

Essays on the Financial Economics of Climate Change

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Abstract

The relative size of economic activity over natural capital has increased exponentially since World War II. We have reached a point where our economy is no longer a marginal phenomenon in our planet. Since this realisation of the endogeneity of the environment in economic processes, economists have developed a new academic field, namely Environmental Economics. Yet, the realization among financial economists of this economic imperative has only been recent and mostly focused around global warming. In this thesis, I discuss a new emerging academic field, namely Climate Finance. I first provide a systematic review of the literature in this new field and discuss some of its branches. I then argue that, in light of the massive externality of carbon emissions, some core tenets of financial economics may need to be reconsidered. I show that climate change is already having a profound impact on financial markets, specifically on how we value assets, how we assess financial risks and, in turn, how we structure regulatory frameworks. Finance is a necessary condition for the net zero carbon transition. The reconsideration of some of these tenets may be essential to empower the financial system to deliver on mitigating global warming.

DPhil papers

1. **The evolving academic field of climate finance**

Matteo Gasparini, Peter Tufano

2. **Are financial markets pricing the net zero carbon transition?**

A reconsideration of the carbon premium

Matteo Gasparini

3. **Model-based financial regulations impair the transition to net-zero carbon emissions**

Matteo Gasparini, Matthew C. Ives, Ben Carr, Sophie Fry & Eric Beinhocker

4. **A re-evaluation of the financial risks of the net zero carbon transition**

Matteo Gasparini, Moritz Baer & Matthew C. Ives

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Part I

Introduction

In the post Second World War era, the push for economic growth and the marginal impact of the economy on nature at a global scale led to the belief that human ingenuity will ultimately enable us to remain within any constraints imposed by our planetary boundaries (Dasgupta, 2021). This impetus for economic growth has brought greater wealth and well-being for many. However, we are increasingly being reminded that economic growth might not be feasible in the face of large unaddressed externalities. Increasing temperatures and an exacerbation of the frequency and magnitude of extreme weather events are costing billions of dollars every year, with much of the costs falling on the poor. Climate change can no longer be ignored as a marginal phenomenon in economic philosophy.

Following the seminal work of Nordhaus (Nordhaus, 1982), economists have shown increased recognition of the importance of addressing climate change. Economists have for more than a century acknowledged that markets are incomplete (Pigou, 1920), that externalities exist. Nordhaus' contribution to introduce the environmental externality of carbon emissions into a traditional economic cost-benefit framework (Nordhaus, 1992), demonstrated the trade-off that our society faces between maintaining the limited supplies of natural capital and the accumulation of other forms of capital (human and physical capital). Although Nordhaus' work has been criticised for its assumptions and limitations (Cai, Lenton, & Lontzek, 2016; Cai & Lontzek, 2019; Haensel et al., 2020), it did open the door to the incorporation of climate change into economics.

Even though various economics sub-disciplines (e.g., Environmental and Agricultural economics) have discussed the importance of the financial economics of climate change (Battiston, Dafermos, & Monasterolo, 2021; Battiston, Mandel, Monasterolo, Schütze, & Visentin, 2017; Campiglio, 2018; Monasterolo, 2020), Finance literature has been mostly

uninfluenced by such considerations. However, this appears to be changing (Edmans & Kacperczyk, 2022; Gasparini & Tufano, 2023; Giglio, Kelly, & Stroebel, 2021; Hong, Karolyi, & Scheinkman, 2020; Starks, 2023). In my systematic review in Chapter II, I identify less than 20 papers on Climate Finance before 2018, but find more than 160 in 2021. Various strands of the finance literature ranging from Asset Pricing (Baker, Bergstresser, Serafeim, & Wurgler, 2022; Bolton & Kacperczyk, 2023; Engle, Giglio, Kelly, Lee, & Stroebel, 2020; Flammer, 2021; Hsu, Li, & Tsou, 2022; Pástor, Stambaugh, & Taylor, 2022), Financial Intermediation (Acharya et al., 2023; Oehmke & Opp, 2022; Papoutsi, Piazzesi, & Schneider, 2021), Corporate Finance (Ilhan, Sautner, & Vilkov, 2021; Sautner, Van Lent, Vilkov, & Zhang, 2023), and Household finance (Anderson & Robinson, 2021) have increasingly studied the implications brought by climate change. This has resulted in an increasing number of papers on Climate Finance being published in the top three finance journals (Journal of Finance, Journal of Financial Economics and The Review of Financial Studies). The importance of this topic has also gained traction among financial policy-making institutions such as central banks and financial regulators (Adrian, Bolton, & Kleinnijenhuis, 2022; Alogoskoufis et al., 2021; BIS, 2020), as well as the private sector (ECB, 2022; Keenan, 2019; TCFD, 2022).

This is a justifiable course correction. This thesis shows that some core tenets of financial economics require rethinking in light of the massive environmental externalities produced by today's economies. The reconsideration of these tenets is important to better understand whether the financial system will be able to deliver its core functions in support of the net zero carbon transition and mitigate the worst effects of climate change. Such issues are central for policy-making and practice as such theories and tools inform the decision making of central banks and investors. This thesis sheds light on novel and so far neglected issues around the valuations of carbon intensive assets, the effects of model-based risk regulations on the net zero carbon transition, and the assessment of climate related financial risks. Specifically, this thesis investigates the following questions:

1. Are the relatively high historical (realised) stock market returns of carbon-intensive

firms reflective of a risk premium (and thus higher cost of capital) of polluting firms? Or are they rather a symptom of financial markets not pricing the net zero carbon transition? (Chapter [III](#))

2. Are model-based financial regulations impairing the transition to net zero carbon emissions by steering investments towards polluting assets? Is there a negative relationship between provisioning requirements of banks and carbon emissions? (Chapter [IV](#))
3. Are current methods that are used in the literature, and in practice, to assess climate related risks in the financial system subject to excessively high levels of uncertainty to make them useful? What is the variability of the possible impacts of the net zero carbon transition on the financial system? (Chapter [V](#))

I employ theoretical and empirical methods drawing from the financial economics literature, but also other academic fields, taking a multi-disciplinary approach. I draw on methods from the asset pricing literature to show that we may require a broader appreciation of environmental externalities in valuing financial assets. My theoretical model builds on traditional present value relations models ([Campbell & Shiller, 1987](#); [Gordon, 1962](#)) and real option theory ([Paddock, Siegel, & James, 1988](#); [Pindyck, 1991](#)), extending some of these notions to the context of global warming. I leverage empirical methods to explore different aspects of the financial valuations of assets and the assessment of financial risks by banks. Similarly to previous literature ([Diether, Malloy, & Scherbina, 2002](#); [Johnson, 2004](#)), I use a dataset of analysts' forecasts, and their disagreement, to proxy uncertainty about the future of fossil fuel firms. I also make use of a novel dataset provided by the European Banking Authority (EBA) to assess differentials in estimates of risk of investments in various sectors by banks in the European Union. The sectoral classification allows me to differentiate among "high carbon" and "low carbon" activities and to test the expected risk of different investments in the net zero carbon transition. Finally, I employ scenario analysis and numerical simulations methods to explore the

uncertainty surrounding different mitigation scenarios (Battiston et al., 2017; Battiston & Martinez-Jaramillo, 2018; Jung, Engle, & Berner, 2021; Monasterolo, 2020; Roncoroni, Battiston, Escobar-Farfán, & Martinez-Jaramillo, 2021; Vermeulen et al., 2021). These methods allow an exploration of some of the outcomes which may be masked by more complex and uncertain socio-economic dynamics in the net zero carbon transition. They also enable a more comprehensive exploration of the financial implications of different possible climate mitigation scenarios on financial risk and the valuations of carbon intensive assets.

In Chapter III, I show that the predominant asset pricing theory that focuses on realised returns as a proxy for expected returns may require a broader appreciation of investors' changing expectations of future cash flows. In the presence of possible structural changes of the system - such as the net zero carbon transition - the effect of risk on future cash flows may become more important (Edmans, 2023). For example, Bolton and Kacperczyk (2021) show that the realised returns of high carbon firms have been higher than their low carbon counterparts. They argue that this is a sign that financial markets are increasingly pricing the risks of a transition to net zero carbon emissions through higher expected returns (*carbon premium*). In contrast, in this paper, I show that the carbon premium may, in part, be a symptom of financial markets not pricing the net zero carbon transition because of the effect of uncertainty on cash flow expectations. Despite ongoing debate in the empirical literature around the presence or absence of a carbon premium (Aswani, Raghunandan, & Rajgopal, 2023) and the identification challenges of isolating climate uncertainty from broader uncertainty, the contribution of this paper is to provide an alternative theoretical interpretation of such phenomenon.

In Chapter IV¹, I show how financial regulations based on risk models (e.g., capital and accounting requirements) may require rethinking in the light of climate change. Risk models utilised by these financial regulations are based on backward looking historical data which may not capture major sources of emergent risks, such as climate change, or

¹This chapter is based on Gasparini, Ives, Carr, Fry, and Beinhocker (2024)

a major transition to net zero carbon emissions. These frameworks, in turn, impact the allocation of resources by financial institutions between “high carbon” and “low carbon” investments, possibly impairing the transition to net zero carbon emissions. In this paper, I find that the global accounting rules set by the International Financial Reporting Standards (IFRS) for the valuation of financial assets (IFRS9) may favor carbon-intensive sectors, potentially discouraging banks from divesting from companies involved in such activities. The mechanism at play is the nexus between the impact of financial regulations on banks’ profitability and the risk assessments required. I show a potential negative correlation between carbon emissions and model-based risk measures used in the accounting framework. This, in turn, may create perverse incentives favoring investments in high carbon activities as opposed to green firms.

In Chapter V, I show that the tools utilised by academics and policymakers to assess climate related risks in the financial system may not allow a sufficient appreciation of the uncertainty surrounding the net zero carbon transition. I argue that the long-term nature of climate change, the non-linearity of the stochastic processes involved, and the complexity of the socio-economic dynamics, may force us to take decisions in absence of a "well-defined" probability distribution. As a consequence, methods on the fringe of financial economics such as decision theory, but also simulations and scenario analysis, might become essential. In this paper, I use such tools to investigate the potential consequences of climate change on financial risk and the inherent uncertainty arising from the unfolding of multiple possible climate mitigation strategies. In doing this, I highlight the high levels of uncertainty that are unaddressed in the literature and the approaches currently applied in practice.

In conclusion, what is so special about climate change that requires its consideration in financial economics research? As I show in Chapter II, financial economists have only began to identify these reasons, including the risks of stranded assets, the impact of climate change hazards on firms’ profitability, changing consumers and investors preferences, and the rise of new collaborative initiatives. In this thesis, I show that climate

change is already having a profound impact on financial markets, including how we value assets, how we assess financial risks and, in turn, how we structure regulations. These are only some aspects of the problem. The impact of our economies on the stability and diversity of our planet's natural systems is no longer marginal at a global scale, and such impacts are, in turn, beginning to influence our economic and financial activity. Understanding these impacts may be essential to empower the financial system on delivering its core functions in the net zero carbon transition.

Part II

Literature Review

The Evolving Academic Field of Climate Finance²

January 2023

Matteo Gasparini, Peter Tufano

Abstract

The urgency and the magnitude of climate change will affect every aspect of our economies, societies and planet. The academic finance research has begun to acknowledge the financial implications of global warming, although a large part of this, still small body of literature, remains outside of the traditional finance domain and conducted by relatively young scholars. In this survey, we explore, quantitatively and qualitatively, the emerging field of climate finance. We discuss its relevance for finance research and teaching and provide some implications for financial economist and practitioners, in particular the incorporation of this massive externality in our approaches to valuation and risk.

JEL Codes: G11, G18, Q51

Keywords: Climate Finance, Financial economics

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Finance and economics provide powerful intellectual frameworks to allocate scarce resources to their highest and best uses in society. The academic field of finance is broad, covering several sectors and institutions (corporations, households, governments, financial institutions, and financial markets). The financial system can be understood in terms of the functions that it performs, including payments risk management; pooling, moving money to the future (investing); moving money from the future (credit); and resolving information asymmetries and moral hazard. We can characterize the field's core principles and beliefs: the time value of money; the law of one price; the trade - off between risk and return; various irrelevance theorems and imperfections that make decisions relevant; game theoretic implications of moral hazard and information asymmetry; behavioral biases; the role of supply and demand in price formation; the substitution of residual (equity value) for broader concepts of enterprise value and social welfare; the calculation of social value as the sum of consumer and producer surplus; and the power of competition to provide optimal resource allocation, to name a few.

Regardless of which perspective one takes - institutional, functional, or intellectual - the climate crisis will affect virtually every sector of the economy and every function of the financial system. It challenges us to adapt the theory and practice of finance to this unprecedented change in the human and planetary condition. Given the post-war priorities of reconstructing Europe and lifting Asia and Africa from poverty, it made sense to leave environmental considerations outside of economic models assuming unlimited resources. But, while in most of human history until World War II the size of the global economy was too small to impact significantly the planet, apart from local impacts, today human activity is so large that it is materially changing our environment which, in turn, will affect societies and economies. Due to this feedback loop, climate and environmental considerations are increasingly becoming an integral element of economics and finance ([Dasgupta, 2021](#)).

There are various estimates of the cost to decarbonize our economies; [McKinsey Global Institute \(2022\)](#) projects that total investment will be USD 9.2 trillion annually, an in-

crease of USD 3.5 trillion over current levels. This figure equals to one half of global corporate profits or one quarter of global tax revenues in 2020. These investments will generate substantial private and social value. For example, [Adrian et al. \(2022\)](#) estimate that the benefits from avoided emissions outweigh the costs of ending coal and replacing it with renewables by around 78 Trillion USD, at present values. This amounts to roughly 1.2% of global GDP per year until 2100. Given the scale of the investments required, and the need to calculate public and private returns, it's no surprise that finance is increasingly focusing on climate. This is true in financial centers around the world, but also in the academic discipline of finance, where Laura Starks, in her 2023 American Finance Association Presidential address, called out the need for greater work in this field.

The purpose of this piece is threefold: First, we seek to explain briefly how the climate emergency we face invites us to refine - and in some cases rethink - our work as finance academics. Second, we briefly review the ever-evolving literature of climate finance, first in quantitative terms and then via a brief summary of various strands of research. Third, we offer our observations on gaps in research and teaching where it is possible to merge a deep knowledge of finance and economics with an evolving appreciation for the systemic nature of the climate crisis. We seek to provide a summary of the collective boundaries of knowledge and to offer suggestions for future work.

1 Why and how does climate matter?

The recent IPCC report lays out the impacts of increasing levels of green-house gas (GHG) concentration into the atmosphere. As of mid-2022, the recorded levels of CO₂, the main GHG, at the Mauna Loa Observatory was 420 parts per million (ppm). In the last 800,000 years until a few decades ago, this number has not been above 300 ppm.

The scientific explanation for this empirical finding and its implications are fairly clear. Throughout the history of the planet, energy from the sun would largely bounce off the Earth's atmosphere. With human-caused increases in the levels of GHG, more of

this energy is trapped and absorbed by the air and transferred to the oceans (and to a lesser degree to the land mass). With deforestation, less of the CO₂ is recaptured through natural means. Warming of the air and seas (global warming) combine to increase sea levels. Sea level rise occurs through the melting of polar ice sheets and through thermal expansion, or the increase in volume of warm water relative to cold water. Warming also leads to higher levels of condensation in the atmosphere, which together lead to changes in atmospheric patterns which amplify weather phenomenon, including massive heat spells, desertification of regions, reduction in rainfall in some areas and extreme rainfall in others. These physical phenomena will disproportionately harm people living in equatorial regions, residents of coastal cities and others, and especially poorer people who will not have the resources to relocate, to pay for conditioned air, switch away from local agriculture, etc.

The IPCC report estimates that human-induced climate change already affects nature and people with more frequent and intense extreme weather events. We have seen irreversible damages to ecosystems requiring significant adaptation efforts. Some 1.9 million animal species and 450,000 plant species have already been lost, half have shifted poleward or to higher altitudes, and 1 million are threatened with extinction. Even if we significantly curb emissions in the coming decades, more than a third of the world's remaining glaciers will melt before the year 2100. Ocean warming has reduced fisheries and food production in some regions leading to malnutrition, while water is increasingly scarce in some parts of the year. Extreme climate has even adversely affected physical and mental health of people, increasing mortality and morbidity, including through the emergence of diseases. We are at risk of triggering irreversible tipping points such as Greenland ice sheet meltdown, West Antarctica ice sheet collapse, Amazon rainforest dieback which will accelerate the rise of temperatures, sea levels, and volatile weather patterns. Without changes in behavior - reducing GHG emissions and finding ways to capture and store GHG - these adverse physical outcomes are more likely, while their timing is less certain.

Actions to mitigate climate risk - which include changes in the way that we produce and use energy, what we eat, how we move from place to place - give rise to other risks, called transition risks. Businesses and investors are increasingly aware of these risks, as they could find themselves owning and managing legacy businesses with little future and stranded assets. They could find themselves facing new taxes or simply less consumer demand as tastes change. But investors are also increasingly concerned with the direct risks arising from a changing climate. More extreme weather events such as hurricanes, floods, or drought-induced wildfires might destroy productive assets. Similarly, chronic global warming might lower the productivity of labor or agricultural production resulting in lower profitability. Corporations and investors are becoming increasingly aware, and concerned, with these climate-related risks.

The science of climate change is broadly accepted, but to date environmental concerns were not central to academic research in finance. More recently, an increasing number of researchers - mostly younger scholars - are working on climate related finance topics. We have compiled a fairly exhaustive database of around 500 working and published papers in the field of climate finance that we characterize to understand the trajectory and contours of the field. In addition, we augment our understanding of the current state of academic work in climate finance with data from the programs of two of the field's leading conferences: the American Finance Association (AFA) and the European Finance Association (EFA) since 2005, and publications of climate finance papers in the top three finance journals (Journal of Finance, Journal of Financial Economics and Review of Financial Studies

By any measure climate finance is a new field. Our database of 500 papers can be put into context by comparing it with another “new” field in academic finance: household finance. While the comparison is not exact, SSRN's Household Finance e-journal has had over 11,000 submissions over the past decade. In another marker, we were not aware of a doctoral course in climate finance until a 2023 offering³. In the next section we provide

³In full disclosure, the authors are part of the multi-school teaching team for the Global Doctoral Course, the Financial Economics of Climate and Sustainability.

data on the recent research on climate finance. The encouraging signs are that research on climate and finance is increasing, in a global, inclusive and young fashion.

2 Quantitative review of research on climate finance

The boundaries of “climate finance” are still porous. In their comprehensive survey on climate finance, [Giglio et al. \(2021\)](#) focus on the covariance properties of asset payoffs with climate change as a systematic risk factor, and therefore they emphasize the link between climate and macro-economic risks and asset prices. In their introductory piece to the RFS special issue on climate finance, [Hong et al. \(2020\)](#) offer a broader definition: “Climate finance is the study of local and global financing of public and private investment that seeks to support mitigation of and adaptation to climate change.” We adopt this latter broader definition, expanding it to include households and to include the financial implications of climate change as well as the financing to support the necessary investment⁴.

To get a sense of the range and depth of climate research and its increasing relevance, we collected over 500 published and working papers and analyzed them in terms of content, authorship, and outlet. To identify the sample, we systematically screened major research repositories with keywords, and then traced the network of citations to find the most extensive list of papers possible. The research repositories included widely-used academic search engines (e.g., Scopus, Web of Science, Google Scholar) and working paper repositories (e.g., SSRN). We examined the bibliography of each paper, tracing earlier climate finance studies that we may have missed in our search. In addition, we looked at the most important conferences in this area in the past 5 years as well as the papers presented in the main Finance conferences in the past 15 years. Our database includes information on journal impact factors, number of citations, author affiliations, region of authors affiliations, type of research organisation, etc. This allows us to create a map of

⁴For this review, we exclude broad work on Environmental, Social and Governance (ESG) metrics.

the main branches of this literature and classify it according to different dimensions that could shed light on the emerging strands as well as summarise the landscape of this field. We do not claim to have captured all papers in this space but believe the sample to be sufficiently comprehensive and representative as of mid-2022. In order to roughly capture the boundaries of academic work in climate finance (vs. work by and for practitioners), our survey does not generally include reports by consulting firms, banks or financial institutions, except to the extent that they appear in journals, working paper series, or SSRN.

