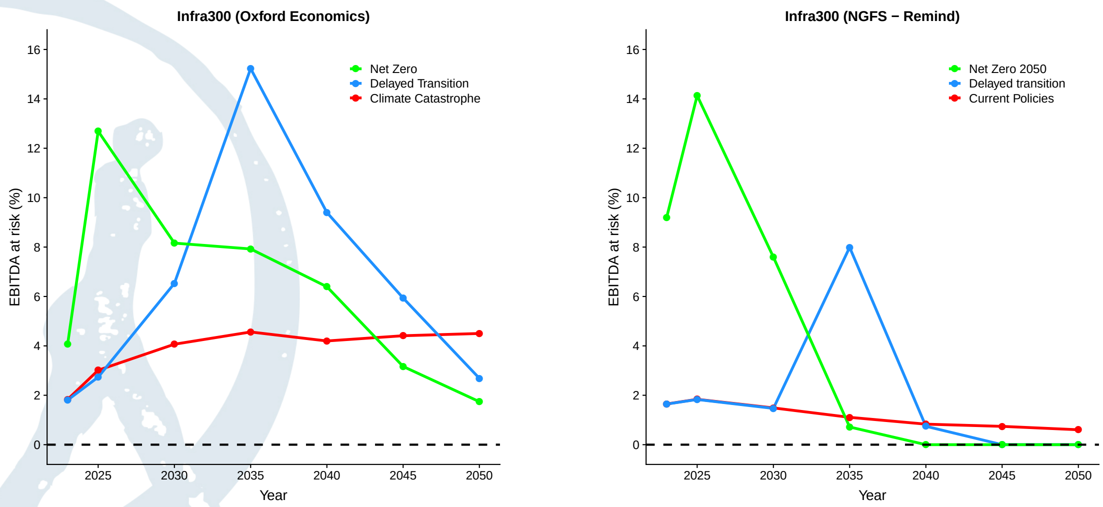

Figure 13: Estimations until 2050 of the EBITDA at risk (average over the infra300 index) in the Orderly Transition scenario (green), Disorderly Transition scenario (blue) and No Transition scenario (red) of both NGFS and Oxford Economics.

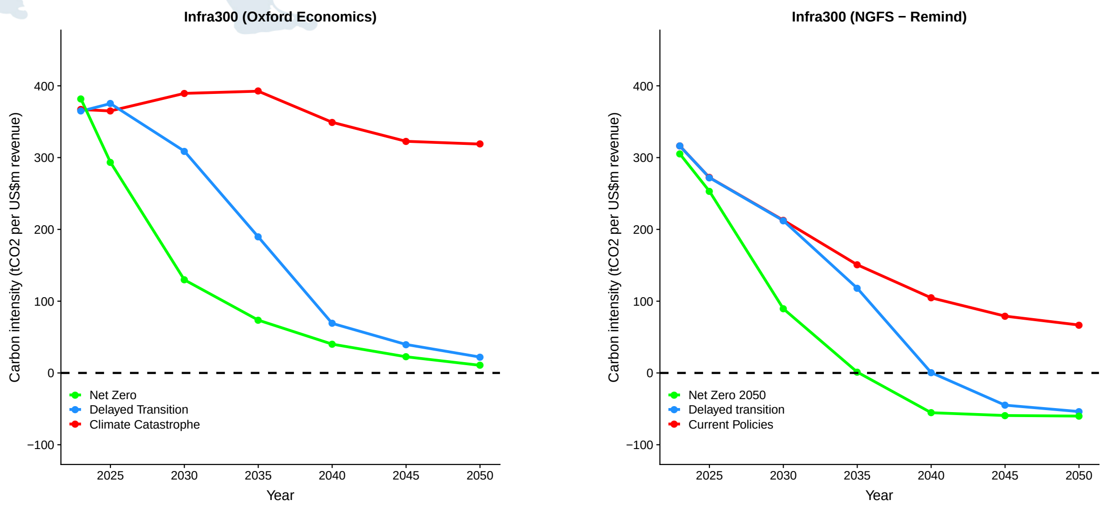

Figure 14: Estimations until 2050 of the carbon intensity per revenue (average over the infra300 index) in the Orderly Transition scenario (green), Disorderly Transition scenario (blue) and No Transition scenario (red) of both NGFS and Oxford Economics.

in NGFS but at a slower pace. This also follows the patterns of carbon emissions in those scenarios where NGFS's Current Policies is much more optimistic than Oxford Economics' Climate Catastrophe.

Note that the carbon intensity can be negative in NGFS (following NGFS projections of carbon emissions, which become negative in most scenarios). As explained in the Chapter 3, we think it is too optimistic, even if carbon capture and storage facilities become widely commissioned.

5.1.4. Financed emissions per NAV

Financed emissions are basically another form of carbon intensity, but with more emphasis on the absolute amount of investment rather than the infrastructure's operations. Here we calculate the financed emissions as the ratio of the company's carbon emission to its NAV. Figure 15 shows the average financed emissions per NAV in different climate scenarios. The conclusion are roughly the same as for carbon intensities per revenue.

5.1.5. Discount rate

The discount rate is the sum of the risk-free interest rate and the risk premium of a company at any given time. It plays an important role when evaluating companies' value as shown in eq. 4.1.

Figure 16 shows the average discount rate of the Infra300 companies in the climate scenarios. In general, there are not big variations across scenarios.