Time and geographical perspective

Our first observation is that the literature on climate finance is *growing*. Figure 1 shows the number of identifiable papers in our sample. Prior to 2018, there were fewer than 20 papers produced annually, but by full year 2021, this figure had grown eight-fold to more than 160 papers produced in that year. The number of published papers has followed the trend, reflecting the increasing acceptance of climate finance as a “legitimate” topic of study. While this work is conducted globally, there has been historically more activity by academics in *European institutions* than elsewhere, although this is changing. The share of papers from European-based scholars (in terms of first author) were around 80% in 2017 and 2018, but by 2021 this number decreased to 65%, with the difference mostly emerging from scholars in the US. But the relative figures mask the growing number of papers from US authors in absolute terms which increased from less than 10 before 2018 to more than 30 in 2021, in our sample. The interest in climate finance has also grown in other countries, and in supranational organisations (e.g., IMF, World Bank). Interestingly, we find little international cooperation, with fewer than 10% of papers with a European- or American - based first author having second author in a different region.

The growing interest of traditional finance in climate change is also highlighted by the increasing presence of climate finance papers in the two major annual academic finance

conferences organised by the European Finance Association (EFA) and the American Finance Association (AFA). Before 2019 less than 2 papers were discussed in each conference, but this figure increased to 10 and 4 in the EFA and AFA conferences respectively in 2021 (Figure 5). Similarly, in the top three finance journals - Journal of Financial Economics (JFE), Journal of Finance (JF) and The Review of Financial Studies (RFS) - less than 4 papers were published before 2019, but this number increased to 9 in 2020 and 2021 (See Figure 6).

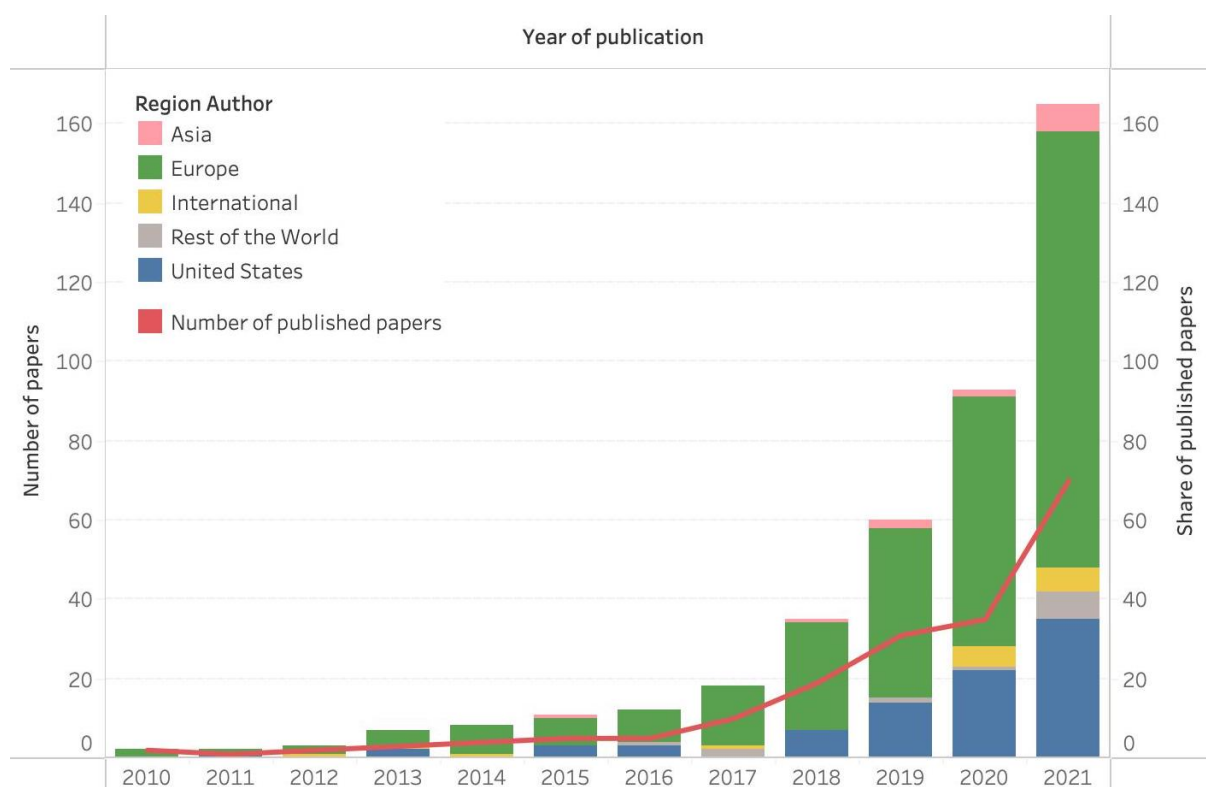


Figure 1: The bars represent the number of published and unpublished papers by year by region of first author. Red line represents the number of published papers as of mid-2022.

Institutional and authors and perspective

While academics are the primary authors of climate finance research, *non-academic institutions* are also important contributors, especially in the financial intermediation branch. In the financial intermediation space, one-fifth of the work comes from central banks,

supervisors and other research organisations. Non-academic research mostly focuses on topics regarding financial regulation and supervision, but also investigates policies for fostering the green transition. In figure 2, we show the number of published papers and working papers or reports by type of organisation, branch and region. The chart also shows that a large part of this research might be published in academic journals in the future being currently working paper or resides outside of traditional academic outlets in the form of policy or industry reports.

This nascent field seems to especially attract *younger researchers*, as also reported by [Hong et al. \(2020\)](#) in their characterization of submissions to a special issue on climate finance by the Review of Financial Studies. In table 1, we show that more than 70% of papers in our sample are from academics below the level of Full Professor. The largest share of papers in our sample is from authors in an early research career position and about 9% PhD students. However, senior academics are increasing finding these issues of relevance. In 2020 and 2021 we find that the absolute number of publications from academics at Professor level has increased.

Author	Percentage of papers
PhD Student	9%
Early career researcher (incl. post doc)	35%
Assistant professor	9%
Associate professor	17%
Professor	30%

Table 1: The table reports the share of published and unpublished papers by author seniority.

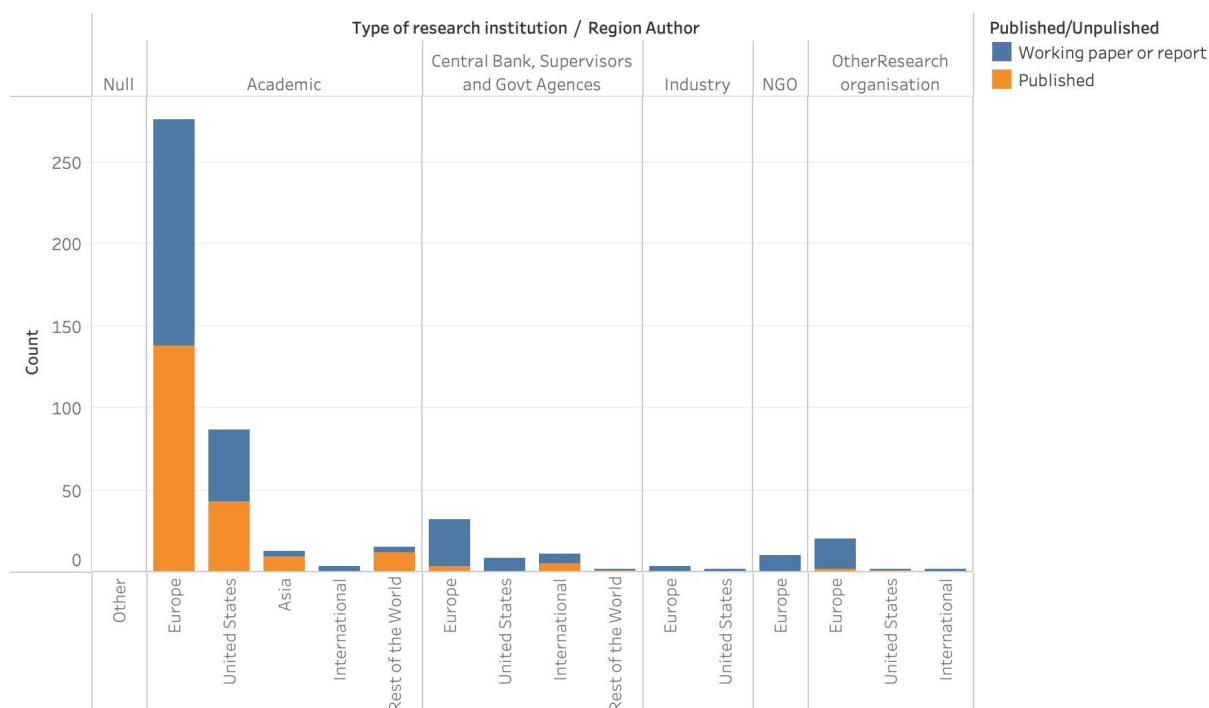


Figure 2: Number of published working papers or reports by type of institution and geography

Disciplines and Journals perspective

The climate finance literature is increasingly published in finance journals, but also in *other outlets*. Prior 2018, the three top Finance journals (Journal of Finance, Journal of Financial Economics and The Review of Financial Studies) published very few climate finance papers, but after this date there were almost a total of 10 published papers every year in our sample. The bulk of this literature prior 2018 was published in journals outside of finance, and still today a large share of this literature is published in non-finance journals. In particular, leading outlets are academic journals that focus on climate and sustainability issues such as Nature Climate Change, Ecological Economics, the Journal of Environmental Economics and Management (JEEM) and others (see Figure 3). The breadth of journals highlights the diversity of disciplines and methods used in this research, which oftentimes span beyond traditional finance. However we note that the citations/paper of publications in the top finance journals is substantial.

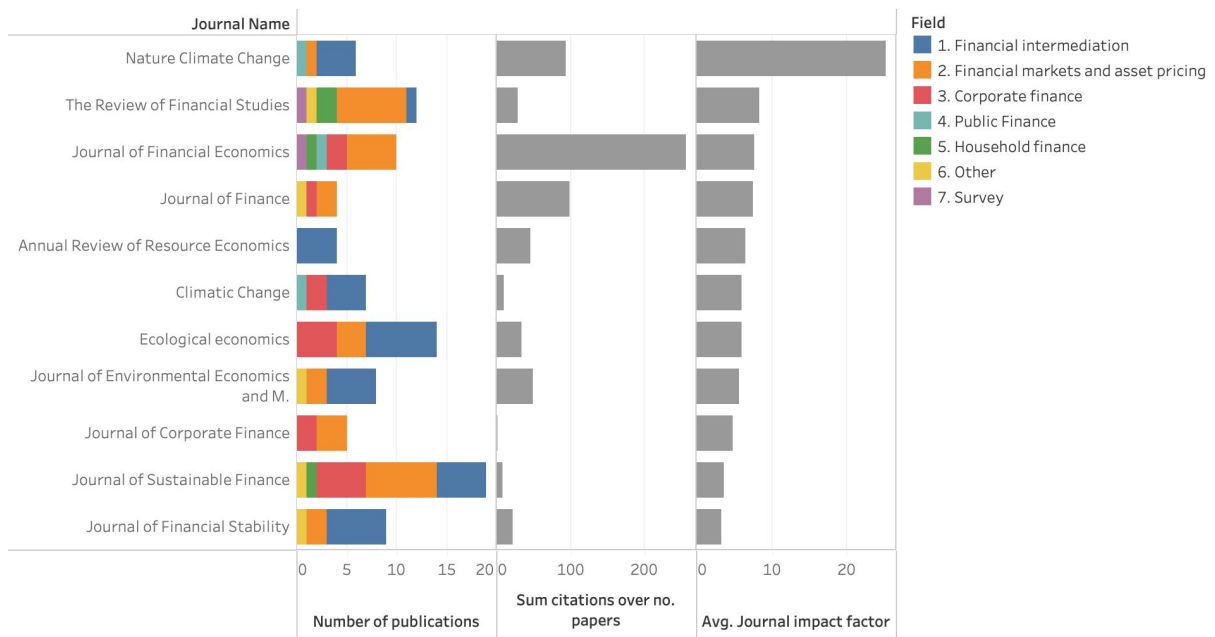


Figure 3: The figure shows the number of publications by journal, the ratio of the sum of citations and the number of papers in each journal and the journal latest impact factor. Published papers between 2010 and 2022. Journals ranked by 2021 impact factor.

Topics

In terms of issues discussed, there are *two larger clusters of work*, broadly in (a) financial intermediation and investment banking; and (b) financial markets and asset pricing. There are smaller segments of work in corporate and household finance. We hand-coded the primary topics of each paper and, in figure 4, we show the breakdown of the work. Around 38% of the papers are on financial intermediation and around 30% on financial markets. Fewer papers are focused on corporate finance, public finance or household finance topics.

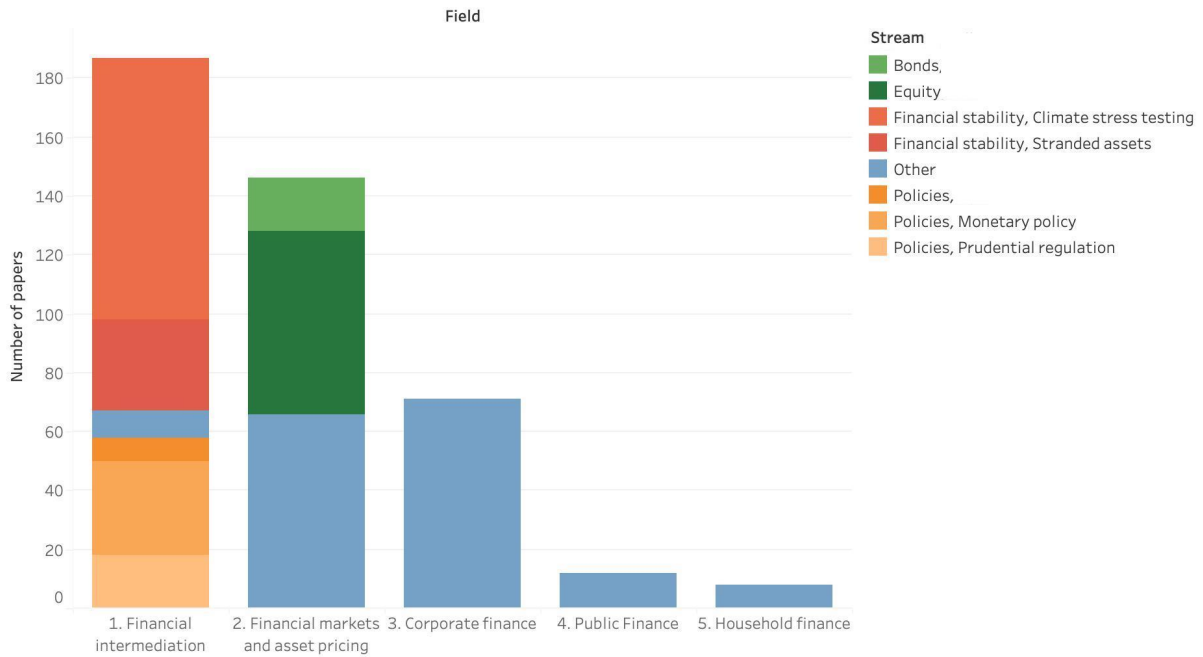


Figure 4: The figure shows the share of the climate finance literature interest in different issues broken down from an institutional perspective. All published and unpublished paper from 2010 to 2022.

There is an identifiable European/US tilt to the work, with the former more likely to work on intermediation topics and the latter to work on financial markets. The financial intermediation work is further divided in two streams discussing financial policies for supporting the low carbon transition through the financial system (e.g., green prudential regulation, green monetary policy) and assessing the impacts of climate change on financial stability. The latter stream mostly involves climate stress testing or discussions around the impact of climate change on the financial system. The branch of literature on financial markets largely focuses on asset pricing in the context of climate change. It covers a vast array of asset classes, but also investigates how markets react to climate events, how changing investors' expectations affect stock prices, and how climate risks can be hedged.

We will use the institutional view reported in our quantitative review of the climate finance literature to frame a selection of some of papers in this space. We highlight the diversity of topics and methods as well as the increasing relevance of these issues for

academic finance.

3 A selected review of climate finance research

There are many excellent surveys of the climate finance literature, including [Giglio et al. \(2021\)](#); [Hong et al. \(2020\)](#), to which the reader is directed. In this selective review of the major streams we categorize above, we touch on points relevant to academics, but also to practitioners and policy-makers. The papers we discuss cover themes that have been highlighted by previous surveys of financial economists, policy makers, and investors (e.g., [Stroebel and Wurgler \(2021\)](#)), in particular three key aspects: *i.* that markets might under-estimate climate related risks, especially long-term physical risks *ii.* environmental policy risk might be one of the main concerns of investors, and *iii.* Increasingly for institutional investors and corporations, pro-environmental behaviours might be a drivers of change.

Financial intermediation and investment banking

A first strand of climate finance literature focuses on the exposure of the financial system to climate-related risks and the potential repercussions on economies and societies. Climate change risks are classified as transition or physical risks. Transition risks are “the financial risks which could result from the process of adjustment towards a lower-carbon economy. Changes in policy, technology and physical risks could prompt a reassessment of the value of a large range of assets as costs and opportunities become apparent.” Physical risks are “the impacts today on insurance liabilities and the value of financial assets that arise from climate- and weather-related events, such as floods and storms that damage property or disrupt trade” . Increasing evidence shows that financial institutions might be susceptible to abrupt climate shocks, either from physical or transition risks⁵. This literature also examines how the financial system might be an enabler of the ecological transition required to prevent global warming through policies by central banks and

⁵The tragedy of the horizon, Mark Carney

financial supervisors.

Caldecott, Clark, Koskelo, Mulholland, and Hickey (2021) discuss the concept of *stranded assets* in the context of climate change, defined as “assets that have suffered from unanticipated or premature write-downs, devaluations, or conversion to liabilities”. They discuss the transmission channels of climate related risks and the possible effects on societies, economies, and the financial system. They also review the growing central banks and supervisors’ responses, including climate disclosure and stress testing⁶.

Jung et al. (2021) develop a *climate stress testing* methodology to assess the resilience of the financial system. They estimate the exposure of financial institutions (beta) to a stranded asset portfolio and calculate an expected capital shortfall conditional to a stressed climate scenario (provided by the Network for Greening the Financial System). They find that some banks might be particularly exposed to these risks and argue that climate change might be a systemic risk for the financial system⁷.

This issue has also drawn a growing interest from disciplines outside of traditional finance. Battiston et al. (2017) use *complexity economics* methods, such as network analysis, to extend climate stress testing to the possible contagion effects among interconnected financial institutions. They use granular information about European Union (EU) banks, investment firms and pension funds to calibrate their model. They also provide a novel sectorial classification of economic activities sensitive to climate related risks (Climate policy relevant sectors). They find that the EU financial system could be exposed to climate related risks, but also that the indirect losses arising from overlapping exposures might magnify these effects⁸.

The changing attitude of the financial system towards climate change might also lead to a re-orientation of financial flows which might affect the real economy. Similarly, financial regulation might be a tool to address carbon externalities. Oehmke and Opp (2022)

⁶Other similar literature (Monasterolo, 2020; Van der Ploeg & Rezai, 2020)

⁷Some studies from regulators and financial supervisors are Bolton, Despres, Pereira da Silva, Svartzman, and Samama (2020); Dunz, Naqvi, and Monasterolo (2021)

⁸Other similar literature: Battiston, Monasterolo, Riahi, and Van Ruijven (2021); Dietz, Bowen, Dixon, and Gradwell (2016); Monasterolo, Roventini, and Foxon (2019); Vermeulen et al. (2021)

discuss whether a financial regulator with a broader mandate might prevent financial instability and foster the green transition through differentiated capital requirements. In particular, they discuss about a *green supporting factor* (lower capital requirements for green loans) and a *brown penalising factor* (higher capital requirements for polluting loans). They make use of a model of banking capital requirements regulation and a policy maker with a broader mandate to address global warming. They find that these tools might be effective in preserving the stability of the financial system (or externalities that manifest inside the financial system), but they have little ability to foster green investments, addressing the global warming externality (or externalities that manifest outside the financial system).

Papoutsis et al. (2021) discuss these issues through the lenses of monetary policy. In their empirical analysis they find that the ECB corporate purchase program favours firms with high GHG emissions because of the structure of the bond market and the methodology used by the ECB for maintaining its objective of market neutrality. They argue that monetary policy is inherently biased towards green or brown firms, but a central bank can construct a portfolio which minimises climate related risks, increasing risk premia for polluting firms. In this regard, they argue, *green monetary policy* initiatives discussed in related literature might seem less unconventional than initially thought, as the central bank has nevertheless to take a stance on the environmental risks of its holdings⁹. However, Hansen (2021) argues that although the independence of central banks might seem appealing for fighting climate change, this could lead to dangers such as harming reputation and hampering independence of central banks, but also distract attention from implementing first-best environmental policies such as carbon taxation.

Financial markets and asset pricing

A second large part of the financial economics literature on climate change discusses empirical and theoretical issues about the pricing of climate related risks in financial

⁹Other similar literature includes Campiglio (2018); Campiglio and Van der Ploeg (2022); Dafermos, Nikolaidi, and Galanis (2018); Monasterolo (2020)

markets. This literature investigates whether these risks are priced in equity markets, but also in other asset classes such as bonds, options, real estate using various methods and providing different theories underlying the rationale of climate risk pricing.