5.1.6. Dividends to revenue ratio

Figure 17 shows the average dividend-to-revenue ratio over the infra300 index for all three scenarios in both NGFS and Oxford Economics.

The dividend-to-revenue ratio increases immediately in the Orderly Transition scenario and after 2030 in the Disorderly Transition scenario, despite the carbon tax being imposed.

In contrast, it continuously decreases over time in the No Transition scenario due to significant losses from physical damage, a consequence of climate change being unmitigated. The ratios are overall lower in Oxford Economics than in NGFS, especially in the No Transition scenario.

5.1.7. Price to sales ratio

The price-to-sales (PS) ratio is one of the commonly used metrics in the market to measure a company's performance. We calculate this ratio as the NAV divided by the revenue. Figure 18 shows the average PS ratio of the infra300 companies under the three climate scenarios of both NGFS and Oxford Economics.

In Oxford Economics, the PS ratio increases in the Orderly (green) and Disorderly (blue) Transition scenarios, while it decreases in the No Transition (red) scenario after a short initial increase. From 2025 on in Oxford Economics, the ratio is the highest in the Orderly Transition Scenario, and the lowest in the No Transition scenario. In NGFS, the same is observed after 2040. But before 2040, the PS ratio's performance alternates between these three scenarios, indicating that the benefits of introducing a carbon tax during this period is not as clear as in Oxford Economics.

We also calculate the price-to-book (PB) ratios for these climate scenarios. These ratios show similar patterns to the PS ratios, so we do not repeat the discussion here.

5.2. Losses associated with climate risks

5.2.1. Alignment risk metrics

One of the common questions posed by infrastructure asset investors and shareholders is how much value would be lost or saved if the world were to align with the Paris agreement immediately (i.e., following the Orderly Transition path) as opposed to aligning late (i.e., following the Disorderly Transition path), or even not aligning at all (i.e., following the No Transition path). Thanks to our robust methodology, we can answer this question quantitatively by constructing the following two metrics that compare the outcomes between climate scenarios in terms of net asset value:

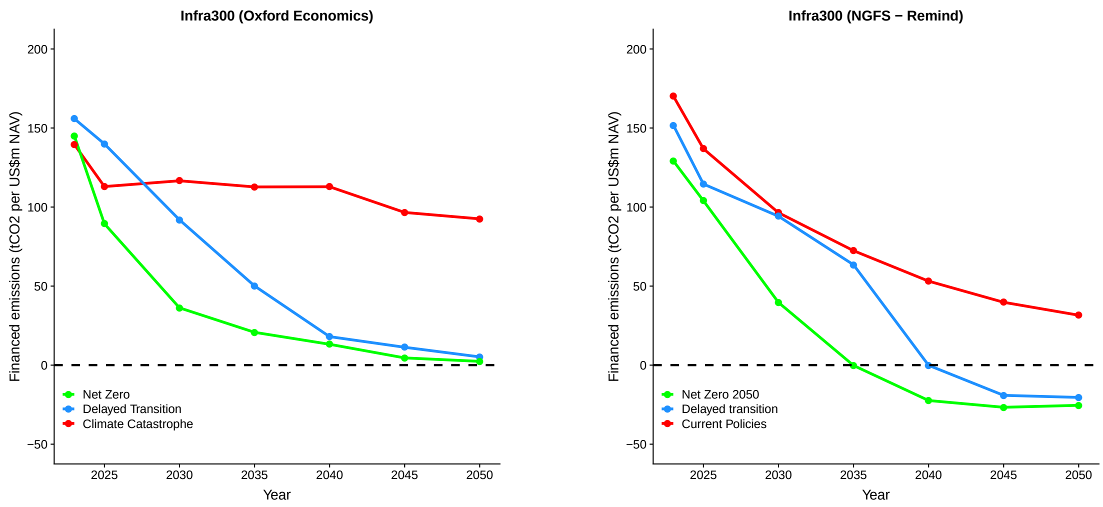

Figure 15: Estimations until 2050 of the financed emissions per NAV (average over the infra300 index) in the Orderly Transition scenario (green), Disorderly Transition scenario (blue) and No Transition scenario (red) of both NGFS and Oxford Economics.