Bolton and Kacperczyk (2023) investigate whether financial markets price climate related risks by looking at the cross section of stock returns and firms carbon emissions. They consider all three scopes of carbon emissions (as defined by the GHG protocol) and three variables: the total level of emissions, the year-on-year change and the emission intensity (defined as carbon emissions over sales). They find a statistically significant *carbon premium* related to the absolute level in carbon emissions. They also find a relationship with the year year-on-year change in emissions, but not with the emission intensity. They argue that financial markets are pricing the risk of higher CO2 emissions, not only in industries targeted by investors divestment (e.g., fossil fuels)¹⁰.

Hsu et al. (2022) theorise the causes of an environmental pollution premium. They first show empirically that a portfolio short of firms with high toxic emissions intensity and long of firms with low toxic emissions intensity (high-minus-low) yields statistically significantly positive returns. They then construct a general equilibrium model where future firms' profits depend on a regime shift in environmental regulation. They assume that if the policy maker tightens environmental regulation the profitability of firms with high toxic emissions intensity declines more than low toxic emissions. They argue that the environmental pollution premium might be explained by firms' exposure to an environmental policy uncertainty and the *policy regime shift risk*.

In contrast, Pástor, Stambaugh, and Taylor (2021) theorise that investors hold green stocks not only because they seek to hedge climate related risks, but also for *non-pecuniary motives* (i.e., preferences for positive environmental impact). They discuss this result in a CAPM framework with a three funds separation: a risk-free asset, a market portfolio and an "ESG" portfolio. Investors with strong preferences for green assets deviate from the market portfolio and tilt their investments towards the "ESG" portfolio. In a CAPM

¹⁰Other literature in this space includes Ilhan et al. (2021); Ramelli, Wagner, Zeckhauser, and Ziegler (2021); Wagner, Zeckhauser, and Ziegler (2018)

framework, green (brown) stocks have negative (positive) alpha, but green (brown) stocks have also a positive (negative) exposure (beta) to an “ESG factor”. A strengthening of ESG concerns leads to green stocks outperforming brown stocks. However, they argue that in equilibrium green assets show lower expected returns than brown ones, but, if ESG concerns change unexpectedly, green assets might show *greater realised returns* than brown ones. In [Pástor et al. \(2022\)](#) they test empirically their theoretical predictions constructing a Green-Minus-Brown portfolio which explains the recent outperformance of green stocks in US stock markets¹¹.

Investors environmental preferences might appear more clearly in the green bonds markets. [Baker et al. \(2022\)](#) provides a review of US green municipal bonds and find that they show a *premium* compared to similar traditional bonds, yielding 5 to 9bp difference. They theorise that investors non-pecuniary preferences are the underlying driver of the green premium. They also argue that green bonds tend to have more concentrated ownership. In contrast, [Flammer \(2021\)](#) does not find that corporate green bonds trade at a premium compared to traditional bonds. She argues that investors are not willing to sacrifice returns for positive social outcomes, but that firms issue green bonds to signal credible environmental commitments. In an event study, she finds that stock prices respond positively to green bond issues with statistically significant cumulative abnormal returns following the announcement. Firms also improve their environmental score after the issuance.

A related issue discussed in this literature is hedging. Due to the increasing climate related risks, investors may wish to hedge against such negative outcomes. [Engle et al. \(2020\)](#) construct a dynamic hedging portfolio against news about climate change. They use textual analysis of newspapers climate news to develop a *climate news index*. They use it to construct a “mimicking” portfolio that is negatively exposed to the index and shows positive returns following negative innovations in the index. [Alekseev, Giglio, Maingi, Selgrad, and Stroebel \(2021\)](#) expands some of these concepts introducing a quantity-based

¹¹Other literature in this space includes [Pedersen, Fitzgibbons, and Pomorski \(2021\)](#); [Riedl and Smeets \(2017\)](#); [Zerbib \(2022\)](#)

approach for mutual funds.

One of the peculiar features of climate change is its high *uncertainty*, especially about future physical damages. [Barnett, Brock, and Hansen \(2020\)](#) apply decision theory and asset pricing methods to investigate optimal climate policy under uncertainty about future damages induced by global warming. They use the social cost of carbon to explore the sensitivity to three components of uncertainty: risk (uncertainty within the model), ambiguity (uncertainty across the models) and misspecification. They show that the social cost of carbon increases if uncertainty is accounted for by an ambiguity-averse policy maker¹².

Future and present risk of extreme weather events damages might also be material for assets valuations. [Hong, Li, and Xu \(2019\)](#) investigate whether stock markets *efficiently* discount such risks focusing on drought and food stocks. They use an index which measures drought intensity and rank different countries in quintiles depending on their vulnerability to drought. They investigate whether a portfolio sorting between the countries in the top and bottom quintile of vulnerability generates excess returns. They find that the drought vulnerability ranking forecast excess returns suggesting that financial markets underreact to climate related risks. They argue the predictability of excess returns is a sign of market inefficiency in pricing the increasing risks brought by global warming¹³.

Corporate finance and institutional investors

Corporates and investors, including institutional investors, are paying increasing attention to climate change. They are increasingly aware of the risks arising from either transition to net zero emissions or from global warming. Institutional investors increasingly engage with firms to consider climate related risks and generally support, together with regulators, broader climate-related disclosure. This literature oftentimes leverages surveys of

¹²Other literature discussing similar issues is [Ackerman \(2019\)](#); [Daniel, Litterman, and Wagner \(2019\)](#); [Lemoine \(2021\)](#); [Weitzman \(2011\)](#)

¹³Similar literature in this space is [Alok, Kumar, and Wermers \(2020\)](#); [Bansal, Kiku, and Ochoa \(2016\)](#); [Choi, Gao, and Jiang \(2020\)](#); [Schlenker and Taylor \(2021\)](#)

corporate management and institutional investors, but also uses novel approaches such as natural language processing.

[Sautner et al. \(2023\)](#) discuss how corporate management and investors are increasingly concerned about climate change. They use machine learning methods and *earnings calls* transcripts to construct an index about the share of discussion focused a set of keywords related to climate change, as a proxy of firms' exposure to climate related risks. They find that the utility sector is the most exposed in terms of risks, and opportunities, but also other sectors are exposed such as transportation and construction. They argue that their measure predicts real outcomes such as green patenting and green tech growth¹⁴.

Institutional investors are particularly concerned with climate change risks. [Krueger, Sautner, and Starks \(2020\)](#) survey *institutional investors* in order to understand whether they consider climate related risks in their investment process. They find that, although climate related risks are ranked after more traditional risks, investors deem them material, with 40% of respondents reporting expectations of temperature increasing above the Paris alignment target of 2°C. The survey also highlights that uncertainty is the greatest challenge to managing climate related risks and most respondents having developed management tools such as portfolio carbon footprint and scenario analysis. Most investors also preferred to engage with the firms they hold rather than divest¹⁵.

Investors are also increasingly demanding greater climate related disclosure. [Ilhan, Krueger, Sautner, and Starks \(2022\)](#) document in a survey that a large share of institutional investors considers *climate disclosure* important and that more disclosure is required. 79% of investors deems it as important as traditional financial disclosure and one-third more important. They also use data of firm's ownership and disclosure from the Carbon Disclosure Project (CDP) to test the relationship between firms' owners and climate disclosure. They find that firms report more about climate if investors are in

¹⁴[Addoum, Ng, and Ortiz-Bobea \(2020\)](#); [Barker and Eccles \(2018\)](#); [Bartram, Hou, and Kim \(2022\)](#) discuss the real effects of climate change on corporates

¹⁵Similar literature on these issues: [Bauer, Ruof, and Smeets \(2021\)](#); [Broccardo, Hart, and Zingales \(2022\)](#); [Dyck, Lins, Roth, and Wagner \(2019\)](#); [Gantchev and Giannetti \(2021\)](#); [Hartzmark and Sussman \(2019\)](#)

countries that require a stewardship code, in countries that have more environmental norms, and if held by universal owners.

Corporate disclosures and promised actions to combat climate change might be questionable. [Bingler, Kraus, Leippold, and Webersinke \(2022\)](#) use machine learning methods to assess firms' TCFD climate disclosure. They find a small increase in the information disclosed by firms after the launch of TCFD recommendations arguing that most of the ambition of greater disclosure have not always matched the facts of more information. [Dai, Duan, Liang, and Ng \(2021\)](#) find that firms *outsource* part of their emissions in order to achieve their domestic objectives, exploiting foreign supply chains to artificially reduce their emissions rather than truly decarbonizing.

Corporations are also increasingly setting *net zero carbon emissions targets*. [Bolton and Kacperczyk \(2022\)](#) discuss the increasing commitments by firms to reduce their emissions in line with the Paris Agreement objectives. Oftentimes these pledges are taken as part of climate alliances or broader forms of cooperation that are increasingly becoming prominent in this space such as the Science Based Target Initiative (SBTi). However, the authors find that so far only the better positioned companies joined these initiatives, as opposed to companies with hard-to-abate emissions. Similarly to climate disclosure and emissions outsourcing, corporates are not always genuinely interested in climate change, but might greenwash their activities in order to try to mitigate the risks emerging from changing investors and consumers tastes.

Household finance

The effects of global warming can go beyond corporate and investors. [Choi et al. \(2020\)](#) examine whether the salience of global warming affects retail investors' beliefs, and in turn stock market prices. They find that people search keywords related to global warming on Google more frequently when their city is impacted by abnormally higher temperatures. They also find that in such periods, firms listed in the local stock exchange and more exposed to a transition to net zero emissions display lower returns. They use stock

ownership data to argue that *retail investors* are the ones reacting to higher temperature rather than institutional investors, which do not sell systematically stocks in warmer periods.

Financial and *climate literacy* might also affect investments in green stocks. [Anderson and Robinson \(2021\)](#) investigate if households' environmental values impact their investment choice. In a survey of Swedish households' pro-environmental values and their pension plan decisions, they find that people with strong environmental values are not more likely to hold green stocks, although people more financially literate are likely to hold ESG label funds. They argue this is because people more environmental engaged are less likely to be interested in investment decisions and that the complexity of determining whether an investment is green or not prevents people to invest in green assets.

Nevertheless, households could be greatly impacted by growing frequency and magnitude and climate disasters. [Baldauf, Garlappi, and Yannelis \(2020\)](#) assess whether expectations about future climate change impact current valuations of *residential real estate* assets. They use granular data about future climate damages, populations beliefs about climate change and house prices. They find that dwellings in areas with strong climate “believers” and projected to be “underwater” show statistically lower prices, as opposed to areas with climate “deniers”. However, in general, [Bernstein, Gustafson, and Lewis \(2019\)](#); [Murfin and Spiegel \(2020\)](#) do not find differences in the prices of houses projected to be impacted by sea level rise.

4 What are the implications for thought leadership?

Financial economists have long been pioneers in advancing powerful concepts: irrelevance theorems that sharpen our understanding of the factors that affect valuation; principle-based valuation models, such as the capital asset pricing model; or engineering-based valuation models, including option pricing models. We have popularized these concepts by teaching them for the past half century, so that every MBA will recognize the acronyms

DCF, WACC, M&M, and CAPM. As we sit in the first half of the so-called decisive decade, where we are likely to exceed the planet's maximum carbon budget to contain global warming to 1.5°C, what concepts and tools do we need to develop and socialize in our finance research and curricula? We suggest six directions to consider:

- Make externalities visible through disclosure
- Value externalities - alongside of traditional financial valuation approaches
- Develop a heightened appreciation for a wider range of risks and uncertainty
- Consider the implications for work-horse economic and finance models and approaches
- Conduct timely and independent research on emissions incentives, promises, and actions
- Acknowledge the limitations of fundamental frameworks in the fact of massive and profound externalities

Make externalities visible through disclosure

The first two recommendations begin with the recognition of the scale of the externalities that are producing profound climate change impacts on economies, societies, and the planet. A first recommendation is to make externalities visible by measuring and disclosing GHG emissions of nations, firms, plants, and households. While recognizing that disclosure may be imperfect and costly, financial economists should call for complete disclosure of GHG emissions - and through their research, recommend better ways to collect, disclose, and report this data. For example, financial economists are helping to sharpen GHG reporting protocols by considering how to attribute emissions to firms and products. Without adequate data on emissions, we will not be able to conduct meaningful research - nor create management systems, incentives or rules to drive new behavior.

Value the externalities - alongside of traditional valuation approaches

Over the past decades, financial economists have developed and popularized various approaches to value firms and projects. DCF valuation of private costs and benefits is core to most finance courses. We generally do not teach students how to calculate the social implications of private projects. Given the enormous scale of the externalities imposed by GHG emissions, a first step would be to teach students to routinely calculate GHG emissions of firms and projects, apply the social cost of carbon (SCC) to these emissions, and calculate the firms' or projects' climate change impacts. This process would have many benefits, including: (a) creating a ready use for emissions disclosures; (b) sensitizing students to the social implications of private wealth creation; (c) encouraging scrutiny of social cost of carbon estimates; (d) putting social costs on the same footing as private benefits; and (e) permitting consideration of not only future but also past externalities. A more elaborate approach would be to include not only GHG externalities, but also other externalities and impacts, as proposed by the Impact Weighted Accounts (IWA) approach.

We will need to help students develop judgment to carefully model these social costs. On GHG emissions, do we consider direct (scope 1) or indirect (scopes 2 and 3) emissions? What is avoidable if the project were not to go ahead? There are a variety of SCC estimates depending on which outcomes we include, the geographic boundaries of the externalities considered, and the discount rate we employ. These rich and substantive discussions parallel those around estimating cash flows and discount rates. By simply making the externalities regularly visible - in every case study, every valuation, every homework assignment, every exam - students will be forced to confront the planetary implications of corporate decisions. Systemically measuring externalities also helps students prepare for when/if carbon taxes are imposed or firms systemically include the cost of carbon in their managerial accounting analyses.

The calculus of climate change is a recognition that the social risk from GHG emissions

is increasingly likely to lead to water shortages for up to 2 billion people, sea level rise that would inundate coastal regions and most of the world's cities, and extinction of many of the world's species. Elinor Ostrom's powerful notion of the tragedy of the commons will become an increasingly core element of our work. As we model the consequences, social discount rates will increasingly play a prominent role in our work. Put another way, our unit of analyses will have to not only consider individuals or organizations, but our social and planetary systems as well, melding our considerations of public and private welfare.

Develop a heightened appreciation for a wider range of risks and uncertainty

Finance centers around considerations of risk and return. Modern finance theory, through the notion of diversification, has focused primarily on non-diversifiable or systemic risk as the primary driver of returns and prices. While this remains a powerful concept, climate related risks force us to ask which risks are systemic, to whom and when.

The impending climate crisis will surely increase the amount of risk and uncertainty we face, both individually and collectively. Risks include not only traditional technological, competitive and market risks, but also transition risks, physical risks, reputational risks, and litigation risks. Recent research and polls of market participants suggest that the range of climate risks may not yet be fully baked into prices and valuations ([Stroebel and Wurgler \(2021\)](#)). Hedging and risk management approaches are in their infancy. A GARP survey of financial institutions shows that, although most firms recognize climate risks, climate risk management is still in its early stages of development ([GARP, 2022](#)).

Economists have long differentiated measurable risk from unmeasurable uncertainty - and many of the outcomes of climate change fall into the latter category. While the IPCC reports put probability weights on various outcomes, these weights are conditional on scenario-based pathways. A broader consideration of risk must become in-scope for finance researchers, or we will risk becoming increasingly irrelevant.

Systematically work through implications for work-horse models

The models we use and teach in finance are the product of decades of refinement, and this long-term familiarity may give us an unwarranted sense of comfort. Yet, climate change should make us far less comfortable with many of these models - and research is beginning to explore how we may need to adjust our business-as-usual approaches. We not only need to help make clearer the impact of corporate decisions on the planet, but also the impact of planetary or policy choices on firms in the form of physical and transition risks.

- Standard DCF approaches often use “terminal values” which assume well-behaved cashflows into the future. However, physical and transition risks may generate very poorly behaved futures, e.g., stranded assets, possibilities of substantial carbon prohibitions and taxes. For example, with stranded assets, terminal values may simply fail to materialize or become negative if there are remediation requirements. In some of the more extreme cases, long-dated investments may simply disappear if the economic bases of activity are fundamentally altered. For example, if we had to limit global warming to 1.5C by 2050 around 60% of oil and gas and 90% of coal could remain in the ground ([Welsby, Price, Pye, & Ekins, 2021](#)). Different estimates vary, but the magnitude will be large. Mark Carney has dubbed this the “tragedy of the horizon.”
- Standard valuation approaches look at expected values, but climate change forces us to consider a broader range and variety of outcomes. The finance toolkit must be expanded so that students and professionals are more comfortable with and conversant with scenario-based analysis. Climate science and models are primarily based on various transition paths or scenarios (e.g., consistent with temperature rises of 1.5° or 2.0° C degree post-industrial age). Long horizon analyses of firms and projects - as well as some short-horizon analyses - need students to master scenario-based modelling.

- Most standard macro-economic models do not consider climate-change impacts, unlike Integrated Assessment Models. We are generally also much more familiar with equilibrium outcomes, whereas planetary models are more likely to generate disequilibrium outcomes, especially if we trigger tipping points. The likelihood of less-rosy disequilibrium outcomes - moving us past dangerous tipping points - is rising. The implication of this, for economic models, is a recognition of the need to model scenarios, rather than expected outcomes; to think in terms of multimodal distributions vs well behaved distributions; to consider tipping points, perhaps in the form of jumps, more commonly. In general, we may lose some of the elegance and analytic simplicity of existing models as we are forced to adopt more computationally-complicated models that link economic outcomes and planetary outcomes more closely.

Conduct timely and independent work on emissions incentives, promises, and actions

While many listed firms have made some sort of Net Zero promise, MSCI - hardly an environmental activist group - estimates that the world's listed companies are on track to contribute emissions consistent with a 2.9 warming outcome¹⁶. Academics can provide independent evidence-based research on the activities of firms - including tracking emissions promises vs. actions. Are reported emissions falling? If so, are they truly reduced or merely shifted up the supply chain or sold to less-public owners? There are a plethora of solutions suggested - from taxes, positive incentives for emissions reduction, outright bans and prohibitions, financial pressure, public pressure, collaboration by industry groups. What is the evidence - in the long and short run - about the effectiveness of these approaches?

¹⁶<https://www.msci.com/zh/research-and-insights/net-zero-tracker>

Acknowledge the limitations of our fundamental economic frameworks in the face of massive and profound externalities

The First and Second Welfare Theorems hold that competitive equilibria can produce pareto-optimal outcomes - assuming full information, no externalities, and complete markets; and with appropriate redistribution. Yet, climate change induced externalities are profound; markets are incomplete in that future claims relating to these externalities are not traded; and the distribution of harm is so uneven that welfare redistribution is unlikely.

We believe in the power of competitive equilibria. While competition has been a powerful force - and while monopolies and concentration of power more problematic, we may need to re-consider the conditions under which collaboration among firms - to set standards, jointly commit to socially beneficial actions, to jointly stimulate demand for new climate solutions - may be optimal.

A touchstone of modern economics is the consideration of marginal impacts. However, because of the scale of climate-related investments required, we will need to consider aggregate impacts as well as incremental impacts. Although there is disagreement among different studies, the scale of investment required to mitigate climate risk is significant, potentially up to around 4% of GDP per year ([McCollum et al., 2018](#)). These investments may require reductions in other spending and will have macro-economic and macro-social impacts. In effect, micro- and macro- analyses will blend uneasily together. Considering the marginal impact of a non-marginal investment might lead to biased appraisals of projects with qualitative and quantitative errors ([Dietz & Hepburn, 2013](#)). For example, the IMF estimated that the scale of the clean energy transition might significantly change relative prices of certain commodities such as copper, cobalt, lithium, nickel. These effects are not generally considered in marginal cost-benefit analysis.

A bedrock of modern finance is the time value of money: generally cash flows received in the future are worth less than cash flows today. This normal reasoning would value future lives - our grandchildren and beyond - as less valuable than us, which is a

deeply morally fraught question. The question of whether species other than humans or biodiversity have “value” is not easily reconciled with financial models. Since the early days of environmental economics this has been a controversial topic, but finance has not been able to respond with traditional frameworks (Nordhaus, 2007). More recently, the question of whether lives in different countries should be valued differently has become more prominent, as the US government’s social cost of calculations use an economic-value approach ¹⁷. These modeling approaches have significant repercussions on our societies.

This is not a call to abandon centuries of careful economic analysis, but rather to modernize core economic theory with consideration of the profound implications of the externalities we face. The growing field of climate finance - and the growing cadre of researchers who are sensitive to these issues - is a cause for optimism and hope. One of the most powerful levers for social change is to alter the way that people think and the paradigms they hold. The new perspectives which climate change forces us to consider may create new ideas to spur action (Meadows, 2008).

5 Conclusion

As we noted earlier, McKinsey estimated that globally, we will need to spend USD 9.2 trillion annually to decarbonize our economies, an amount equal to half of global profits or a quarter of global tax receipts. Other work shows that these investments will produce positive economics returns, even beyond the harder-to-quantify planetary benefits. These investments - and many more to adapt to the climate crisis - will involve virtually every financial decision maker: policy makers, corporations, and households. The neat dividing lines between public finance, corporate finance, and household finance will get blurred because the causes and consequences of investing revolve around a huge externality that has to date largely been ignored in financial calculations.

One of the core elements of academic finance over the past decades has been to refine

¹⁷The tricky business of putting a dollar value on a human life

our metrics for investment analysis, help us think more deeply about risk and return, and teach this material to students and practitioners around the world. The climate crisis provides a huge opportunity to showcase the contributions that financial economists have and can make.

The field has already begun to move in this direction. We document a growing and evolving field of climate finance research from a quantitative and qualitative perspective. We see growth and the geographical expansion of this field, and also the increasing awareness of the importance of this issue for traditional finance with top journals and conferences beginning to cover climate finance issues more fully. We see a breadth of topics and interdisciplinarity of the field, so far welcoming many from related and further afield disciplines

Our brief qualitative review mostly discussed empirical work at the intersection of climate change and finance, but also some theoretical work. The empirical work has so far mostly focused on the asset pricing implications of climate change and quantified the potential exposure of the financial system to climate related risks. The theoretical work provided some preliminary theories on the pricing of instruments with different levels of exposure to climate related risks (e.g., carbon premium) or the assets using proceeds for green purposes (e.g., green premium). The review also discussed the growing interest from institutional investors and corporations in climate change, but also how households' finances might be impacted by global warming.

We offered some observations about directions that climate finance might take, and how it might influence our teaching and research in order to spur discussion, debate-and action. Future generations of finance professionals must be much more sensitive to this externality, and that sensitivity can begin with our teaching. We must use this inflection point to revisit some of our workhorse models and techniques, realizing that they may be less relevant in a period of profound uncertainty.

The development of the fields of economics and finance in the past centuries provided powerful frameworks that allowed societies to best allocate scarce resources. This work

supported the modern economies that allow many people to thrive, but this is increasingly at the expenses of our planet's natural resources that are rapidly depleting. We are confronted with these constraints on a daily basis with the massive damages brought by global warming in the form of destructive extreme weather and changing climate at different latitudes. As in the past, academic finance can provide clear thinking to support change in this decisive decade.

6 Appendix

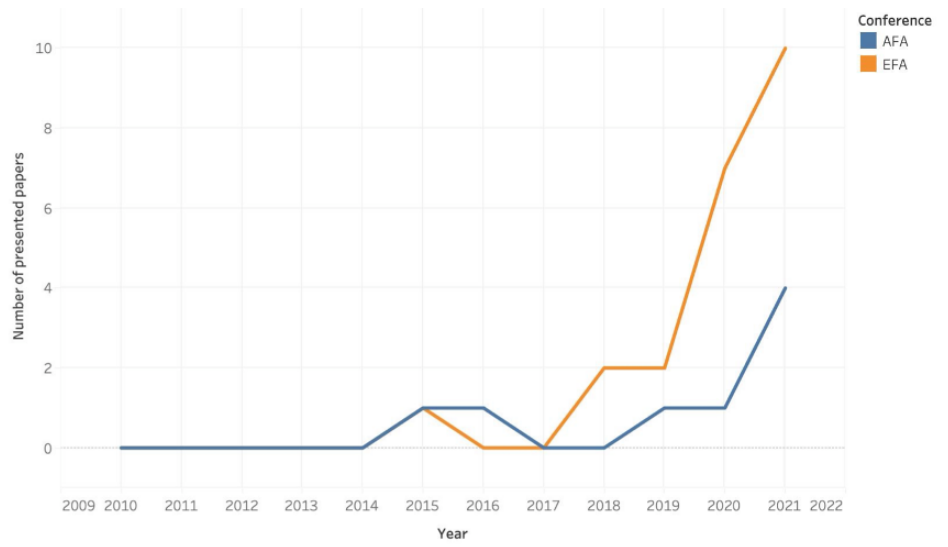


Figure 5: The figure shows the number of climate finance papers discussed the American Finance Association (AFA) annual conference and European Finance Association (EFA) annual conference.

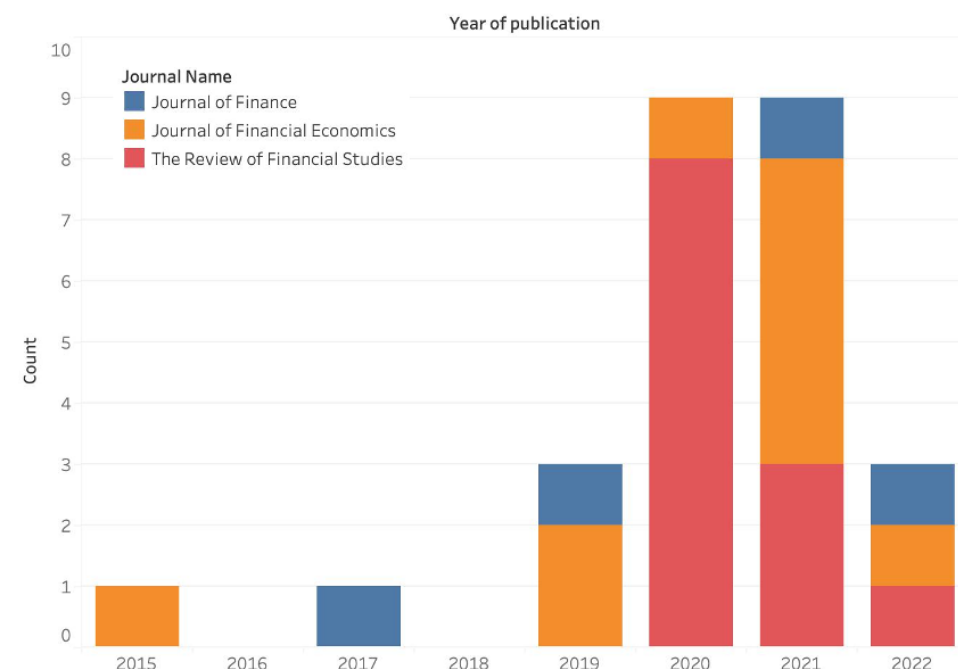


Figure 6: The figure shows the number of climate finance published in three finance journals: Journal of Finance (JF), Journal of Financial Economics (JFE) and The Review of Financial Studies (RFS) through time. 2022 refers to mid- year figures.

Part III

Assets valuations and environmental externalities

Are financial markets pricing the net zero carbon transition? A reconsideration of the carbon premium¹

Matteo Gasparini

April 2024

Abstract

Previous research has highlighted a positive correlation between realised returns and carbon emissions suggesting the presence of a carbon premium. I show that this relationship may be partially the result of climate policy uncertainty. For this reason, realised returns may not be representative of expected returns. To show this, I develop an asset pricing model with uncertain expectations about the future cash flows of fossil-fuel firms; the price-dividend ratio increases with uncertainty about a climate policy regime shift. I confirm this proposition empirically using data on analysts' forecasts; I find that analysts' forecast disagreement, as a proxy for climate policy uncertainty, may explain part of the valuations of a large sample of fossil-fuel stocks. Using my model, I show with forward-looking scenarios that cash flow expectations implied in the valuations of fossil-fuel firms may be inconsistent with a net zero carbon transition.

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JEL Codes: G11, G18, Q51

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1 Introduction

Countries, businesses, and non-profit organisations collectively accounting for almost the entire world's GDP have pledged to reach net zero carbon emissions by 2050 in line with the objectives of the Paris Agreement². If credible, these commitments represent an unprecedented financial risk for high-carbon emitting firms. Yet, various surveys show that investors believe stock markets may not be pricing climate-related transition risks (Krueger et al., 2020; Stroebel & Wurgler, 2021). This could be because the valuations of high-carbon emitting firms may not be pricing expected cash flows consistently with the increasing likelihood of a future without carbon-intensive energy sources. Extant literature has focused on realised returns, but if we were to prevent global warming in line with the climate pledges, the main effect of risk may be on the cash flows of carbon-intensive firms, which should arguably decline substantially by 2050 (Edmans, 2023).

Climate policy uncertainty may provide a first explanation for the current valuations of high carbon-emitting firms despite the increasing number of climate pledges. The financial economics literature concerned with climate change has highlighted that investors may be pricing the uncertainty around a transition to net zero carbon emissions through higher expected returns and lower valuations (Bolton & Kacperczyk, 2023; Hsu et al., 2022). However, in a present value framework, (idiosyncratic) uncertainty may right-skew expected cash flows, leading to higher valuations (Pástor & Veronesi, 2003, 2006). Contrary to what is suggested in previous literature, the positive correlation between realised returns and carbon emissions (or *carbon premium*) may not be a sign of financial markets pricing the increasing likelihood of a transition to net zero carbon emissions through higher expected returns.

In this paper, I show that the relatively high realised returns of carbon-intensive firms may be driven by climate policy uncertainty and they are unlikely to be purely reflective of a risk premium. I show that the high uncertainty surrounding climate policy

²Source: Oxford net zero tracker

may affect cash flow expectations and explain part of the valuations of some of the most carbon-intensive energy producers: fossil-fuel firms. A climate policy regime shift can influence the trend of the stochastic process governing high and low-carbon energy demand, shifting the respective firms' cash flows growth. A rational investor prices stocks, discounting future expected cash flows by an expected rate of return, which increases for more risky and uncertain assets. But uncertainty increases the *expected value* of future cash flows. The investor discounts a state of the world wherein high-carbon energy will continue to grow. The uncertain occurrence of a climate policy regime shift means that the investor is unable to anticipate whether and when the prospective shift will occur - that is, the sustained high levels of climate policy uncertainty affect the valuations of fossil-fuel firms.

To conceptualise this effect, I develop a partial equilibrium asset pricing model with uncertainty wherein the long-term growth of fossil-fuel firms depends on whether an uncertain climate policy regime shift occurs. I show that the valuations of fossil-fuel stocks are positively related to a rational investor's expectations about the trend of future cash flows and their variance. The latter describes the uncertainty faced by the investor in the absence of learning about the prospective climate policy regime shift, which I refer to as climate policy *regime shift uncertainty*. Moreover, I discuss how the different levels of exposure to the regime shift could exacerbate or mitigate the effects of uncertainty on assets' valuations. Firms with an elasticity of dividends to energy expenditure less than one are less exposed to the policy *regime shift risk* while values greater than one magnify the impact of possible climate policies on valuations.

To discuss the magnitude of the effect of climate policy uncertainty on stock market valuations, I test my proposition on a large sample of fossil-fuel firms with an empirical analysis of analysts' forecasts of dividends per share. I find that climate policy uncertainty may have weighed significantly on the valuations and realised returns of carbon-intensive firms. I report a positive and statistically significant relationship between analysts' estimates of growth in future dividends and the valuations of fossil-fuel firms. In a panel

regression, using analysts' forecast disagreement as a proxy for market uncertainty, I find that the variance in dividends per share (DPS) forecasts - and similarly that for earnings per share (EPS) forecasts - are positively correlated with the valuations of fossil-fuel companies. This effect is generally higher for more carbon-intensive firms and is consistent across the various dimensions explored in the robustness analysis.

Employing forward-looking climate scenarios, I show that financial markets are unlikely to be pricing a net zero carbon transition. I observe that the valuations of fossil-fuel stocks may be more closely aligned with the right tail of the distribution of price-dividend ratios conditional to a no climate policy regime shift estimated with my model. This alignment suggests that either markets do not believe that policymakers will shift their climate policy to meet their pledges to prevent global warming or that markets are over-optimistic about possible technological breakthroughs that allow the continued use of fossil-fuels, such as carbon capture and storage. These results show that the effect of climate policy uncertainty on cash flow expectations may lead to financial markets not pricing the net zero carbon transition. In turn, high realised returns may be a poor proxy for expected returns, as investors may reprice their cash flow expectations.

This paper contributes to various strands of the recent climate finance literature (Edmans & Kacperczyk, 2022; Gasparini & Tufano, 2023; Giglio et al., 2021; Hong et al., 2020; Starks, 2023). Firstly, I provide a novel perspective on the extent to which financial markets price a transition to net zero carbon emissions. A growing strand of empirical literature has recently shown that market agents are paying increasing attention to global warming and this is reflected in stock market prices (Bolton & Kacperczyk, 2023; Ramelli et al., 2021; Sautner et al., 2023; Wagner et al., 2018). Unlike previous research that has focused on realised returns, this paper discusses some asset pricing implications of the net zero carbon transition, focusing on a forward-looking cash flow perspective³. In particular,

³Similar evidence has also been found across various asset classes such as corporate and municipal bonds (Baker et al., 2022; Flammer, 2021; Painter, Chaifetz, & Louis, 2020), derivatives (Ilhan et al., 2021; Schlenker & Taylor, 2021), real estate (Bernstein et al., 2019), and mortgages (Nguyen, Ongena, Qi, & Sila, 2022). However, some opposite evidence has also emerged (Aswani et al., 2023; Hong et al., 2019). Furthermore, it should be noted that changes in expectations (or news) around cash flows may better explain the variability in stock market prices of 'value' stocks such as fossil-fuel firms than that of

I show that the valuations of fossil-fuel firms may not be aligned with a transition to net zero carbon emissions. I also provide a first explanation as to why surveys of professional investors indicate that financial markets are yet to sufficiently reflect the risks emerging from a net zero carbon transition residing in climate policy uncertainty.

Secondly, this paper contributes to the climate finance literature by reconsidering the recent evidence on the presence of a carbon premium. I show that, even though the realised returns of high-carbon emitting firms may have been higher than their low-carbon counterparts in the past - disclosing a carbon premium (Bolton & Kacperczyk, 2023) - they are unlikely to be representative of higher expected returns. Instead, high realised returns may be a product of the effect of uncertainty on cash flow expectations. If the uncertainty around the net zero carbon transition will resolve, investors may revise their expectations about the growth of cash flows of carbon-intensive firms leading to lower future returns. As also discussed by Atilgan, Demirtas, Edmans, and Doruk (2023), this paper provides further evidence showing that the carbon premium may not be a symptom of financial markets pricing climate-related transition risks and that, in turn, realised returns may not be purely reflective of expected returns and cost of capital⁴. Despite recent discussions in the literature around the presence or not of a carbon premium (Aswani et al., 2023), this paper provides a different conceptual interpretation of this phenomenon.

Finally, this study contributes to the financial economics literature on uncertainty. The net zero transition may be analogous to the early 2000s, when there was high uncertainty about the growth of the fundamentals of internet firms, which led to high valuations (Pástor & Veronesi, 2003, 2006). Even though the subsequent literature on policy uncertainty discusses how endogenous learning about political costs lowers uncertainty over time and thus leads to a higher risk premium and lower prices (Kelly, Pástor, & Veronesi, 2016; Pástor & Veronesi, 2012, 2013)⁵, I argue that the inability to learn

discount rate news (Campbell & Vuolteenaho, 2004; La Porta, Lakonishock, Shleifer, & Vishny, 1997)

⁴Pástor et al. (2022) show that using past returns as a proxy of expected returns for green stocks may not be appropriate.

⁵Similar results have also been found extending these models to the environmental policy (Hsu et al.,

about the perspective climate policy maintains high levels of cash flows uncertainty for carbon-intensive firms. With the simple model I developed, I show that uncertainty, in turn, could contribute to maintaining high the valuations of fossil-fuel firms.

In the following section, I present a valuation framework of climate-sensitive firms and discuss some asset pricing implications. In Section 3, I outline the empirical strategy and the econometric specifications. In Section 4, I provide the results of the analysis and discuss the empirical evidence. In Section 5, I provide numerical simulations of the valuations of fossil-fuel stocks conditional to a set of possible climate scenarios.

2 Valuation framework

In this section, I describe a simple valuation framework of climate-sensitive firms exposed to an uncertain policy regime shift to curb carbon emissions. I consider a closed economy with two firms $i \in [d, c]$, one producing carbon-intensive energy and one low-carbon energy, a representative investor, and an infinite time horizon $t \in [0, \infty]$. Let $E_{i,t}$ denote an exogenous level of energy expenditure from firm i at time t . Energy supply matches energy demand. For all $t \in [0, \infty]$ energy expenditure for energy from firm i follows a specific and independent geometric Brownian motion with drift μ_i and standard deviation ω_i , where dW_t is a process with mean zero and unit variance $dW_t \sim \mathcal{N}(0, 1)$. The drift μ_i remains constant for all $t \in [0, \infty]$ unless the policymaker takes an irreversible decision to shift its climate policy.

$$dE_{i,t} = \mu_i E_{i,t} dt + \omega_i E_{i,t} dW_t \quad (1)$$

At time 1 the policymaker can decide to maintain its current climate policy regime a or to shift towards restricting energy expenditure in carbon-intensive energy b in order to prevent global warming. If a climate policy regime shift occurs, the drift μ_i is shifted by

2022)

a known amount δ_i . This parameter for high-carbon energy δ_d is assumed to be strictly less than zero, while for low-carbon energy δ_c it is assumed to be strictly higher than zero. Loosely speaking, if the policymaker decides to take action to prevent global warming, he can implement policies for curbing high-carbon energy (e.g., carbon tax) or fostering low-carbon energy (e.g., stimulating innovation), thereby shifting the growth balance between high and low-carbon energy. For simplicity, I assume that the future path of low and high-carbon emitting energy expenditure only depends on the climate policy regime, but this can be thought of as a proxy for many unknown factors surrounding the transition⁶.

I then assume that the representative investor's expectations of μ_i are distributed normally with mean g_i and variance σ_i^2 . The latter term depends on the uncertainty introduced by the policymaker about the climate policy regime shift. The more uncertain is the signal from the policymaker about a possible shift in its climate policy regime from a to b , the more uncertain the representative investor is about the drift of the stochastic process governing carbon-intensive and low-carbon energy expenditure μ_i . I refer to σ_i^2 as *regime shift uncertainty* as the value of μ_i is ultimately defined by the decision of the policymaker. For simplicity, I assume that the magnitude of the possible policy is known and the decision is irreversible, but I acknowledge that these components introduce additional uncertainty and could be considered as a possible extension of the model.

I now want to use this framework in a simple present value asset pricing model. Let $D_{i,t}$ denote the dividend paid by firm i at time t . I assume that for all $t \in [0, \infty]$ the change in the level of dividends is proportional to the change in energy expenditure scaled by a known and constant firm-specific factor $dD_i = \gamma_i dE_i$. γ_i denotes the elasticity of dividends to changes in energy expenditure and represents the exposure of each firm to the regime shift. I therefore refer to γ_i as the exposure of each firm to the *regime shift risk*. Consequently, if we set $\omega_i = 0$ in Equation (1) without loss of generality, dividends grow at an exponential rate $\gamma_i \mu_i$ for all $t \in [0, \infty]$ ⁷.

⁶For example, the development of a new breakthrough energy technology, the possible continuation of the decline in the costs of renewable energy and storage

⁷The reader should note that the model can be generalised to values of ω_i greater than zero. The motivation for this assumption is that I am interested in considering the uncertainty that investors face

The investor has to price both firms at time 0 before the policy decision is taken. I assume that the price of firm i is the expected present value of future dividends discounted by an exogenous rate r_i given by a known model of expected returns. Importantly, differently from previous research that focuses on realised returns, I use my model to discuss the asset pricing implications of climate policy uncertainty from a cash flows perspective. I argue the effect of uncertainty on cash flow expectations in this context could be considerable given that, if we were to reach net zero carbon emissions, high-carbon energy may need to be almost entirely replaced by low-carbon energy.

$$P_{i,t} = \mathbb{E}_0 \int_0^{\infty} D_{i,t} \exp(-r_i t) dt \quad (2)$$

Following some simple manipulations described in Appendix A, I find a convex relationship between four parameters and the price-dividend ratio. Substituting $D_{i,t}$ in the present value Equation (2) with the growth process of dividends emerging from the energy expenditure path in Equation (1), the price of firm i at time t depends on a dividend stream growing at a rate $\mu_i \gamma_i$ and discounted at a rate r_i . If we take the expectations, dividends $D_{i,t}$ are log-normally distributed, and μ_i has mean $\exp(g_i + \sigma_i^2/2)$. For $r_i > g_i$, the price-dividend ratio of either low or carbon-intensive firm i at time $t = 0$ is positively related to the energy growth expectations, described by its mean g_i and variance σ_i^2 , a known constant representing the elasticity of dividends to changes in energy expenditure γ_i and negatively related to the required rate of return $r_{i,t}$:

$$P_i/D_i = 1/[r_i - (g_i + \sigma_i^2/2)\gamma_i] \quad (3)$$

This simple model shows that the uncertainty about climate policy action might have

about the probability distribution of the drift (i.e., the long-term path of energy demand) rather than the volatility around it. The reader should also note that the previous step is only a useful construct to link climate policy with asset valuations, but from a theoretical standpoint, assuming uncertainty about the drift of the diffusion process of dividends is equivalent.

an effect on the valuations of climate-sensitive assets through cash flow expectations. The higher the uncertainty about the growth of the fundamentals of climate-sensitive firms the higher the prices, everything else being equal. Contrary to the case where learning is possible and uncertainty decreases with the passing of time (e.g., [Pástor and Veronesi \(2012\)](#)), here uncertainty remains high until it is fully resolved⁸. Investors do not know whether high-carbon energy will remain predominant (leading to global warming) or whether, thanks to a policy regime shift, the world will move towards net zero carbon emissions. In such a case, uncertainty around policy action may lead to higher valuations (compared to a state of the world where global warming is prevented) by right-skewing expected cash flows.