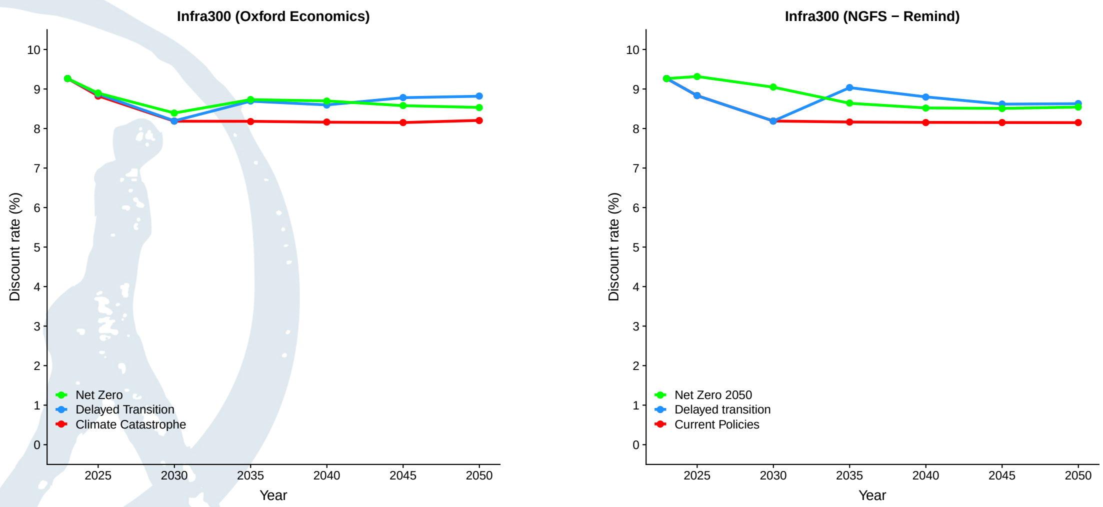

Figure 16: Estimations until 2050 of the discount rate (average over the infra300 index) in the Orderly Transition scenario (green), Disorderly Transition scenario (blue) and No Transition scenario (red) of both NGFS and Oxford Economics.

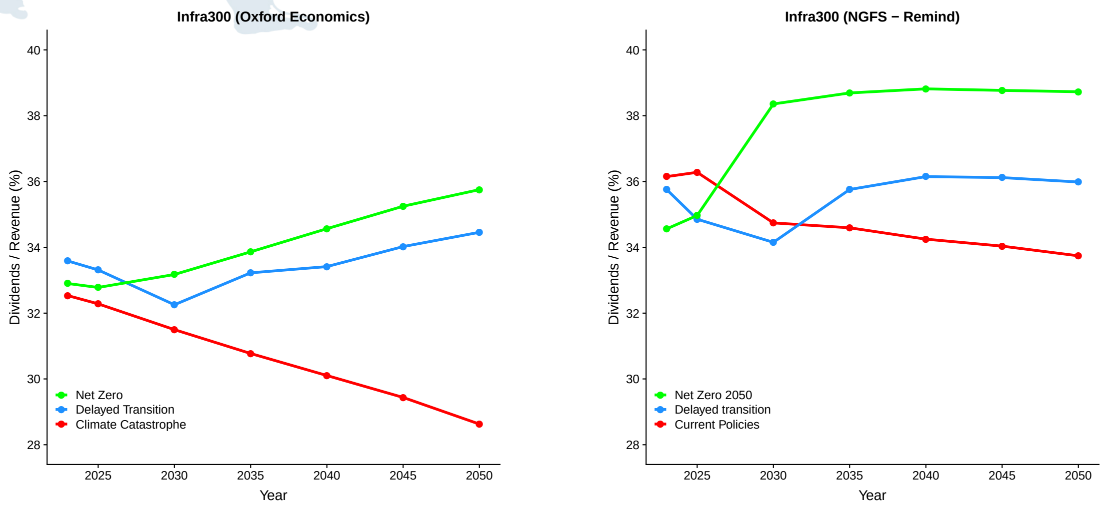

Figure 17: Estimations until 2050 of the dividend to revenue ratio (average over the infra300 index) in the Orderly Transition scenario (green), Disorderly Transition scenario (blue) and No Transition scenario (red) of both NGFS and Oxford Economics.

- **Late Alignment Risk metric**: relative difference in NAV between the Disorderly and the Orderly Transition scenarios. It measures the potential losses of starting alignment actions late (i.e. 2030).
- **No Alignment Risk metric**: relative difference

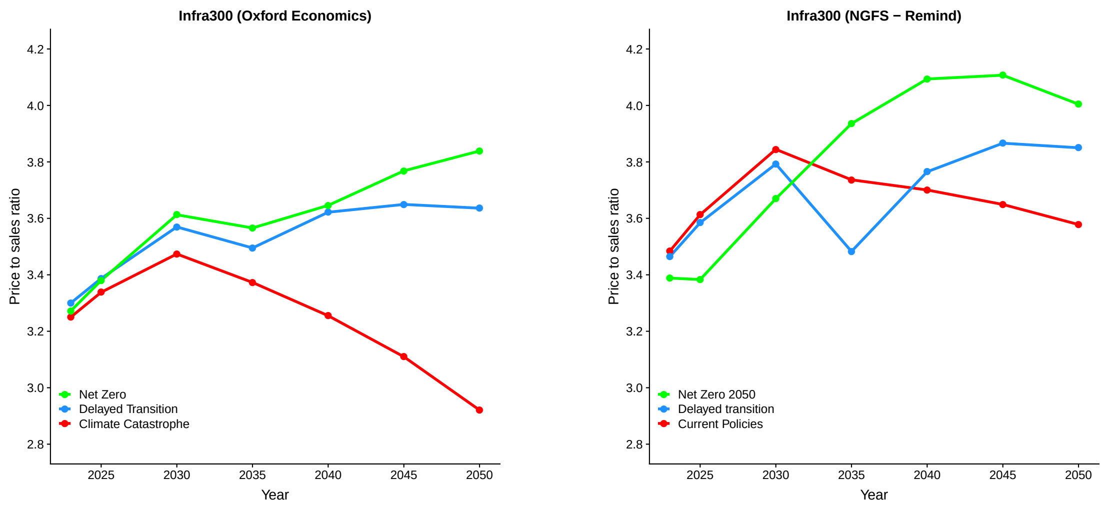

Figure 18: Estimations until 2050 of the price to sales ratio (average over the infra300 index) in the Orderly Transition scenario (green), Disorderly Transition scenario (blue) and No Transition scenario (red) of both NGFS and Oxford Economics.

in NAV between the No Transition and the Orderly Transition scenarios. It measures the potential losses of no alignment actions at all.