A second observation is that the price-dividend ratio can be impacted by growth expectations and uncertainty, depending on the level of exposure of firms to the *policy regime shift risk* γ_i . The exposure of firms to the policy regime shift risk could be, in the first instance, proportional to carbon emissions (intensity), as highlighted by extant literature (e.g., [Bolton and Kacperczyk \(2023\)](#)). However, it may also be influenced by a broader set of factors such as the capacity of firms to cost-effectively abate emissions, the increasing or decreasing returns to scale of production, and the difference in efficiency and profitability of companies. In general, the impact of a transition to net zero carbon emissions on high carbon firms may vary greatly depending on a broader set of factors than just carbon emissions. In turn, this implies that the heterogeneous exposure of climate-sensitive firms to the policy regime shift risk may be a material driver of their valuations.

⁸This situation is similar to the case of internet companies in the dot.com bubble ([Pástor & Veronesi, 2006](#)) or the uncertainty about the future profitability of newly listed firms ([Pástor & Veronesi, 2003](#)) and more generally common in real option approaches ([McDonald & Siegel, 1986](#); [Paddock et al., 1988](#)). However, it should be noted that in this model, uncertainty emerges from the unknown level of the drift rather than the volatility around it. See [Pastor and Veronesi \(2009\)](#) for a review of learning in a context of uncertainty.

3 Empirical specifications

In this section, I outline an empirical strategy to study the magnitude of the effect of climate policy uncertainty on the valuations of fossil-fuel firms. Even though the theoretical framework described in the previous section allows for a more general assessment of climate policy uncertainty on climate-sensitive firms, I focus on companies involved in the extraction, refinement, and commercialisation of fossil-fuel. Fossil-fuel firms are arguably some of the most exposed businesses to the risks of a net zero carbon transition given that carbon-intensive energy would need to be almost entirely replaced by low-carbon energy in the absence of technological breakthroughs on carbon capture and storage.

I use professional analysts' forecasts of fossil-fuel firm's fundamental value to proxy investors' expectations and their uncertainty. In line with previous literature, I measure investors' uncertainty using forecast disagreement and focus on its time-varying component (E. Anderson, Ghysels, & Juergens, 2009; Diether et al., 2002; Johnson, 2004)⁹. Specifically, I am interested in testing whether investors' expectations about future cash flows and their time-varying uncertainty affect valuations. In the context of climate change, the levels of uncertainty may vary when there is news about events that affect, directly or indirectly, the likelihood of more stringent climate policy.

I use data from CRSP/Compustat to identify a set of fossil-fuel energy stocks. I select sub-industries related to oil & gas consumable fuel companies according to the Global Industry Classification Standard (GICS)¹⁰. This gives me a large set of stocks and their respective market data, including prices, earnings, and dividends. I then merge this data with Refinitiv's IBES and Refinitiv's carbon emissions. IBES reports data about analysts' forecasts of financial indicators monthly (e.g., Dividends per share, Earnings

⁹Various methods have been used in the literature to proxy investors' (climate) uncertainty: *i.* ARCH conditional variance discussed by Engle (1983), *ii.* market-based methods (Bekaert & Hoerova, 2014; Brenner & Izhakian, 2018), *iii.* text-mining methods (Baker, Bloom, & Davis, 2016; Bloom, 2009), of which some applied to climate policy uncertainty (Berestycki, Carattini, Dechezleprêtre, & Kruse, 2022; Gavriilidis, 2022; Noailly, Nowzohour, & Van Den Heuvel, 2022)

¹⁰GICS Sub-industries selected: Integrated Oil & Gas (10102010), Oil & Gas Exploration & Production (10102020), Oil & Gas Refining & Marketing (10102030), Oil & Gas Storage & Transportation (10102040), Oil & Coal & Consumable Fuels (10102050)

per share). I use the summary dataset, which reports the mean, standard deviation, high and low of analysts' estimates (including the number of underlying forecasts) as well as a set of aggregated statistics about the detailed estimates. Joining IBES with CRSP gives me a total of 480 fossil-fuel stocks, followed by stock market analysts. The data report analysts' forecasts for different forecast horizons (FH) in the future, from 1 to 3 years. For example, estimates could be for the next fiscal year (FH 1) or for 3 years in the future (FH 3). These data has monthly records (forecast date) corresponding to more than 800,000 underlying estimates, which summarise analysts, and arguably investors' beliefs, of a representative sample of fossil-fuel companies. Table 2 shows some descriptive statistics.

I perform the following data cleaning and transformations to ensure the data is adequate for the analysis. In line with previous literature, I set a threshold for the minimum required number of analyst's forecasts. I set the threshold at 10 to ensure enough estimates are included without reducing substantially the number of records. I also remove stocks with a price lower than 5 USD at the forecast date. Further, I select the decade starting at the beginning of 2010 and ending in 2019 as it is particularly suitable for the empirical analysis, but also because of data limitations and major global upheavals in the surrounding years. Firstly, if we consider a minimum number of analysts' forecasts for each forecast date, the number of estimates before 2010 is low. Secondly, the period between the global financial crisis and COVID-19 has been relatively stable from a macroeconomic standpoint while various major climate policy events occurred (e.g., Paris agreement in 2015, Trump's election in 2016) without being overly influenced by other exogenous events. This limits the concerns about the influence of other major economic and policy developments on the valuations of the stocks in the sample that might bias the results (e.g., global financial crisis).

I construct two metrics of analysts' forecasts as a proxy for market's expectations and uncertainty. First, I define: *i.* mean earnings per share (EPS) growth forecasts relative to the most recent earnings per share at forecast date ($EPS_G_{i,t}^{FH}$). Secondly, I define: *ii.* the standard deviation of EPS growth forecast (or forecast disagreement about the

growth of earnings) relative to the most recent absolute value of earnings per share at forecast date ($EPS_STD_{i,t}^{FH}$). I use the latter metric as a proxy of analyst's uncertainty. More formally, I define $EPS_{i,t,k}^{FH}$ as the EPS forecast for the forecast horizon FH for firm i at time t of analyst k (where K is the total number of analyst estimates). Further, I define $EPS_{i,t}$ as the most recent earnings per share at forecast date t and $\overline{EPS}_{i,t}^{FH}$ as the arithmetic average of the K analysts' forecasts for firm i for each forecast horizon.

$$EPS_G_{i,t}^{FH} = \frac{\overline{EPS}_{i,t}^{FH}}{EPS_{i,t}} - 1$$

$$EPS_STD_{i,t}^{FH} = \frac{\sqrt{\sum_{k=1}^K (EPS_{i,t,k}^{FH} - \overline{EPS}_{i,t}^{FH})^2 / K}}{|EPS_{i,t}|}$$

In the first specification, I estimate a panel regression model between the price-earnings ratio and the two metrics. I control for firm-fixed effects because I am interested in the time-varying level of uncertainty. Loosely speaking, I am interested in understanding whether, during a period of higher climate policy uncertainty, the relative valuations of climate-sensitive assets are higher, given a certain level of expected growth in earnings, rather than understanding whether firms that are more exposed to uncertainty show higher prices¹¹. Moreover, I replicate the same specification for the price-dividend (P/D) and dividends per share (DPS) forecasts in the dataset. Earnings per share allow us to avoid concerns about non-dividend paying stocks and use a larger number of data points, but results are generally equivalent¹².

$$P/E_{i,t} = \beta_1 * EPS_G_{i,t}^{FH} + \beta_2 * EPS_STD_{i,t}^{FH} + Controls_{i,t} + \epsilon_{i,t} \quad (1)$$

¹¹It is already postulated in the financial economics literature that firms more exposed to idiosyncratic uncertainty tend to have higher stock market valuations all else being equal (Pástor & Veronesi, 2003)

¹²The reader should note that, in most cases, fossil-fuel stocks are not "growth" companies and generally pay dividends with a constant pay-out. Consequently, EPS and DPS results are expected to follow a similar pattern

In the second specification, I estimate a panel regression model between the price-earnings ratio and the interaction of total carbon emissions (Scope 1,2,3), and the standard deviation of analysts' forecasts (forecast disagreement). This allows for a better identification of climate policy uncertainty. If forecast disagreement at least partially represents climate policy uncertainty, firms with higher carbon emissions should have a higher coefficient for the interaction term. I provide some reassurance about the correlation between my metric and climate policy uncertainty for fossil-fuel firms by exploiting this instrument. I corroborate this evidence with further identification analyses.

$$\begin{aligned}
 P/E_{i,t} = & \beta_1 * EPS_STD_{i,t}^{FH} + \beta_2 * TOTAL_EMIS_{i,t} \\
 & + \beta_3 * TOTAL_EMIS_{i,t} * EPS_STD_{i,t}^{FH} + Controls_{i,t} + \epsilon_{i,t}
 \end{aligned}
 \tag{2}$$

In Appendix B, I report some additional identification analyses. Firstly, I show the two metrics described above are, in aggregate, sensitive to climate policy events. Secondly, I show the metric of uncertainty broadly correlates with other climate policy uncertainty measures in the literature but not substantially with general uncertainty metrics. Finally, I show that forecast disagreement tracks the average implied option volatility of fossil-fuel firms. These analyses, together with the empirical set-up described in this section, should ensure that the results capture, at least to a certain extent, the effects of climate policy uncertainty on investors' expectations.

4 Empirical results

In the first part of this section, I investigate some of the determinants of uncertainty around the fundamentals of fossil-fuel firms, particularly focusing on elements that may increase climate policy uncertainty. In this part, I also investigate some of the drivers of the changes in mean analysts' expectations. In the second part, I turn to the main results

of my empirical analysis, reporting first the effects of uncertainty on the valuations of fossil-fuel firms and then exploring the interaction between carbon emissions and climate policy uncertainty. With this analysis, I show that the effect of climate policy uncertainty on the valuations of fossil-fuel firms could be material.

4.1 Some determinants of analysts' expectations and climate policy uncertainty

To get a better understanding of the drivers of the valuations of fossil fuel firms, I regress some possible factors of uncertainty on my measure of forecast disagreement (*EPS_STD*). The objective of this analysis is to first describe what may drive uncertainty around fossil-fuel stocks' fundamentals before turning to its effects on the valuations of firms. In particular, I focus on three elements: climate policy events, climate disasters, and political beliefs proxied using analysts' locations in Democratic or Republican-leaning states in the United States.

I first consider a set of climate policy events. In order to do that, I retrieve a list of climate policy events collected by [Barnett \(2023\)](#). I then create a dummy variable that equals one if, in the month the forecast was published, a climate policy event occurred, and equals zero otherwise. In [Table 3](#), I show that there is a weak positive correlation between my measure of uncertainty and climate policy events. The regression is not significant for a one and two-years forecast horizons but it is significant and positive for a three-years forecast horizon. This may indicate that during periods of climate policy events, analysts are generally more uncertain about the medium- and long-term future performance of fossil-fuel firms. The list of climate policy events is provided in [Appendix A10](#).

I then consider a set of climate disasters that may increase the salience of climate change. I use data from Spatial Hazard Events and Losses Database for the United States (SHELDUS)¹³ which reports historical property damages and fatalities of natural

¹³<https://sheldus.asu.edu/SHELDUS/index.cfm?page=members>

hazards. I classify a major disaster as an occurrence that led to either fatalities or property damages (expressed in terms of inflation adjusted Dollars at 2021 values) above the 90th percentile of the decade 2010-2020. I consider Coastal Flood, Drought, Flooding, Heat, Hurricane/Tropical Storm, Severe Storm/Thunder Storm, Tornado, and Wildfire. I focus on the US as most analysts in my sample reside in this country. Similarly, for climate policy events, I create a dummy variable tracking whether an event occurs in the month the estimate was published. In Table 3, I show that there is a weak positive correlation between my measure of uncertainty and the occurrence of physical climate events. The coefficient is positive and significant for the one-year forecast horizon. The list of events is provided in Appendix A11.

Thirdly, I consider whether analysts' headquartered in states that are leaning towards the Democratic or Republican party disclose differences in their uncertainty about the future of fossil-fuel firms. I use this as a proxy for political beliefs, which may indicate different views about climate change. I use data from Gerken and Painter (2023)¹⁴ about analysts' location and classify Democratic and Republican states depending on the outcome of the previous four elections. I classify states as Democratic or Republican-leaning where the respective party consistently won the election between 2004 and 2020. I do not consider states where there have been mixed results in the past four elections. In Table 3, I show that analysts headquartered in Democratic-leaning states (e.g., California) tend to be more uncertain about the future performance of fossil-fuel firms than analysis in Republican-leaning states (e.g., Texas). The classification of states is provided in Appendix A12.

In Table 4, the analysis is extended to the mean earnings growth forecast (EPS_G). I find that in months when climate policy events or climate related disasters occur, the mean analysts' forecast is generally lower than in other periods. The coefficients for the variables in the regressions are negative and significant. Specifically, for policy events, the coefficients are significant for a two and three-years forecast horizons. For climate

¹⁴I thank the authors for sharing the data

disasters, the only significant coefficient is for a forecast horizon of two years ahead. Turning to political beliefs, the results suggest that analysts located in Democratic-leaning states are not only more uncertain about their forecasts but tend to have higher mean estimates than their counterparts in Republican-leaning states. However, it should be noted that more than two-thirds of analysts are located in Democratic-leaning states (e.g., California) as opposed to Republican-leaning states (e.g., Texas).

These analyses show some of the drivers of analysts' uncertainty about fossil-fuel firms. When climate policy events and climate disasters occur, and arguably become more salient, my measure of uncertainty is generally higher and mean earnings' growth forecasts lower. Even though analysts headquartered in Democratic or Republican states may not share the predominant political belief of their geographical area, analysts in states where the predominant political orientation is towards the more climate-conscious Democratic party tend to be more uncertain about the future of fossil-fuel firms as opposed to states with a predominant orientation towards the Republican party. Analysts seem also to pay attention to climate policy and climate disasters in revising their mean forecasts, which are generally lower in the months such events occur.

4.2 The effects of uncertainty on the valuations of fossil-fuel firms

I now provide the results of the main empirical analysis. I start by averaging the forecast disagreement across the three forecast horizons in order to capture a stronger signal. Table 5, shows a positive and statistically significant relationship between analysts' forecast disagreement and the price-earnings ratio (Specification 1). I show that given a mean forecast growth, periods with higher forecast disagreement tend to have a higher price-earnings ratio, consistent with my model's prediction. This result seems to indicate that financial markets discount climate policy uncertainty through their cash flow expectations with higher average prices, everything else being equal.

In Table 5, I show that in months when climate policy events or climate disasters occurred, the valuations of fossil-fuel firms are generally lower. The coefficients of the

regressions are significant and negative. Introducing a dummy variable equal one on the date of the occurrence of such events does not affect the results, which remain significant and in line with expectations. Complementing these results with the findings in the previous subsection, it seems that analysts revise their expectations and their levels of uncertainty when climate policy or climate disasters occur, and, in turn, these beliefs have a significant impact on the valuations of firms.

In Table 6, I break down analysts' forecasts by different forecast horizons (FH 1,2,3). The signs of the coefficients are consistently positive across the three forecast horizons and highly significant. The coefficients are also economically significant: an expectation of doubling of the EPS in a three-years forecast horizon leads to around 14-points increase in the price-earnings ratio. A 50% standard deviation (i.e., EPS remaining constant or doubling in the next three years) leads to around 5 points increase in the price-earnings ratio. Similar results are also confirmed using the price-dividend ratio (P/D) in Table A1. The only exception is the standard deviation of forecasts for a two-years forecast horizon where the sign turns negative, although this model has a much lower explanatory power compared to the regression with earnings per share.

In Table 6, I show a negative and statistically significant relationship between Scope 1 emissions and the price-earnings ratio. I report that the coefficients for Scope 1 emissions expressed as intensity of revenues, assets, and log absolute emissions are negative and significant. The only exception is again for a two-years forecast horizon and log absolute emissions where the coefficient is not significant. Without considering the effects of uncertainty on cash flow expectations, higher carbon emissions entail lower price-earnings ratio in line with other empirical studies (Bolton, Halem, & Kacperczyk, 2022)¹⁵.

In Table 7, I show the results are robust to a set of control variables representing firms' characteristics. The relationships outlined above remain in line with expectations and significant after introducing ROE, liquidity, profit margin, market to book, leverage, and

¹⁵It should be noted that, this result is based on Scope 1 emissions that are relatively low for fossil-fuel firms. The exposure of fossil-fuel firms to the risks of a transition could be better captured by the total emissions of their products (i.e., including Scope 3). For this reason, in subsequent analyses, I consider total emissions.

cash to debt ratio. The only exception is the EPS growth estimate (EPS_G) for one-year forecast horizon (FH 1) where the coefficient turns negative. But the R^2 also decreases substantially in this case, to around 7%. Alternatively, the variance explained by the regression models for the two and three-years forecast horizons remains high (around 30% and 70% respectively). Interestingly, after controlling for firms' characteristics, the longer the time horizon of the estimate, the higher the variance explained by the model. The coefficients for Scope 1 emissions also remain generally negative and significant. Similar results could be found for dividends per share in Table A2¹⁶.

In Table A3, I show that the results hold after removing outliers. I winsorize to the 5th/95th percentile all variables in the sample and re-estimate the model to ensure my results are not sensitive to outliers. The coefficients for earnings per share growth forecast and earnings per share forecast disagreement remain positive and strongly significant. The explanatory power of the model slightly decreases, but remains broadly in line with the results based on a non-winsorized sample. Scope 1 emission coefficients also remain negative and significant with the only exception of three-years forecast horizon and log absolute emissions, which becomes not significant.

In Table A5, I show the results are robust to different thresholds of minimum number of analysts' forecasts. To test the sensitivity of the results to the cut-off I use for the minimum number of estimates, I increase it from 10 to 15 and decrease it to 5. The results generally persist in increasing the minimum number of estimates, although with a few exceptions. The sample size decreases substantially when considering only records with at least 15 estimates, thereby decreasing the robustness of the model. Alternatively, decreasing the minimum number of estimates increases the sample size, but the metrics are less robust. The results are confirmed also in this case, with a few exceptions, but I am cautious when using these metrics with fewer than 10 analysts' forecasts because it may not be sufficiently robust. These results are reported only for comparison with the baseline model. Nevertheless, this robustness analysis shows that the results are not

¹⁶The only exception in the DPS case are the coefficients of the standard deviation of analysts forecasts which become non-significant for a three-years forecast horizon

particularly sensitive to the cut-off threshold above a certain level.

In Table 8, I find a positive and significant relationship between the interaction term of total emissions (Scope 1, 2, and 3) and forecast disagreement and the price-earnings ratio (Specification 2). This may indicate that the valuations of firms that are more exposed to the policy regime shift risk (i.e., those with higher emissions) might be more impacted by the effect of uncertainty. This result also shows that at least a portion of forecast disagreement may be due to climate policy uncertainty. In line with the previous finding, the coefficient of forecast disagreement remains generally positive and significant, although the sign turns negative for absolute emissions.

In Table A7, I report additional robustness analyses. I find that in some instances, the relationship between the interaction term of total emissions and uncertainty and the price-earnings ratio does not hold to the set of control variables. However, after including firms' characteristics, the R^2 of the model decreases substantially, and in some instances, the coefficients of the interaction term turn negative or not significant. Such results suggest that there could be only a limited relationship between the interaction of emissions and uncertainty. Broader political and economic uncertainty may also contribute to the effects described in this paper. I am indeed aware that climate policy may only be one source of uncertainty that may affect cash flow expectations of fossil-fuel stocks. But I argue this analysis is sufficient to show it may, at least partially, contribute to this broader uncertainty¹⁷.

These results show that there may be a positive relationship between time-varying uncertainty and the valuations of fossil-fuel stocks. Although some anomalies emerge in the robustness analysis, my results suggest that this effect might be stronger for carbon-intensive firms - indicating that, at least in part, it could be attributed to climate policy uncertainty. Such findings highlight how climate policy uncertainty may have weighed significantly on the valuations of fossil-fuel firms and on their realised returns. In turn,

¹⁷Previous literature has also shown that a part of uncertainty in the S&P 500 may be due to climate change. Arguably, the share of climate policy uncertainty is even higher for fossil-fuel stocks (Rocciolo, 2022)

this result suggests that realised returns may be a poor proxy for expected returns and cost of capital.

5 The valuations of fossil-fuel firms and the net zero carbon transition

To calculate some numerical results of the valuations of fossil-fuel stocks conditional to a world with a climate policy regime shift and without, I calibrate the model described in Section 2 with some climate scenarios. In order to find a representative basket of fossil-fuel stocks, I run the model on a stock index representing high-carbon emitting energy sources: the S&P 1200 Global Energy Index. This index represents investments in traditional energy companies involved in the extraction, refinement, and commercialisation of fossil-fuel. I follow an approach similar to [Campbell and Shiller \(1989\)](#) and use my model to estimate a distribution of price-dividend ratios conditional to a set of climate scenarios. Specifically, I use climate scenarios to generate projections of dividends rather than using their historical realisations as proposed by [Campbell and Shiller \(1989\)](#). I use a set of climate scenarios from the the Network for Greening the Financial System ([NGFS, 2021](#)) to calculate the yearly growth rate of global energy expenditure on fossil-fuel energy (projected energy demand multiplied by energy prices) g_d and its standard deviation σ_d^2 ¹⁸. I then use a sensitivity parameter γ_d to link the change in carbon-intensive energy expenditure to the change in dividends.

I calibrate the discount rate r_d equal to 6.3%, the growth rate of carbon-intensive energy expenditure conditional to no climate regime shift $g_{d,a}$ equal to 1.37% and the standard deviation of the energy expenditure growth conditional to no climate regime shift $\sigma_{d,a}^2$ equal to 1.13%. The growth rate of carbon-intensive energy expenditure conditional to a climate regime shift $g_{d,b}$ equal to -0.92% and the standard deviation of the energy

¹⁸NGFS Scenarios used: Climate regime shift: Below 2°C, Net Zero 2050, Delayed transition, Divergent Net Zero. No climate regime shift: Current Policies. Models used: GCAM 5.3+ NGFS, MESSAGEix-GLOBIOM 1.1-M-R12, REMIND-MAgPIE 3.0-4.4.

expenditure growth conditional to a climate regime shift $\sigma_{d,b}^2$ equal to 1.41%¹⁹. In the baseline model, I set the elasticity of dividends to energy expenditure $\gamma_d=1$. This is the only parameter that is not possible to calibrate due to data limitations, but I use a range of plausible parameters ranging from 0.5 to 1.5 to show that the results do not change²⁰.

It should be noted that the calibration of my model conditional to a climate policy regime shift is fairly conservative. A decrease in primary energy expenditure of around 1% per year results in only around 30% lower levels of energy expenditure in 2050 compared to 2020. The total fossil-fuel expenditure in such a scenario decreases from around 4 trillion USD in 2020 at 2010 prices to only around 3 in 2050 in real terms. This is because the NGFS scenarios consider a sizeable use of carbon capture and storage (CCS) which allows for an extended use of carbon-intensive energy. Arguably less conservative scenarios would put the decline in high-carbon energy expenditure higher. Further, the estimates consider a linear and smooth decline in dividends, but a sharper drop in high-carbon emitting energy may be required to meet the ambitious goals of the Paris Agreement. This implies that the estimates conditional to a climate policy regime shift are likely to be on the high-end of possible values and conservative, but are already sufficiently different to illustrate the results.

To examine the potential impact of climate policy uncertainty, I generate two probability distributions of the price-dividend ratio conditional to the two set of scenarios (climate policy regime shift and no climate policy regime shift). I use the two conditional probability distributions of μ_d to calibrate the model. In Figure 7, I show the resulting probability distribution of yearly global energy expenditure growth μ_d and the price-dividend ratio conditional to a no climate policy regime shift (brown curve) and to a climate policy regime shift scenario (green curve). In line with expectations, the

¹⁹Consider that in the period between 2010 and end of 2019 this value increased by around 2% per year in real terms

²⁰Consider the total value of carbon-intensive energy expenditure (coal, oil and gas) between 2010 and end of 2019 increased around 20%, similarly to the total value of dividends of companies in the index in the same period. This entails an elasticity of dividends to energy expenditure of around 1:1. It seems reasonable to assume that firms dividends cannot increase substantially more than their revenues, except for relatively limited economies of scale. It should also be noted that the relative comparison is not affected by a changing r or γ_d , but purely by different levels of μ .

price-dividend ratio distribution conditional to a climate policy regime shift scenario is to the left of the one conditional to a no climate policy regime shift scenario. We would expect that in a world with climate policy high-carbon emitting firms will grow slower or decline, as opposed to scenarios where climate policies lead to a transition to low-carbon energy. I also show the range of the price-dividend ratio in the period after the Paris agreement (2016-2019) and the price-dividend ratio at the end of 2019. This ratio is fairly stable for "value" stocks such as fossil-fuel with a standard deviation of around 2.5.

To control for model misspecification, I then generate the conditional probability distributions of the price-dividend ratio by varying selectively some of the baseline parameters. This approach is useful because it allows me to make some observations on actual prices as long as it covers a wide range of plausible calibration parameters. It is possible that the baseline model might also be misspecified, but I argue at least one model calibration might be plausible. I test various levels of discount rate r_d , uncertainty around the growth rate of carbon-intensive energy expenditure σ_d^2 , and elasticity of dividends to energy expenditure γ_d . In Table 10, I show the mean and the standard deviation of the distribution while in Figure A4 I show the respective probability distributions. Reassuringly, the analysis shows that the mean values of the model are not substantially sensitive to the only parameter not calibrated empirically, γ_d , but rather that the unknown level of μ_d is the key driver of the results²¹.

In this analysis, the average valuations of fossil-fuel firms in the period 2016-2019 (after the Paris Agreement) and at the end of 2019 have been at the right of the distribution of the price-dividend ratio conditional to no climate policy regime shift. This result is consistent across the set of plausible model calibrations. Loosely speaking, high-carbon energy stocks have been broadly pricing a high likelihood of a no climate policy regime shift scenario. Depending on the model calibration, the valuations of the S&P 1200

²¹It should be noted that it is likely that the baseline calibration of the discount rate is in the lower range of possible values in light of the recent literature showing increasing levels of expected returns for carbon-intensive firms (Bolton & Kacperczyk, 2023). In a context of higher climate related risks and uncertainty, the required rate of return might arguably have a tendency to increase, moving both price-dividend ratios distributions to the left. It is also more likely than not that the model is under-estimating the required rate of return r .

Global Energy Index moved historically either in the range of the probability distribution conditional to no climate policy regime shift or to the right of it. If we assume that at least one of these model calibrations is plausible, the results show that it is unlikely that carbon-intensive stocks over the period following the Paris agreement priced dividends, or cash flows, growth rates substantially different than a no climate policy regime shift scenario.

The numerical simulations show that it is very unlikely that financial markets price a high probability of a net zero carbon transition. It would be sensible to expect the valuations of fossil-fuel firms to discount, at least to a certain extent, the possible effect of a net zero carbon transition on cash flows. Governments worldwide have made various commitments to fighting climate change, and the NGFS estimates are quite conservative given they entail a world with only 30% less fossil-fuel energy expenditure in 2050. An alternative explanation for these results may be that markets discount the low probability outcome of technological breakthroughs that could allow for an extended use of fossil-fuels (e.g., carbon dioxide removal)²². Nevertheless, these results show that investors' uncertainty about climate policy may, at least partially, explain the valuations of fossil-fuel stocks in light of the increasing number of climate pledges.

6 Conclusion

This paper investigates the extent to which financial markets price a transition to net zero carbon emissions. I reconsider the evidence around a correlation between realised returns and carbon emissions (*carbon premium*) in the light of climate policy uncertainty. In a present value framework, the main effect of transition risk on the valuations of high-carbon emitting firms may be on the expected cash flows rather than on the discount rate. Uncertainty may right-skew the expected value of future cash flows, maintaining

²²According to the latest IPCC assessment report the likelihood of a possible future scenario where fossil-fuel energy may be combined with Carbon Capture and Storage (CCS) has decreased substantially due to the increasingly lower prices for renewable energy

high the valuations of high-carbon emitting firms relative to a state of the world where a transition to net zero carbon emissions unfolds. In turn, the carbon premium may be a product of financial markets not pricing a transition to net zero carbon emissions rather than a symptom of pricing of transition risk. I showed that uncertainty may have weighed significantly on the valuations of some of the most carbon-intensive businesses: fossil-fuel firms. I provided evidence showing that part of this uncertainty may be due to climate policy. I then showed that it is unlikely that following the Paris Agreement financial markets consistently priced expected cash flows in line with a transition to net zero carbon emissions. In conclusion, a better understanding of the reasons underlying the carbon premium may be required in order to shed light on the extent to which financial markets price the risk of a transition to net zero carbon emissions.

7 Tables

	FH	<i>P/E</i>	<i>EPS_G</i>	<i>EPS_STD</i>
Mean	1	27.2895	0.0993	0.5778
	2	31.8017	0.5507	1.1493
	3	33.8423	0.5518	1.7515
Standard dev.	1	460.9999	10.0607	5.6415
	2	855.1199	39.8871	15.1574
	3	1073.6872	44.5025	16.1923
5th Percentile	1	-41.5	-1.6878	0.0199
	2	-47.6731	-4.0534	0.0351
	3	-58.8291	-6.1899	0.0373
95th Percentile	1	99.5296	1.4664	1.6207
	2	101.737	3.6	2.9583
	3	95.5333	5.45	4.4
N	1	68822	68809	60848
	2	60092	60081	54053
	3	39038	39028	29755

Table 2: Descriptive statistics Sample descriptive statistics. Values between January 2010 and December 2019. From top to bottom: mean, standard deviation, 5th percentile, 95th percentile and number of observations. FH refers to different forecast horizons from 1 fiscal year ahead up to 3 fiscal years ahead.

	(1)			(2)			(3)		
	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3
Policy Event	0.0184 (0.1152)	-0.0284 (0.3515)	7.6375*** (2.5396)						
Climate Disaster				0.3949*** (0.156)	0.0638 (0.4844)	1.9637 (3.5334)			
Democratic leaning							5.0871*** (0.6255)	10.8242*** (1.0582)	13.5304*** (2.8844)
Republican leaning							1.0901 (3.0861)	0.558 (5.1662)	0.8337 (27.4018)
R^2	0.00	0.00	0.0031	0.0009	0.0000	0.0001	0.0333	0.0546	0.0572
N	7467	8145	2909	7467	8145	2909	1924	1811	363

Table 3: Panel regression of forecast disagreement. Panel regression of earnings per share forecast disagreement - defined as the ratio between the standard deviation of analysts' estimates and the absolute value of the latest earnings per share - (EPS_STD) and a dummy variables representing: (1) if in the month of the forecast a major global policy event occurred (e.g., COP); (2) if in the month of the forecast the US experienced a major climate disaster (Coastal Flood, Drought, Flooding, Heat, Hurricane/Tropical Storm, Severe Storm/Thunder Storm, Tornado, Wildfire); (3) if the analyst publishing the forecast is headquartered in a Democratic or Republican leaning state. From left to right: analysts' estimates for 1 fiscal year ahead (FH+1) up to 3 fiscal years ahead (FH+3). Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

	(1)			(2)			(3)		
	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3
Policy Event	-0.035 (0.1818)	-1.4015*** (0.5119)	-18.5299*** (6.3945)						
Climate Disaster				0.0469 (0.2462)	-2.2958*** (0.7052)	-0.3256 (8.8961)			
Democratic leaning							36.1986*** (3.9326)	43.9854*** (4.6419)	46.7472*** (10.1583)
Republican leaning							17.9902 (19.4024)	5.3912 (22.6627)	3.9158 (96.5035)
R^2	0.0000	0.0013	0.0000	0.0000	0.0009	0.0029	0.0426	0.0473	0.0551
N	7467	8145	2909	7467	8145	2909	1924	1811	363

Table 4: Panel regression of mean earnings growth forecast. Panel regression of earnings per share growth mean forecast (EPS_G) and a dummy variables representing: (1) if in the month of the forecast a major global policy event occurred (e.g., COP); (2) if in the month of the forecast the US experienced a major climate disaster (Coastal Flood, Drought, Flooding, Heat, Hurricane/Tropical Storm, Severe Storm/Thunder Storm, Tornado, Wildfire); (3) if the analyst publishing the forecast is headquartered in a Democratic or Republican leaning state. From left to right: analysts' estimates for 1 fiscal year ahead (FH+1) up to 3 fiscal years ahead (FH+3). Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. Controlling for firm fixed effect. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

	(1)	(2)	(3)	(4)	(5)
	Emission intensity revenues	Emission intensity assets	Log absolute emission		
<i>EPS_G</i>	10.9458*** (0.2847)	11.2541*** (0.2807)	11.519*** (0.2767)		0.8627*** (0.0296)
<i>EPS_STD</i>	17.7839*** (0.7799)	16.8048*** (0.7674)	15.987*** (0.7565)		1.6472*** (0.0711)
<i>SCOPE_1</i>	-0.0024*** (0.0003)	-0.0024*** (0.001)	-3.887*** (1.1323)		
<i>SCOPE_2</i>	0.0362*** (0.0082)	0.1014*** (0.055)	3.4302* (2.497)		
<i>SCOPE_3</i>	-0.0002*** (0.0001)	-0.0007 (0.0008)	0.7659 (1.0117)		
Policy Event D				-8.7912*** (4.0842)	-7.6727** (3.9767)
Physical Event D				-10.5935*** (5.5972)	-10.6058** (5.4478)
<i>R</i> ²	0.9374	0.9366	0.9359	0.0002	0.0533
N	4269	4314	4395	18524	18524
Firm FE	Yes	Yes	Yes	Yes	Yes

Table 5: Panel regression of price-earnings ratio. From 1 to 3, panel regression of price-earnings ratio, earnings per share growth mean forecast (*EPS_G*), earnings per share forecast disagreement - defined as the ratio between the standard deviation of analysts' estimates and the absolute value of the latest earnings per share - (*EPS_STD*), Scope 1,2,3 GHG emissions expressed in absolute and relative term (revenue and asset intensity). From 4 to 5, panel regression of price-earnings ratio on dummy variables indicating whether in the month of the forecast was published policy events (e.g., COP) or climate disasters occurred. Mean values across three forecast horizons from 1 fiscal year ahead up to 3 fiscal years ahead. Controlling for firm fixed effect. Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

	Emission intensity revenues			Emission intensity assets			Log absolute emissions		
	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3
<i>EPS_G</i>	17.2967*** (0.6355)	12.98*** (0.1166)	13.7058*** (0.136)	16.6831*** (0.6346)	13.0224*** (0.1151)	14.1021*** (0.1261)	17.8769*** (0.5862)	13.2896*** (0.1193)	14.2496*** (0.1196)
<i>EPS_STD</i>	26.6804*** (1.4345)	6.5801*** (0.3245)	10.8526*** (0.37)	27.2408*** (1.4405)	6.454*** (0.3187)	11.37*** (0.3833)	24.2669*** (1.3306)	5.7001*** (0.3298)	11.7554*** (0.3799)
<i>SCOPE_1</i>	-0.0026*** (0.0006)	-0.0006*** (0.0002)	-0.004*** (0.0006)	-0.0063*** (0.0023)	-0.0013*** (0.0006)	-0.0458*** (0.0079)	4.4049*** (1.8606)	-0.6993 (0.6258)	-4.2443*** (1.0644)
<i>SCOPE_2</i>	-0.1652*** (0.0129)	-0.0015 (0.0045)	-0.036*** (0.0096)	-0.6457*** (0.091)	-0.0207 (0.0295)	0.0742 (0.0576)	-15.008*** (4.0411)	-0.5093 (1.3719)	5.3516*** (2.2089)
<i>SCOPE_3</i>	0.0017*** (0.0002)	0.0001 (0.0001)	-0.0003*** (0.0001)	0.0028*** (0.0013)	0.0003 (0.0004)	-0.0021*** (0.001)	5.5713*** (1.611)	0.8104 (0.5528)	-1.2405 (0.8759)
R^2	0.8945	0.9828	0.9418	0.889	0.9828	0.9386	0.8842	0.9815	0.9389
N	3419	4004	1346	3438	4043	1348	3508	4116	1366
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 6: Panel regression of price-earnings ratio by forecast horizon. Panel regression of price-earnings ratio, earnings per share growth mean forecast (*EPS_G*), earnings per share forecast disagreement - defined as the ratio between the standard deviation of analysts' estimates and the absolute value of the latest earnings per share - (*EPS_STD*), Scope 1,2,3 GHG emissions expressed in absolute and relative term (revenue and asset intensity). Controlling for firm fixed effect. From left to right: analysts' estimates for 1 fiscal year ahead (FH+1) up to 3 fiscal years ahead (FH+3). Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

	Emission intensity revenues			Emission intensity assets			Log absolute emissions		
	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3
<i>EPS_G</i>	-5.9818*** (1.1138)	9.156*** (0.2746)	10.0781*** (0.2055)	-5.9823*** (1.1115)	9.1595*** (0.2745)	10.0377*** (0.2072)	-5.6565*** (1.0935)	9.1349*** (0.2716)	9.9935*** (0.205)
<i>EPS_STD</i>	9.7193*** (1.7533)	2.8072*** (0.6202)	7.7574*** (0.3773)	9.3767*** (1.7438)	2.7101*** (0.6195)	7.7124*** (0.3814)	8.5685*** (1.7162)	2.628*** (0.6149)	7.7015*** (0.3767)
<i>SCOPE_1</i>	-0.0011*** (0.0003)	-0.0006*** (0.0003)	-0.0025*** (0.0006)	-0.0105*** (0.0035)	-0.0077*** (0.0038)	-0.0093 (0.0096)	0.0621 (1.1531)	0.9973 (1.0902)	-3.617*** (1.3278)
<i>SCOPE_2</i>	0.0063 (0.0092)	0.0104 (0.0089)	0.0138 (0.01)	-0.0042 (0.0456)	0.0009 (0.0422)	0.0588 (0.0558)	-2.2137 (1.7632)	-2.3698 (1.7122)	4.1329*** (1.9595)
<i>SCOPE_3</i>	0.0001 (0.0001)	0.0001** (0.0001)	0.000 (0.0001)	0.0023*** (0.0007)	0.0017*** (0.0007)	0.0002 (0.0009)	2.6191*** (0.643)	1.5062*** (0.6362)	-0.8795 (0.7416)
ROE	13.159** (7.0958)	-13.7406** (7.1305)	9.1733 (9.9804)	11.5323* (7.2646)	-15.1511*** (7.353)	11.4629 (10.7163)	13.7655*** (6.8544)	-11.4116** (6.8847)	12.6821 (10.0069)
Liquidity	-0.6898*** (0.1019)	0.6429*** (0.1)	0.0955 (0.0946)	-0.7145*** (0.102)	0.6118*** (0.1003)	0.1126 (0.0937)	-0.7719*** (0.1022)	0.586*** (0.1008)	0.1293 (0.0934)
Profit Margin	-0.3498 (4.4942)	23.0589*** (4.5884)	-23.5791*** (5.4822)	1.1262 (4.5518)	24.3493*** (4.6522)	-24.0866*** (5.7136)	-0.3925 (4.4237)	22.1099*** (4.5331)	-22.2324*** (5.5078)
M/B	0.9747 (0.6852)	0.4465 (0.7097)	2.4517* (1.6169)	0.8564 (0.6877)	0.4259 (0.7119)	2.8574** (1.6796)	0.6531 (0.6751)	0.5024 (0.7021)	2.5215* (1.6377)
Leverage	-86.478*** (10.356)	19.2268** (10.1505)	-20.5334 (14.7254)	-91.5516*** (10.5015)	17.7566** (10.4688)	-28.4941** (15.6561)	-96.6882*** (15.9301)	8.0353 (15.1902)	7.8166 (20.6833)
Cash to Debt	105.3083*** (12.948)	-115.3787*** (12.603)	-10.0038 (14.9239)	105.0166*** (13.4048)	-112.0413*** (13.1935)	-13.6987 (15.6913)	81.9258*** (17.2169)	-126.5316*** (16.6157)	23.6891 (21.1556)
R^2	0.0671	0.3398	0.7116	0.0704	0.3401	0.7074	0.0751	0.3383	0.707
N	2366	2479	1043	2366	2479	1043	2418	2532	1060
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 7: Robustness analysis of price-earnings ratio on forecast disagreement regression. Panel regression of earnings per share growth mean forecast (*EPS_G*), earnings per share forecast disagreement - defined as the ratio between the standard deviation of analysts' estimates and the absolute value of the latest earnings per share - (*EPS_STD*) and the price-earnings ratio. Including as control variables: Return on Equity (ROE), Interest coverage rate (Liquidity), Profit Margin, Market to Book (M/B), Assets to debt ratio (Leverage), and Cash to Debt. Controlling for firm fixed effects. From left to right: analysts' estimates for 1 fiscal year ahead (FH+1) up to 3 fiscal years ahead (FH+3). Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