Figure 19 shows the Late Alignment (in blue) and No Alignment (in red) risk metrics. They are averaged over the infra300 companies under both NGFS and Oxford Economics scenarios. Positive/negative values imply that the percentage of NAV shown is saved/lost as compared to the Orderly Transition scenario.

In both Oxford Economics and NGFS, the Late Alignment Risk starts positive but becomes negative shortly after 2030, when the carbon tax is introduced. This means that avoiding to pay the carbon tax until 2030 will initially benefit companies, but will cost more when it is introduced in 2030. NGFS scenarios imply higher risks than Oxford Economics, because of a higher carbon tax in the Disorderly Transition scenario there (Figure 6).

If the world does not align with the Paris agreement at all, the infrastructure companies will initially face little impact, and would even benefit somewhat in NGFS until 2030. But after 2030, losses start soaring as more severe physical damages happen more frequently. Based on the No Transition scenario of Oxford Economics, the infrastructure companies' NAV will be about 25% less than in the Orderly Transition scenario in 2050 on average. Even in NGFS scenarios which are more optimistic as seen in chapter 3, the average loss in 2050 approaches 12% among the infra300 companies.

5.2.2. Extreme risk metrics

The alignment metrics above do not distinguish between the effects of transition risks and physical risks, because they are designed to address the overall effects of aligning with the Paris agreement or not. However, there are many situations where it would be useful to understand the potential risks derived solely from either carbon taxes or physical damage. So, we also run simulations with and without carbon taxes or physical damage within a given scenario, and define the following metrics:

- **Extreme Transition Risk metric**: relative difference in NAV, within the Disorderly Transition scenario, between a simulation where carbon emissions are counted and a simulation where they are set to zero. This metric measures the potential losses that are purely due to carbon emissions in the Disorderly Transition scenario. Since this scenario has the highest transition risks, we add an "extreme" label to it.

- **Extreme Physical Risk metric**: relative difference in NAV, within the No Transition

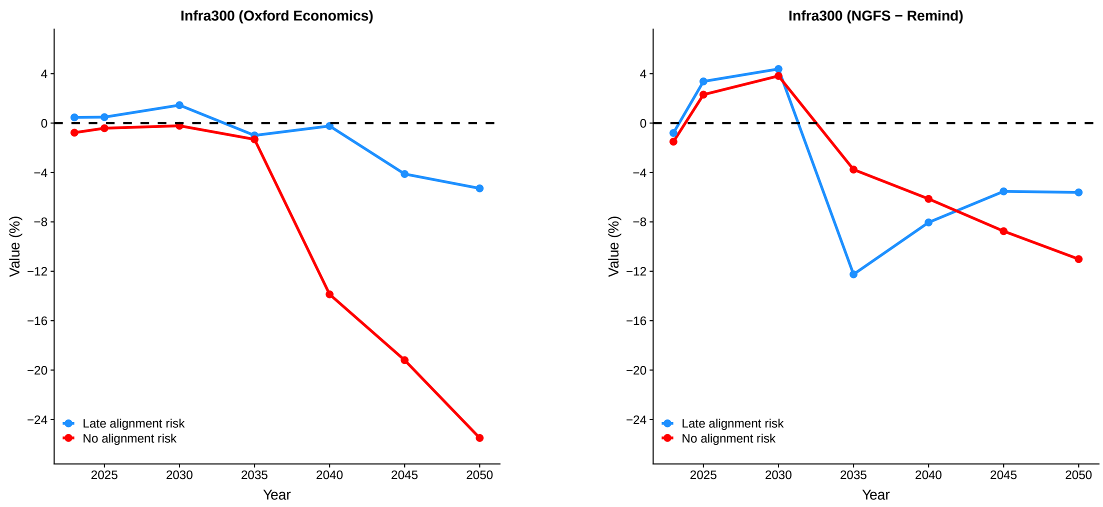

Figure 19: Estimations until 2050 of the late alignment and no alignment risk metrics (average over the infra300 index) for both NGFS and Oxford Economics.

scenario, between a simulation where physical damage are counted and a simulation where they are set to zero. This metric measures the potential losses purely due to potential physical damage in the No Transition scenario. Since this scenario has the highest physical risks, we add an "extreme" label to it.

Note that calculating the difference within the same scenario cancels the macroeconomic effects. Therefore, the metrics measure the potential losses that are purely due to a company's specific exposure to transition and physical risks. Figure 20 shows the Extreme Transition and Extreme Physical Risk metrics, averaged over the infra300 companies.

Extreme Transition Risks (blue lines) are the highest between 2025 (Oxford Economics) and 2030 (NGFS) and then steadily increase back to 0 (i.e., lower risks) due to the decreasing use of carbon emissions. 0 is reached in 2040 in NGFS and shortly after 2050 in Oxford Economics.

In contrast, Extreme Physical Risks becomes more severe over time in both NGFS and Oxford Economics, and reach about -8% in the former and about -18% in the latter by 2050.

These results support the necessity of taking actions to mitigate the adverse effects of climate change, even if this implies that the infrastructure sectors would have to invest more in the short-term. Indeed, in the medium to long run, this initial investment will turn into much higher benefits.