	Emission intensity revenues			Emission intensity assets			Log absolute emissions		
	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3
<i>EPS_STD</i>	58.9609*** (1.0358)	38.1219*** (0.295)	9.4497*** (0.8938)	21.2152*** (2.0554)	23.4367*** (0.5306)	-0.301 (0.5886)	-280.7932*** (6.7288)	-129.6253*** (2.3791)	-192.1518*** (4.2255)
<i>TOT_EMISS</i>	-463.4163*** (53.42)	-50.1747** (27.1214)	-539.8365*** (219.3579)	-7255.9721*** (607.1296)	-472.6214*** (232.4031)	-2507.1871*** (929.4158)	-0.7676*** (0.2072)	-0.5625*** (0.1095)	-2.4857*** (0.2624)
<i>TOT_EMISS_STD</i>	10.9375*** (2.1538)	16.1093*** (1.3115)	235.0278*** (6.8984)	1694.9267*** (80.6763)	913.0794*** (26.3322)	4213.7354*** (54.4091)	17.4751*** (0.3416)	8.6794*** (0.121)	13.7564*** (0.2603)
R^2	0.8661	0.9307	0.6862	0.8802	0.9446	0.8803	0.9158	0.9667	0.7709
N	3421	4006	1348	3440	4045	1350	3510	4118	1368
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 8: Panel regression of price-earnings ratio with emissions and forecast disagreement interaction. Panel regression of price-earnings ratio, Scope 1,2,3 GHG emissions expressed in absolute and relative term (USD mln revenues and assets) and interaction term between earnings per share forecast disagreement - defined as the ratio between the standard deviation of analysts' estimates and absolute value of latest earning per share - (*EPS_STD*) and total emissions *EMISS_STD*. Controlling for firm fixed effect. From left to right: analysts' estimates for 1 fiscal year ahead (FH+1) up to 3 fiscal years ahead (FH+3). Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

	Emission intensity revenues			Emission intensity assets			Log absolute emissions		
	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3
<i>EPS_STD</i>	-144.9668*** (18.6816)	17.2523*** (6.9441)	79.0991*** (7.8942)	6.6337*** (2.1868)	-1.9701*** (0.9511)	7.6546*** (1.0198)	11.4046*** (2.0249)	-2.0635*** (0.883)	4.4649*** (0.8813)
<i>TOT_EMISS</i>	0.9471*** (0.3428)	0.9494*** (0.4058)	0.8876 (0.6985)	1694.2122*** (551.2063)	1119.5393** (650.9953)	3877.4815*** (1484.9827)	162.2697*** (77.3247)	173.0214** (100.2057)	413.732*** (195.3629)
<i>TOT_EMISS_STD</i>	10.3639*** (1.2652)	-1.3157*** (0.4671)	-5.2424*** (0.5407)	1849.2289 (1284.9045)	-195.1936 (647.3618)	-5759.0534*** (944.0303)	-234.1549*** (78.7568)	-16.154 (52.299)	-238.4999*** (86.7956)
ROE	13.8686*** (6.7981)	-20.9593*** (8.206)	-30.3121** (16.7672)	12.603** (7.1708)	-22.5162*** (8.6291)	-44.5367*** (18.31)	17.2699*** (7.0454)	-19.0173*** (8.4301)	-29.5146** (17.6469)
Liquidity	-0.4449*** (0.1061)	0.862*** (0.1202)	0.7805*** (0.1591)	-0.6069*** (0.1042)	0.9129*** (0.12)	0.81*** (0.1647)	-0.6341*** (0.1023)	0.9419*** (0.1197)	0.7976*** (0.1685)
Profit margin	-0.3932 (4.3367)	21.476*** (5.3536)	-5.049 (9.3553)	2.9232 (4.5136)	23.3105*** (5.5224)	-3.3259 (9.8724)	0.1967 (4.4827)	20.8166*** (5.4684)	-6.5806 (9.9053)
M/B	1.0849* (0.6656)	0.579 (0.8348)	-2.1039 (2.6995)	0.8802 (0.6921)	0.38 (0.8568)	-6.079*** (2.9889)	1.1504** (0.6884)	0.398 (0.8547)	-3.795 (2.8924)
Leverage	-105.1858*** (13.9495)	-20.563 (16.6605)	-38.3963 (32.9231)	-92.3705*** (10.56)	2.5909 (12.369)	-3.766 (26.107)	-92.1502*** (10.3969)	5.6423 (12.0416)	1.6264 (26.2242)
Cash to Debt	43.6282*** (15.3307)	-110.4863*** (18.1628)	1.877 (32.5835)	79.7646*** (12.9072)	-95.0741*** (15.1379)	-14.1229 (26.549)	90.7292*** (12.7333)	-94.2473*** (15.0395)	-28.0553 (26.6984)
<i>R</i> ²	0.0817	0.0441	0.1253	0.0544	0.0419	0.0774	0.0526	0.042	0.052
N	2420	2534	1062	2368	2481	1045	2368	2481	1045
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table 9: Panel regression of price-earnings ratio with emissions and forecast disagreement interaction robustness.

Panel regression of price-earnings ratio, Scope 1,2,3 GHG emissions expressed in absolute and relative term (USD mln revenues and assets) and interaction term between earnings per share forecast disagreement - defined as the ratio between the standard deviation of analysts' estimates and absolute value of latest earning per share - (*EPS_STD*) and total emissions (*EMISS_STD*). Including as control variables: Return on Equity (ROE), Interest coverage rate (Liquidity), Profit Margin, Market to Book (M/B), Assets to debt ratio (Leverage), and Cash to Debt. Controlling for firm fixed effect. From left to right: analysts' estimates for 1 fiscal year ahead (FH+1) up to 3 fiscal years ahead (FH+3). Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

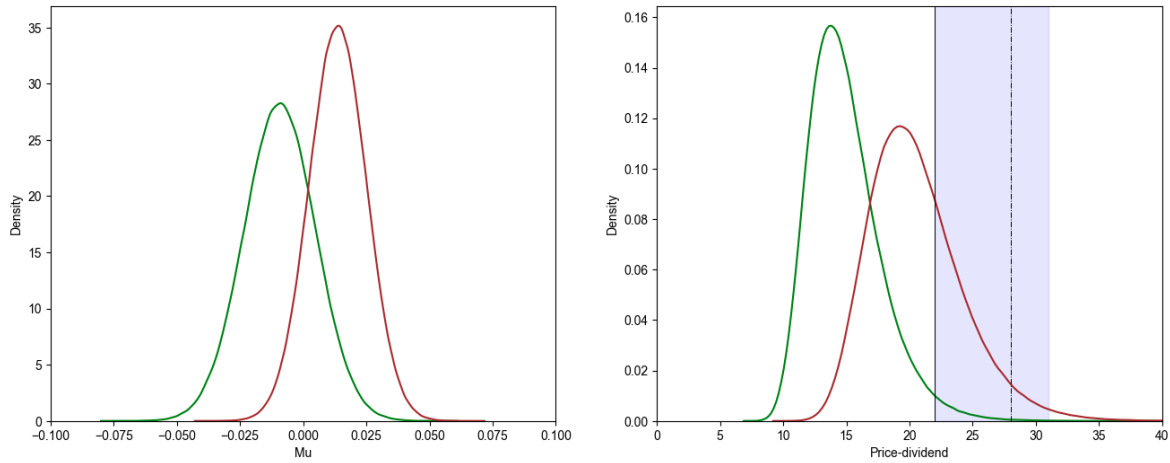


Figure 7: Scenario energy expenditure growth probability distributions and Price Dividend ratio. Left hand side chart shows yearly energy expenditure growth distribution (μ) from Network for Greening the Financial System (NGFS) scenarios. Right hand side chart shows distribution of price-dividend ratio simulated with the model. Green lines are distributions conditional to a set of scenarios assuming a climate policy shift (Net zero emissions by 2050 target). Brown lines are distributions conditional to a set of scenarios with no climate policy shift (Business as usual target). Values generated from parameters estimated based on an ensemble of NGFS climate scenarios. Full vertical line represents price-dividend ratio in Q4 2019, dashed line represents price-dividend ratio of the period 2016-2019 following the Paris Agreement. Shadow area shows the range of values in the period following the Paris Agreement. NGFS Scenarios used: Policy shift: Below 2°C, Net Zero 2050, Delayed transition, Divergent Net Zero. No policy shift: Current Policies. Models used: GCAM 5.3+ NGFS, MESSAGEix-GLOBIOM 1.1-M-R12, REMIND-MAgPIE 3.0-4.4

		Mean Price-Dividend		Std Price-Dividend	
	Value	No policy scenario	Policy scenario	No policy scenario	Policy scenario
Baseline		19.7249	14.9237	3.0995	2.8669
r_i	0.05	29.2781	19.9925	6.2523	4.6582
	0.07	17.6959	13.2081	2.9093	2.2933
	0.09	12.689	10.0354	1.6725	1.381
	0.11	9.8684	8.1313	1.0582	0.922
σ_i^2	0.02	21.5722	15.3742	7.382	4.4199
	0.03	23.7984	16.6053	13.9412	8.1763
	0.04	27.6246	18.7428	25.9365	14.924
	0.06	45.6795	28.441	115.54	61.4787
γ_i	0.5	18.198	15.5276	1.5155	1.4913
	0.7	19.0611	15.2486	2.289	2.0398
	1.3	22.2754	14.6574	5.5039	3.7066
	1.5	23.6145	14.5426	6.9424	4.2835
2016-2020			25.7681		2.68
Q4 2019			22.1188		

Table 10: Price and μ probability mean and standard deviation sensitivity. Model generated mean and standard deviation of price-dividend ratio using different calibration parameters. From top to bottom: simulation of three levels of discount rate (r) from 0.05 to 0.11, simulation of three levels of uncertainty (σ^2) from 0.02 to 0.06, simulation of three levels of elasticity of dividends to energy expenditure (γ) from 0.5 to 1.5. NGFS Scenarios used: Policy shift: Below 2°C, Net Zero 2050, Delayed transition, Divergent Net Zero. No policy shift: Current Policies. Models used: GCAM 5.3+ NGFS, MESSAGEix-GLOBIOM 1.1-M-R12, REMIND-MAgPIE 3.0-4.4

8 Appendix

A Full derivation of the model

Let $E_{i,t}$ denote the level of energy expenditure for energy produced by firm i . Energy supply matches energy demand. Let $E_{i,t}$ follow the process in (1), where dW_t is a process with mean zero and unit variance $dW_t \sim \mathcal{N}(0, 1)$

$$dE_{i,t} = \mu_i E_{i,t} dt + \omega_i E_{i,t} dW_t \quad (1)$$

The drift μ_i in (1) remains constant for all $t \in [0, \infty]$. The level of μ_i is not known a priori and depends on an exogenous decision from the policy-maker about climate action. The representative investor expectations of μ_i are distributed normally with mean g_i and variance σ_i^2 as in (2)

$$\mu_i \sim \mathcal{N}(g_i, \sigma_i^2) \quad (2)$$

I assume that the change in the level of dividends D_i is proportional to the change in energy expenditure E_i for the respective energy production technology of firm i . Therefore the parameter γ_i denotes a known and constant scaling factor between the change in the energy expenditure and the change in dividends for firm i . In (1), I set $\omega_i = 0$ without loss of generality.

$$dD_i = \gamma_i dE_i \quad (3)$$

With the assumptions in (3), dividends grow at an exponential rate $\gamma_i \mu_i$ for all $t \in [0, \infty]$

$$D_{i,t} = D_{i,0} \exp(\gamma_i \mu_i t) \quad (4)$$

Let $D_{i,t}$ denote the dividend paid by firm i at time t . The price of an asset at time 0 is the expected present value of future dividends from 0 to infinity discounted by a known rate r_i as in (5):

$$P_i = \mathbb{E}_0 \int_0^{\infty} D_{i,t} \exp(-r_i t) dt \quad (5)$$

I assume that the discount rate r_i is based on an exogenous and known model of expected returns $\mathbb{E}_t[r_i] = r_i$. Substituting $D_{i,t}$ in equation (5) with the process in equation (4) and taking the expectations:

$$P_i = \mathbb{E}_0 \int_0^{\infty} D_{i,0} \exp[(\mu_i \gamma_i) t] \exp[(-r_i) t] dt \quad (6)$$

$$P_i = \mathbb{E}_0 \int_0^{\infty} D_{i,0} \exp[(\mu_i \gamma_i - r_i) t] dt \quad (7)$$

$$\frac{P_i}{D_{i,0}} = \mathbb{E}_0 \int_0^{\infty} \exp[(\mu_i \gamma_i - r_i) t] dt \quad (8)$$

$$\frac{P_i}{D_{i,0}} = \int_0^{\infty} \exp\left\{[(g_i + \sigma_i^2/2)\gamma_i - r_i] t\right\} dt \quad (9)$$

Equation (9) is a perpetuity growing at the rate $\alpha = (g_i + \sigma_i^2/2)\gamma_i$ and discounted at the rate r_i . Solving the integral between 0 and infinity results in the following equation:

$$P_i/D_i = 1/[r_i - (g_i + \sigma_i^2/2)\gamma_i] \quad (10)$$

Equation (10) shows a relationship between the price-dividend ratio and the four parameters discussed in the paper.

B Additional identification analyses

Firstly, I control analysts' forecasts are sensitive to climate policy events. The average forecast of the growth rate of earnings across all firms in the sample ($EPS_G_{i,t}^{FH}$) and the average disagreement ($EPS_STD_{i,t}^{FH}$) varies throughout time in line with key policy events (Figure A1). In the period around the announcement of the Paris agreement and following President Trump's subsequent withdrawal, I observe spikes in forecast disagreement, demonstrating the sensitivity of this metric to climate policy. Similarly this measure increases around the UN Climate action summit in 2019 and the release of the fourth IPCC report in late 2014. The forecast disagreement for one year ahead forecast horizon is more volatile than three years ahead which reacts more slowly. Analysts' forecasts about the growth of earnings also seem to react to policy events such as the Paris agreement and President Trump withdrawal. Following the former, all three measures of average earnings' growth start decreasing, although the metric for three years ahead forecast horizon is more stable.

Secondly, I compare the average forecast disagreement with general economic uncertainty. In Figure A2, I compare the average forecast disagreement for a three years ahead forecast horizon with two general uncertainty indexes: the VIX of the S&P 500 index and the measure proposed by Bloom (2009). This analysis highlights that the average forecast disagreement has a low correlation with general political and economic uncertainty. The VIX and the GEPU indexes are low in the period between the release of the IPCC Fourth Assessment report and the Paris agreement, contrary to the average forecast disagreement which peaks in the months preceding the Paris Agreement. The VIX is also low around the election of President Trump, although the GEPU spikes in the months preceding the nomination and then returns to normal levels around the elections. In this period, the average forecast disagreement does not spike in the months preceding the election, but only around and after the election when discussions about the US withdrawal from the Paris Agreement started. Although the VIX index is flat for most of the periods where climate policy developments unfolded, the GEPU index shows a somewhat

negative correlation with the average forecast disagreement showing how it may not be substantially biased by general uncertainty.

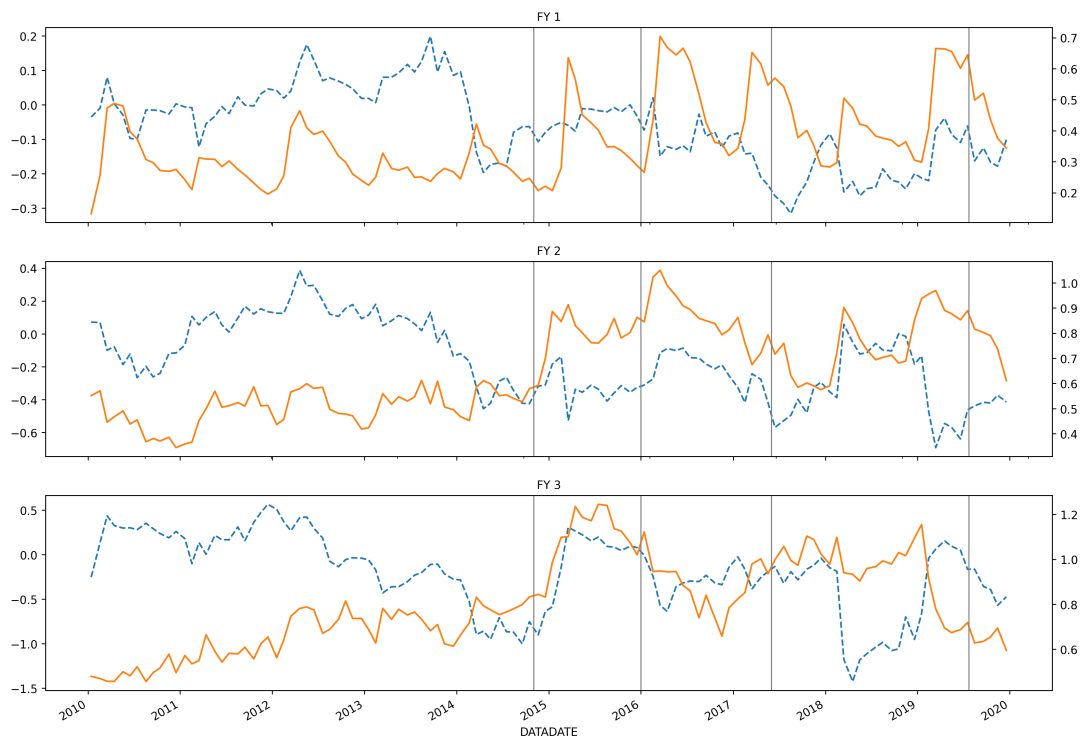


Figure A1: Average forecast estimates time series. Average Mean EPS growth forecast ($EPS_G_{i,t}^{FH}$) and earnings per share forecast disagreement ($EPS_STD_{i,t}^{FH}$) relative to the absolute value of EPS. 480 fossil-fuel companies in the sample. Blue line on left hand side axis represents $EPS_G_{i,t}^{FH}$ and orange line on right hand side axis represents $EPS_STD_{i,t}^{FH}$ for forecast horizons (FH) 1,2,3. Vertical lines from left to right represent Fourth IPCC assessment report release, Paris Agreement, President Trump withdrawal from it and 2019 UN Climate action summit.

Thirdly, I compare the average forecast disagreement with other climate policy uncertainty (CPU) measures. In Figure A2, I compare the average forecast disagreement for three years ahead forecast horizon with three CPU indexes: the text mining approaches of Gavriilidis (2022), Noailly et al. (2022) and Berestycki et al. (2022). Opposite to general macroeconomic uncertainty indexes, the average forecast disagreement co-moves with the indexes of climate policy uncertainty, especially in the first part of President Trump’s term. All measures of climate policy uncertainty increase in the periods around and after President Trump election, consistently with the measure of forecast disagreement.