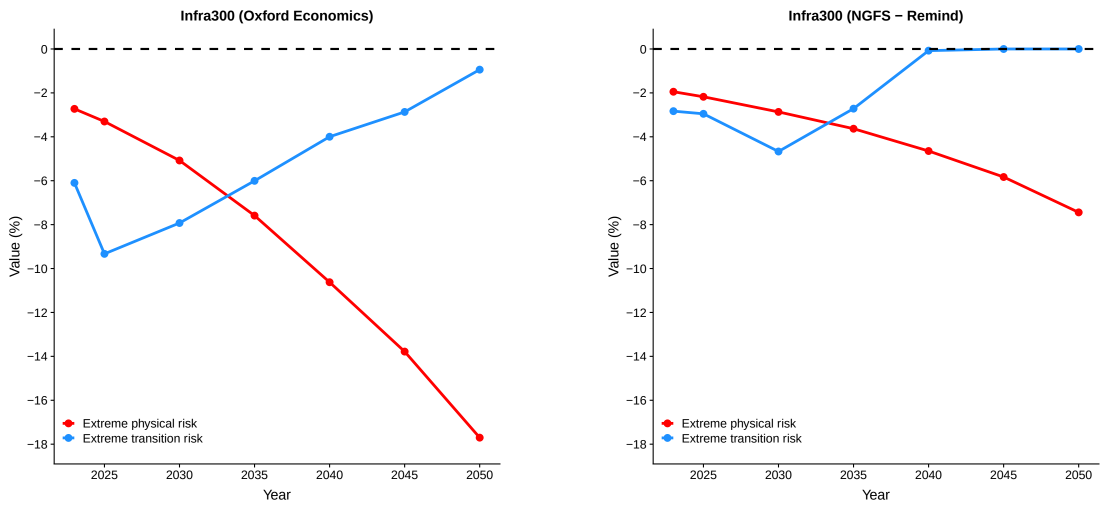

Figure 20: Estimations until 2050 of the extreme transition and physical risk metrics (average over the infra300 index) for both NGFS and Oxford Economics.

6. Conclusions

Infrastructure assets are increasingly exposed to the risks associated with climate change, such as rising sea levels, extreme weather events, and changes in precipitation patterns. In this paper, we presented a cutting-edge methodology that combines financial and macroeconomic variables with climate risk data to project financial variables in infrastructure assets and estimate their future value under various climate risk scenarios. This novel methodology enables us to tackle the challenging exercise of making a quantitative assessment of the impact of climate risks on the value of infrastructure assets.

Comparing our results across various metrics of companies' financial performance, we show that infrastructure companies will fare the best if they follow an orderly transition path, which starts the energy transition soon. By delaying the transition, companies could expose themselves to significant losses in terms of carbon cost. **However, transitioning late is still by far preferable to not transitioning at all.** Indeed, our estimations show that the No Transition scenario will be far more costly than the Disorderly Transition scenario for infrastructure assets in terms of NAV and financial performances. This is all the more obvious in Oxford Economics' No Transition scenario (i.e. Climate Catastrophe), where governments fail to meet their policy pledges. Importantly, this scenario looks more realistic than the NGFS Current Policies scenario, which is supposed to stand for "business as usual". It better reflects the risks posed by an absolute lack of action toward the Paris alignment, and is a better benchmark to compare the potential gains and losses associated with any other scenario.

Our work thus shows three things:

- First, it is possible to *quantitatively* estimate climate risks and their impact on the value of infrastructure assets. We have developed a robust method to do so.
- Second, considering these risks in the evaluation of infrastructure investments is essential. Disregarding these risks will lead to sub-optimal decisions and significant losses. We hope that this paper will motivate investors to use our method, and the data that it helped us produce, to inform their investment decisions.
- Finally, even though initial expenses may be required, our results show that the transition to a low-carbon economy will significantly benefit the infrastructure investors and portfolio managers in the long run – and the earlier the transition, the better.

Moreover, we must emphasise that our results are conservative for several reasons: (i) other aspects of transition risks, such as reputation or consumer preferences, are so far not included directly in climate scenarios; (ii) only damages from floods and storms are currently included in our model; (iii) physical risks will become increasingly material over time, such that much more severe consequences of inactions are to be expected in the second half of the century, be they direct (hazard-related damages) or indirect (e.g. social acceptability risks and more expenditure on social and health welfares).

The method developed by EDHECinfra and presented in this paper can prove particularly useful to investors and asset managers, who increasingly seek to evaluate the potential risks posed by climate change. We believe that our method will help them achieve these goals by providing them with robust climate risk estimates.

Appendix

A. Carbon estimations

Our transition risk metrics (and climate change metrics) rely on estimating the carbon footprint of assets. While financial metrics directly come from InfraMetrics®, the scopes of emissions are derived from two main types of models: factor-based models (FBMs) and regression-based models (RBMs), as illustrated in Figure 21. These models are defined by prioritising the most relevant variables giving access to the level of operations that generate carbon emissions. These variables are identified from literature review, internal expertise, experience from sustainability report disclosure, and test of correlations with emissions. The fully detailed methodology for estimating carbon footprints is explained in [Nugier and Marcelo (2022)].

The FBMs rely on a direct approach that does not require to have reported emissions. Instead, they employ physical characteristics of assets that best represent their level of operations and convert these characteristics into emissions for different years and scopes (Scopes 1, 2, and 3). These models are advantageous where little reported data is available (hence offering low statistics) and when there exist operational, consumption, or production variables that are directly related to emissions.

The RBMs combine reported emissions with asset-level characteristics known for their correlation with the emissions, through expert knowledge and verification from data. These models employ a model dataset that relates relevant characteristics with emissions levels of assets that are not the assets for which we are establishing a prediction. These models can be established independently for different years and Scopes 1, 2, and 3. They are adapted to situations where enough statistics are available or when several characteristics have been collected, with some having a lower correlation with the produced emissions.

FBMs and RBMs can be developed in parallel when sufficient physical characteristics and reported emissions are present, choosing the best model after a comparison with reported emissions. As we can understand from the above, FBMs tend to rely on a single asset characteristic which is strongly correlated with the level of emissions, while RBMs can rely on more parameters not necessarily highly correlated, but for which the combined considerations provide a good description of sources of emissions (see Figure 22).

Once emission scopes are predicted, carbon intensity metrics are derived by dividing these predicted emission scopes by revenue, total assets, equity price, and EVIC (enterprise value including cash), which are financial metrics directly coming from InfraMetrics®. As already mentioned, Scope 1+2 emissions are used for such metrics as they describe the emissions on which the asset owner has control, and that is why they are at the center of these metrics.

These metrics all represent a different carbon-to-financial ratio and provide insight into the level of operational emissions of assets compared to their financial performance, i.e., their carbon efficiency.

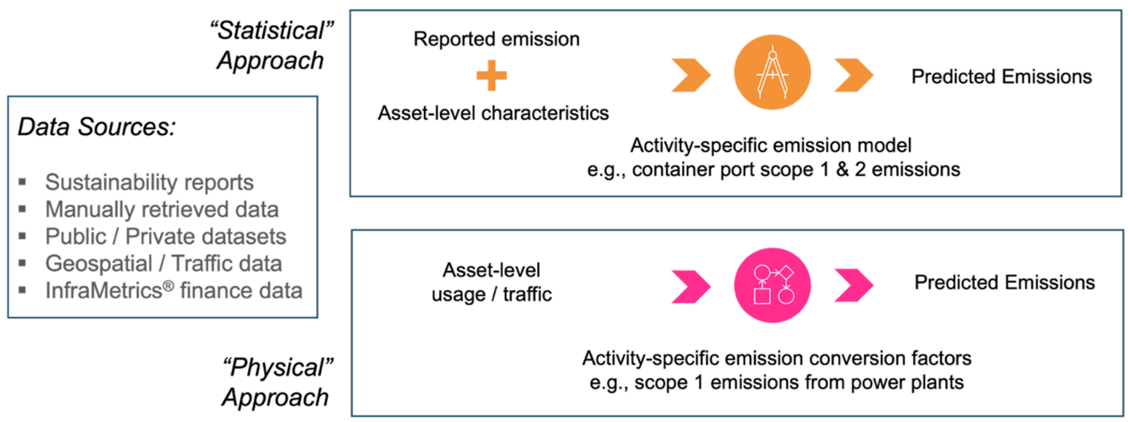

Figure 21: Models applied to estimate Scope 1, 2, and 3 emissions.

Models	Design TICCS Coverage	Scope 1	Scope 2	Scope 3
Energy (fossils & renewables)	IC10 + IC70	FBM: type of fuel, energy production, capacity	Negligible	Negligible
Waste & Water	IC20	FBM: (waste / water) x mass **OR** Negligible	FBM: (waste / water) x (mass / volume) **OR** Negligible	FBM: (waste / water) x volume **OR** Negligible
Social Infrastructures	IC30	FBM: area, consumption, country	FBM: area, consumption, country	No Model
Pipelines	IC4010	FBM: length **OR** No Model	Negligible	FBM: capacity / volume **OR** No Model **OR** Negligible
LNG & Oil	IC4020	FBM: throughput mass **OR** No Model	Negligible	FBM: Throughput Volume **OR** No Model
Storage	IC4030	FBM: Volume stored	No Model	FBM: Volume stored
Com. Satellites	IC501030	Negligible	Negligible	Negligible
Data Centers	IC502010	RBM: electricity consumption in MWh	RBM: electricity consumption in MWh	RBM: electricity consumption in MWh
Airports	IC601010	RBM / FBM: multiple regressors (cf. description)	RBM / FBM: multiple regressors (cf. description)	RBM / FBM: multiple regressors (cf. description)
Ports	IC6030	RBM: revenue and throughput	RBM: revenue and throughput	No Model
Rails	IC6040 + IC6060	RBM: rail length	RBM: rail length, electrification	RBM: rail length
Roads	IC6050	RBM: road area (length x lanes)	RBM: road area (length x lanes)	RBM: road area (length x lanes)
Distribution Networks	IC80	RBM: customers, employees, revenue	RBM: customers, employees, revenue	RBM: customers, employees, revenue

Notations:
- **FBM:** Factor Based Model
- **RBM:** Regression Based Model
- **Negligible:** based on the assessment of the infrastructure, the emission is considered negligible.
- **No Model:** values are strictly NaN for all assets in the TICCS category, based on the lack of data or the complexity of modelling.
- **"/":** a slash between two regressors means one or the other is used (not both).

Figure 22: Models summary with their main explanatory variables.

B. Physical risk estimation

EDHEC*infra* developed physical risk metrics following a three-level approach (see Figures 23 and 24):

• First, each asset in the infraMetrics' reference dataset is geolocated, and its corresponding physical footprints or shape, including main physical components, is extracted in the form of geospatial shapefiles.

In parallel, high-resolution hazard models, including floods, extratropical storms, and tropical cyclones across different return periods (100, 50, and 30 years), are transformed into physical damage maps using asset-type damage functions. Damage functions describe the relationship between hazard intensity (e.g., water depth for flooding and wind speed for storms) and expected physical damage. We identified damage functions for 34 asset types.

• Second, we use the assets' shapefiles mentioned above to select their corresponding damage values per type of climate hazard from the damage maps generated in the previous step. For example, we extract all the 100-year flood damage values within the shape or polygon representing a given asset (e.g., an airport or a coal-fired power plant) to calculate its average physical damage.

• Finally, financial physical risk metrics, including physical value at risk (PVaR) and expected losses, are calculated by combining the damages (i.e., flood-, cyclone-, and extratropical storm-related) at the asset level from the previous step with the infraMetrics proprietary financial data for the reference dataset. To calculate PVaR and expected losses, we use the total asset value of each asset.

The fully detailed methodology for estimating physical risks is explained in [Marcelo and Blanc-Brude (2022)].

Location of assets in the reference dataset

One of the most critical steps to calculate the asset level physical risks is the geolocation and identification of the footprint of infrastructure assets. We have completed this process for our reference dataset. Figure 25 summarises the global share of assets per country.

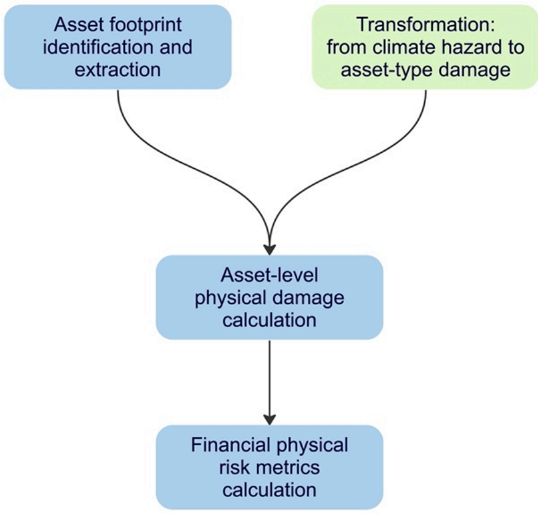

Figure 23: Physical risk metrics approach.

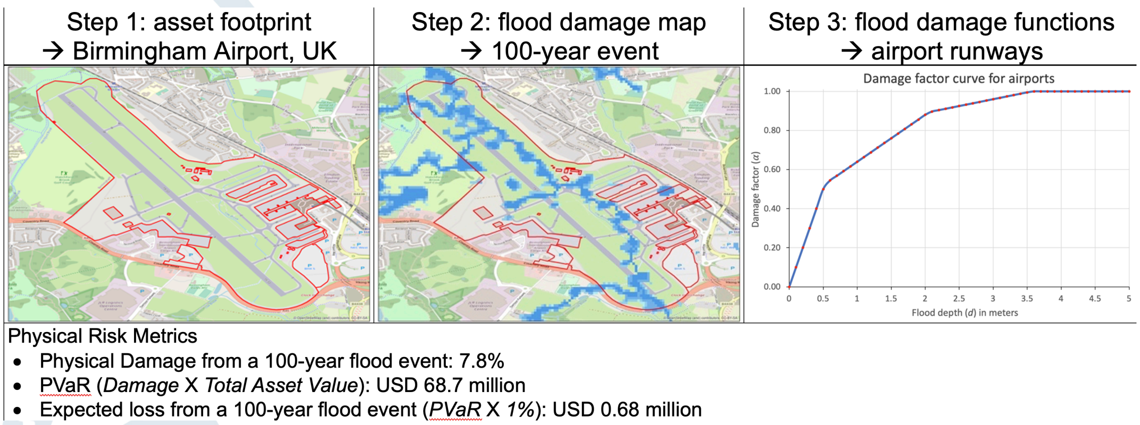

Figure 24: Flood risk metrics approach applied to Birmingham Airport, UK.

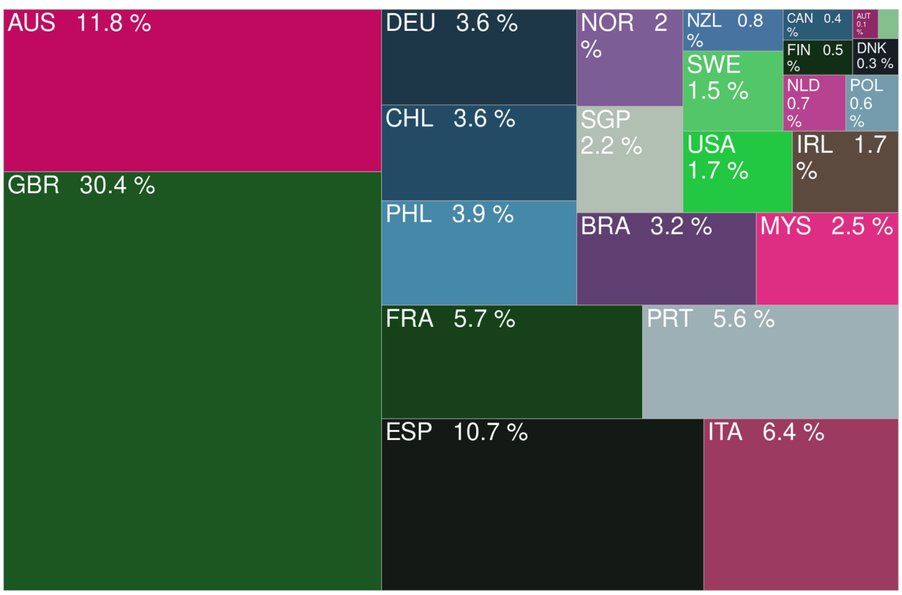

Figure 25: Country of location and global share of assets in the sample of physical risk data.

C. Asset pricing model: proof-of-concept

For the 250+ transactions that correspond to companies tracked in the EDHEC*infra* universe and for which observed secondary market prices are also available (the test dataset) we can compare observed and model-predicted valuations directly. Figure 26 shows a comparison between model-predicted IRR (Internal Rate of Return), risk premia and EV/EBIDTA (Enterprise Value to EBITDA) ratios with actual values for the test dataset of 250+ observed transactions between 2000 and 2020. Model-predicted prices are accurate. The prediction error is typically within 5% of observed prices (Table 1).

The 45 degree lines in Figure 26 indicate an (ideal) perfect match between model and predicted prices. Deviations from such a perfect match can be explained by the fact that:

1. The model predicts the average price a typical investor would pay for a given asset. In reality, buyers may pay more or less than the model predicted average due to their own price preferences.
2. The model itself is imperfect and while it captures the systematic part of the pricing in markets well, it may not embed all the assumptions or hypotheses made by buyers at the time of the transaction.

In general, the match is very good, as also emphasised in Table 2: the predicted valuation ratios are very close on average to the observed ones. Estimated prices for all assets in the universe are thus a reliable estimate of the fair value of these investments.

Having shown the robustness of this valuation approach, we can be confident about the projected valuations of infrastructure companies based on a robust dataset.

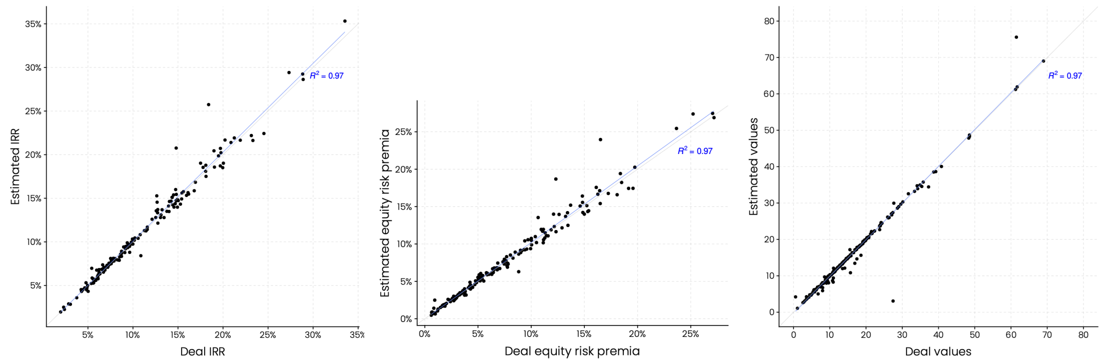

Figure 26: Comparison between model-predicted IRR, risk premia and EV/EBIDTA ratios with actual values for the test dataset of 250+ observed transactions between 2000 and 2020.

Table 1: Quantiles of model errors

10% Quantile	25% Quantile	Median	Mean	75% Quantile	90% Quantile
-5.00%	-1.95%	-0.22%	-0.55%	1.64%	3.85%

Table 2: Estimated VS reported valuation ratios and model's goodness-of-fit.

Ratio	Reported Mean	Estimated Mean	Reported Median	Estimated 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

D. Regression model: proof-of-concept

Table 3: Regression results for corporate companies (L1 denotes the first lag of a variable).

	Dependent variable:	
	Total Assets	Revenues
	(1)	(2)
Total Assets L1	0.078***	
	(0.016)	
GDP L1	0.344***	
	(0.076)	
Inflation L1	1.274***	
	(0.157)	
Total Assets		0.236***
		(0.024)
Constant	−0.006***	
	(0.002)	
Observations	3,486	1,107
Adjusted R^2	0.032	0.077
Note:	*p<0.1; **p<0.05; ***p<0.01	

Table 4: Regression results for project companies (L1 denotes the first lag of a variable).

	Dependent variable:	
	Total Assets	Revenues
	(1)	(2)
Total Assets L1	0.043***	
	(0.013)	
GDP L1	0.163***	
	(0.046)	
Inflation L1	0.631***	
	(0.087)	
Percent Lifetime	−0.038***	
	(0.003)	
Total Assets		0.243***
		(0.018)
Constant	−0.006***	
	(0.002)	
Observations	5,195	1,871
Adjusted R^2	0.042	0.085
Note:	*p<0.1; **p<0.05; ***p<0.01	

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For more information, please contact:
Nataliia Gaidarenco
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

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