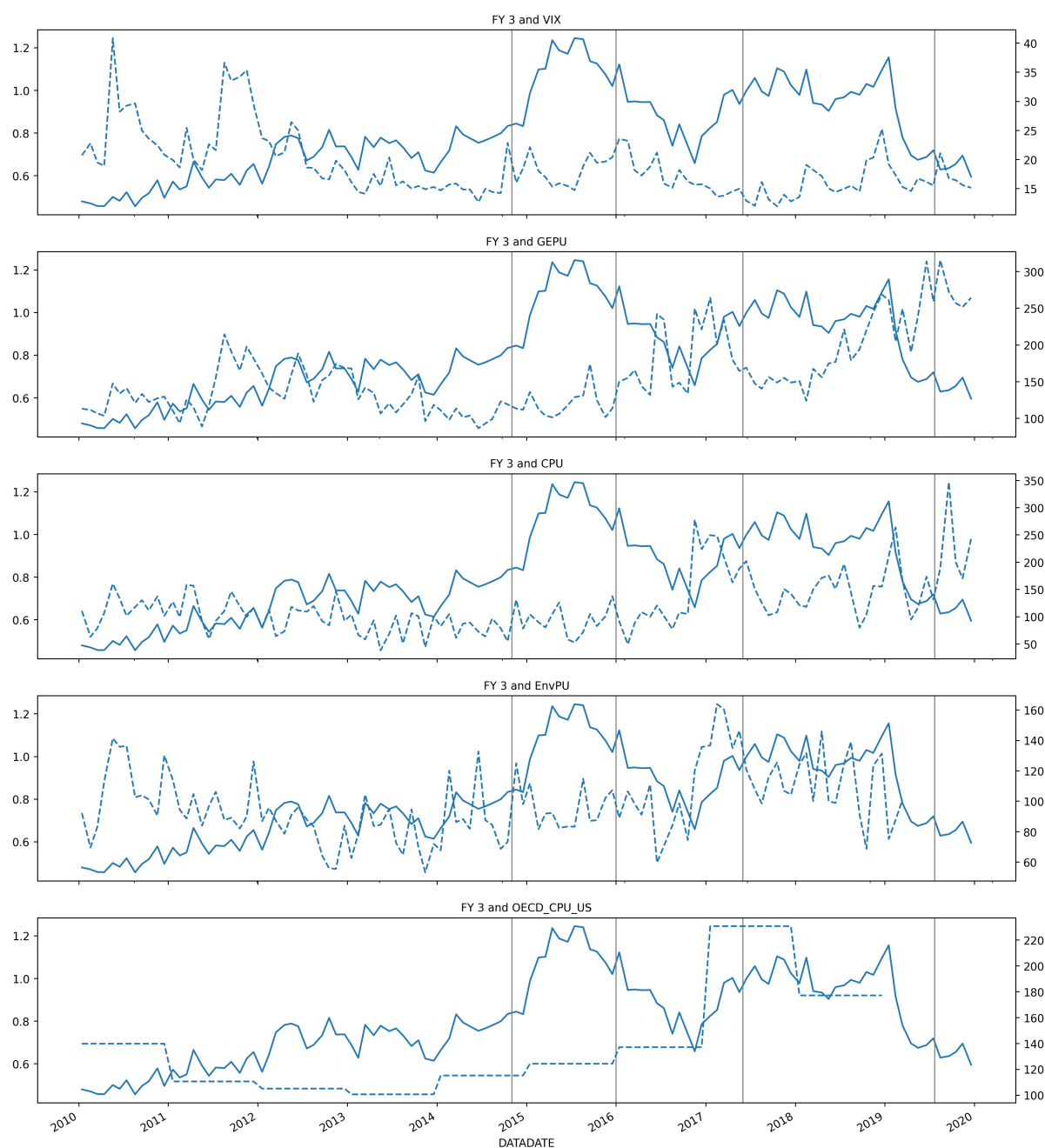


Figure A2: Uncertainty indexes comparison. Comparison of earnings per share forecast disagreement ($EPS_STD_{i,t}^{FH}$) relative to the absolute value of EPS (Full line, left axis) and three indexes of uncertainty (Dashed lines, right axis). From top to bottom Vix of the S&P 500 index retrieved from Fred Database, Global Economic Uncertainty Index of Bloom (2009), Climate Policy Uncertainty index of Gavriilidis (2022) used by Chan and Malik (2022), EnvPU from Noailly et al. (2022) and OECD CPU index of Berestycki et al. (2022). Vertical lines from left to right represent Fourth IPCC assessment report release, Paris Agreement, President Trump withdrawal from it and 2019 UN Climate action summit. Excluding the 15 renewable energy companies in the sample.

Interestingly, the text-based measures of climate policy uncertainty do not increase in the periods around the Paris Agreement, as opposed to the average of forecast disagreement, which peaks in the months preceding the Paris Conference of Parties (COP). Arguably in such case uncertainty may have been high given the relevance of such accord for the future of the fossil-fuel industry. Nevertheless, with the exception of the Paris Agreement, the measure seems to track fairly well the trend of the EnvPU index proposed by [Noailly et al. \(2022\)](#) giving comfort that the measure used in this paper tracks, to a good extent, climate policy uncertainty.

Finally, I compare the average forecast disagreement with the average implied option volatility for the fossil-fuel firms in my sample. In [Figure A3](#), I show that this market measure of uncertainty co-moves with the level of forecast disagreement. This suggests that analysts' forecasts may be related to actual investment decisions and market outcomes. Moreover, I remove from the average implied volatility (IMVOL) the general stock market volatility using the S&P 500 volatility index (VIX) index. This additional analysis shows that the spikes in uncertainty may emerge from fossil-fuel companies specific events as opposed to general market uncertainty. The implied volatility of the S&P 500 remains flat throughout major climate events in the sample. This provides further support to the main assumption that forecast disagreement about the fundamentals of fossil-fuel firms may be a sensible measure of market climate policy uncertainty. Correlation coefficients are reported in [Table A9](#).



Figure A3: Investors disagreement and implied option volatility. Comparison of earnings per share forecast disagreement ($EPS_STD_{i,t}^{FH}$) - orange line - and average implied option volatility for the 303 companies with traded options (out of 480 fossil-fuel companies) removing S&P 500 option volatility - dashed line. Vertical lines from left to right represent Fourth IPCC assessment report release, Paris Agreement, President Trump withdrawal from it and 2019 UN Climate action summit. Excluding the 15 renewable energy companies in the sample.

C Additional figures and tables

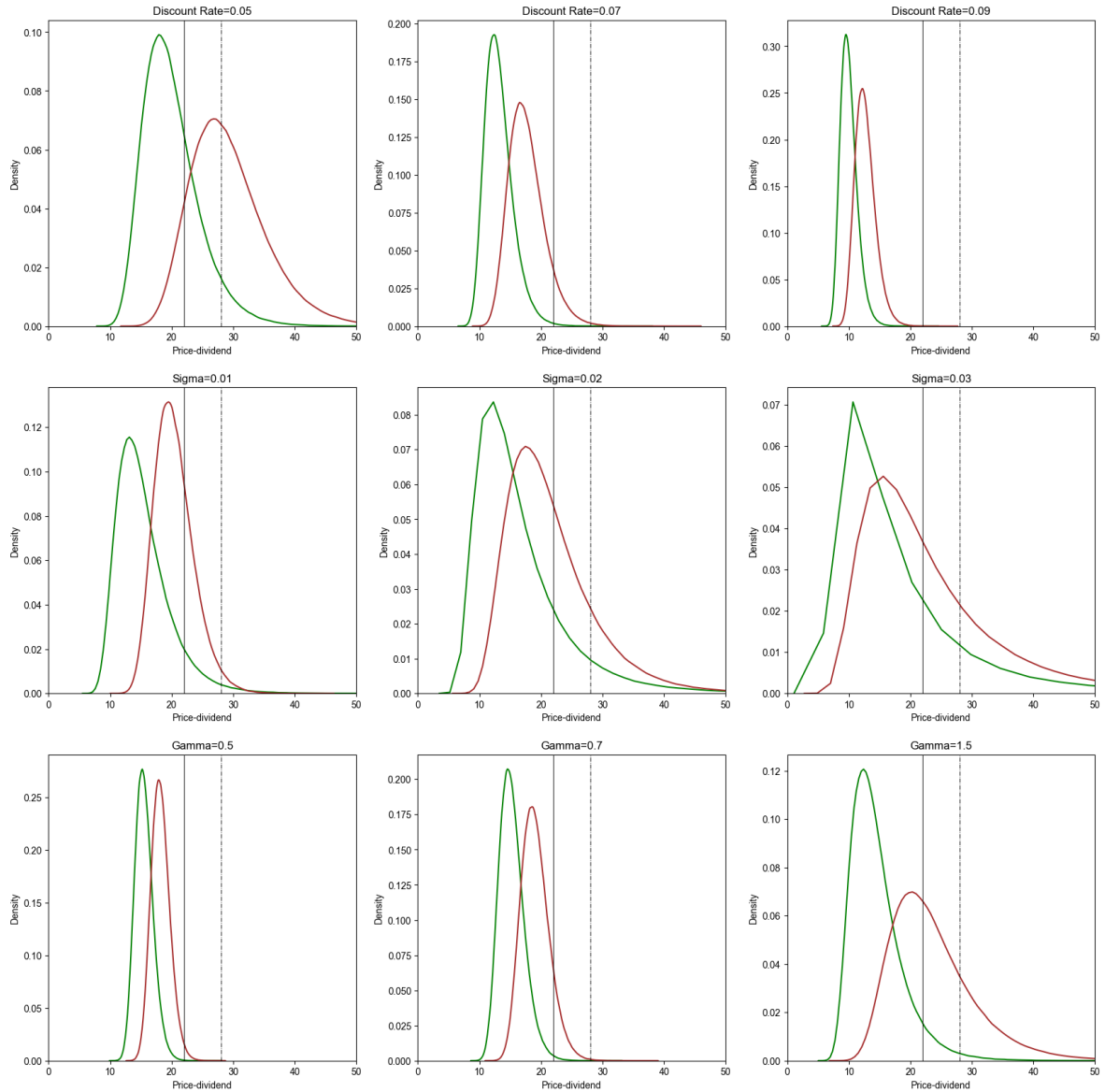


Figure A4: Price and μ probability distributions sensitivity. The chart shows the model generated distribution of price-dividend ratios using different calibration parameters. The green distribution represents climate policy shift scenarios and brown distribution represent no climate policy scenario. Values generated from parameters estimated based on an ensemble of NGFS climate scenarios conditional to the respective emission scenario. Full vertical line represents price-dividend ratio in Q4 2019, dashed line represents price-dividend ratio of the period 2016-2019 following the Paris Agreement. From top to bottom: simulation with three levels of discount rate r from 0.05 to 0.11, simulation of three levels of uncertainty σ^2 from 0.02 to 0.04, simulation of three levels of γ from 0.5 to 1.5. NGFS Scenarios used: Policy shift: Below 2°C, Net Zero 2050, Delayed transition, Divergent Net Zero. No policy shift: Current Policies. Models used: GCAM 5.3+ NGFS, MESSAGEix-GLOBIOM 1.1-M-R12, REMIND-MAGPIE 3.0-4.4

	Emission intensity revenues			Emission intensity assets			Log absolute emissions		
	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3
<i>DPS_G</i>	24.299*** (2.6987)	9.9384*** (0.6192)	7.5175*** (0.3029)	24.3938*** (2.7126)	9.9013*** (0.6181)	7.5369*** (0.3023)	26.1994*** (2.6838)	10.077*** (0.5966)	7.2865*** (0.3022)
<i>DPS_STD</i>	11.5108*** (3.336)	-7.8267*** (2.1587)	3.1553*** (2.0133)	12.2022*** (3.2911)	-7.7941*** (2.153)	2.9109*** (2.0166)	9.0567*** (3.2416)	-7.4911*** (2.0798)	3.4721** (2.0011)
<i>SCOPE_1</i>	-0.0003*** (0.0001)	-0.0001 (0.0001)	-0.0001 (0.0001)	0.0011*** (0.0001)	0.0002 (0.0001)	-0.0001 (0.0011)	0.8328*** (0.3403)	0.7727*** (0.3379)	0.7703*** (0.2331)
<i>SCOPE_2</i>	-0.0076*** (0.0019)	-0.0092*** (0.0019)	-0.0042*** (0.0012)	-0.0091 (0.0084)	-0.0314*** (0.0083)	-0.0185*** (0.006)	-2.7757*** (0.8272)	-2.6441*** (0.8179)	-1.7497*** (0.5387)
<i>SCOPE_3</i>	0.0001*** (0.000)	0.0001*** (0.000)	0.0001*** (0.000)	-0.0001 (0.0001)	0.0002 (0.0001)	0.0002* (0.0001)	1.0441*** (0.3689)	0.9102*** (0.3667)	0.5196*** (0.247)
R^2	0.0926	0.1651	0.6335	0.1098	0.1628	0.6334	0.1311	0.2179	0.6447
N	2421	2152	529	2436	2164	529	2445	2172	529
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table A1: Panel regression - price-dividend and forecast disagreement regression. Panel regression of price-dividend ratio, dividends per share mean growth forecast (*DPS_G*), dividend per share forecast disagreement - defined as the ratio between the standard deviation of analysts' estimates and the latest dividend per share - (*DPS_STD*), Scope 1,2,3 GHG emissions expressed in absolute and relative term (revenue and asset intensity). Controlling for firm fixed effect. From left to right: analysts' estimates for 1 fiscal year ahead (FH+1) up to 3 fiscal years ahead (FH+3). Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

	Emission intensity revenues			Emission intensity assets			Log absolute emissions		
	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3
<i>DPS_G</i>	33.2981*** (3.6959)	21.1773*** (1.308)	7.7613*** (0.3889)	33.7498*** (3.761)	21.4658*** (1.3224)	7.9534*** (0.4284)	34.9199*** (3.6524)	21.0423*** (1.3424)	8.2046*** (0.3648)
<i>DPS_STD</i>	7.6224** (4.5945)	10.3006* (6.5555)	1.6168 (2.4623)	8.4008** (4.7473)	11.6957** (6.4825)	1.723 (2.5508)	4.196 (4.5519)	13.1327*** (6.5077)	2.9484 (2.7698)
<i>SCOPE_1</i>	-0.0004 (0.0013)	0.0049*** (0.0018)	0.0016 (0.0015)	0.0369*** (0.0087)	0.0651*** (0.0093)	0.0094 (0.0075)	5.722*** (0.6209)	5.4706*** (0.6825)	-1.066** (0.6145)
<i>SCOPE_2</i>	-0.0233*** (0.0052)	-0.0278*** (0.0058)	-0.0022 (0.0043)	-0.1277*** (0.0266)	-0.2176*** (0.0279)	-0.0071 (0.0261)	-11.4157*** (1.4268)	-11.3648*** (1.5959)	2.0791** (1.1271)
<i>SCOPE_3</i>	0 (0.0001)	-0.0005*** (0.0001)	-0.0001 (0.0001)	-0.0008** (0.0005)	-0.0026 (0.0005)	-0.0001 (0.0005)	4.349*** (0.6415)	4.083*** (0.723)	-0.6663 (0.534)
ROE	77.528*** (6.8535)	33.7519*** (7.8033)	29.3699*** (6.8127)	81.6477*** (6.8106)	45.6709*** (7.7396)	30.1598*** (6.6137)	90.7101*** (6.5991)	45.691*** (7.622)	25.9262*** (6.5938)
Liquidity	0.0682* (0.043)	0.1172*** (0.0445)	-0.0269 (0.0274)	0.0975*** (0.0433)	0.1493*** (0.0441)	-0.0231 (0.0278)	0.0809** (0.0421)	0.1628*** (0.0442)	-0.0461** (0.0276)
Profit Margin	-10.1111*** (3.5488)	-4.113 (3.8186)	20.2271*** (4.3397)	-10.902*** (3.5133)	-6.5535** (3.7553)	21.1993*** (4.3444)	-14.2733*** (3.381)	-7.2457*** (3.7295)	22.9878*** (4.3008)
MB	1.2782*** (0.5222)	0.8824** (0.5321)	0.678*** (0.2706)	1.2111*** (0.6773)	1.4515*** (0.6831)	0.3591 (0.3127)	1.2796*** (0.5133)	0.9623** (0.5335)	0.8321*** (0.2666)
Leverage	3.3987 (6.4159)	9.9118* (6.7951)	-27.85*** (5.2577)	-2.9169 (6.6125)	14.3385*** (7.0163)	-30.2166*** (7.8147)	-19.4244** (10.2668)	4.7369 (11.5347)	-37.0031*** (7.8575)
Cash Debt	-50.8202*** (7.4716)	-57.9809*** (8.0707)	-10.4426 (7.7089)	-73.9358*** (7.8679)	-89.5926*** (8.2113)	-15.1901** (9.1075)	-98.0335*** (11.3734)	-94.5473*** (12.3614)	1.8338 (11.7244)
R^2	0.3323	0.4149	0.7771	0.308	0.4053	0.7796	0.3498	0.4036	0.7787
N	1078	956	285	1078	956	285	1079	956	285
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table A2: Robustness analysis - price-dividend and forecast disagreement regression. Panel regression of dividends per share growth mean forecast (*DPS_G*), dividend per share forecast disagreement (defined as the ratio between the standard deviation of analysts' estimates and the latest dividends per share - *DPS_STD*) and the price-dividend ratio. Controlling for firm fixed effects. From left to right: analysts' estimates for 1 fiscal year ahead (FH+1) up to 3 fiscal years ahead (FH+3). Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

	Emission intensity revenues			Emission intensity assets			Log absolute emissions		
	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3
<i>EPS_G</i>	27.2502*** (0.1603)	12.98*** (0.1166)	13.7058*** (0.136)	27.2028*** (0.1617)	15.3939*** (0.0511)	14.9817*** (0.1401)	27.1435*** (0.1629)	15.3985*** (0.0493)	14.9737*** (0.1394)
<i>EPS_STD</i>	76.5105*** (3.5108)	6.5801*** (0.3245)	10.8526*** (0.37)	71.1351*** (3.5313)	24.6416*** (1.3739)	19.1861*** (2.528)	70.937*** (3.6797)	27.5642*** (1.4774)	23.9605*** (2.8263)
<i>SCOPE_1</i>	-0.011*** (0.0008)	-0.0006*** (0.0002)	-0.004*** (0.0006)	-0.0917*** (0.0085)	-0.0367*** (0.0045)	-0.0363*** (0.0156)	-2.5105*** (0.9262)	-1.5041*** (0.3202)	-0.1005 (0.7964)
<i>SCOPE_1</i>	-0.0355*** (0.0177)	-0.0015 (0.0045)	-0.036*** (0.0096)	-0.0205 (0.0949)	0.0597 (0.0467)	0.0242 (0.1148)	2.9446*** (1.4499)	0.2718 (0.3062)	-0.5699 (0.7669)
<i>SCOPE_3</i>	-0.0028*** (0.0003)	0.0001 (0.0001)	-0.0003*** (0.0001)	-0.0061*** (0.0018)	0.0013 (0.0009)	-0.0026 (0.0021)	-2.1393*** (0.6594)	0.4487 (0.3157)	-0.8871 (0.5971)
R^2	0.7819	0.9828	0.9418	0.778	0.9174	0.7888	0.7745	0.9176	0.7898
N	8282	4004	1346	8282	9251	3172	8282	9251	3172
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table A3: Price-earnings and forecast disagreement - Winsorised regression. Panel regression of price-earnings ratio, earning per share growth mean forecast (*EPS_G*), earnings per share forecast disagreement - defined as the ratio between the standard deviation of analysts' estimates and latest earnings - (*EPS_STD*), Scope 1,2,3 GHG emissions expressed in absolute and relative term. Controlling for firm fixed effect. From left to right: analysts' estimates for 1 fiscal year ahead (FH+1) up to 3 fiscal years ahead (FH+3). Winsorising to the 5th and 95th percentile. Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

	Emission intensity revenues			Emission intensity assets			Log absolute emissions		
	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3
<i>EPS_G</i>	-45.0162*** (7.4724)	-34.8575*** (0.979)	-26.9768*** (1.0041)	7.9701*** (7.5738)	8.1953*** (0.9473)	9.0198*** (1.2481)	6.2517*** (7.0996)	5.6326*** (0.8978)	7.6415*** (1.0991)
<i>EPS_STD</i>	71.7916*** (9.1957)	56.0785 (7.1545)	39.0953*** (29.4485)	0.0745*** (10.403)	0.7899 (7.2033)	-3.6653*** (34.6903)	139.4269*** (9.1495)	159.3744 (6.6003)	106.0413*** (31.4603)
<i>SCOPE_1</i>	0.0099 (0.0004)	-0.0001 (0.0005)	2.0661*** (0.0007)	-0.0001*** (0.0034)	-0.0005 (0.0035)	2.4151 (0.0052)	-0.0065*** (0.3829)	-0.0017*** (0.3896)	-0.4583* (0.3003)
<i>SCOPE_2</i>	-0.0347*** (0.002)	-0.0103*** (0.0022)	-5.0708 (0.0032)	-0.0668*** (0.0105)	-0.0154*** (0.0112)	-6.185 (0.0157)	0.0131*** (0.94)	0.004*** (0.9312)	-0.915 (0.6405)
<i>SCOPE_3</i>	-0.0005*** (0.0001)	0.0001 (0.0001)	1.8509 (0.0001)	0.0008* (0.0003)	0.0002*** (0.0003)	2.2671 (0.0004)	0*** (0.4295)	0.0001*** (0.4393)	1.027*** (0.2908)
R^2	0.1713	0.1863	0.2342	0.2664	0.2761	0.3863	0.8757	0.8879	0.9334
N	492	492	492	367	367	367	34	34	34
FE Firm	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table A4: Panel regression considering minimum number of estimates greater than 15. Panel regression of price-earnings ratio, earning per share growth mean forecast (*EPS_G*), earnings per share forecast disagreement - defined as the ratio between the standard deviation of analysts' estimates and the absolute value of the latest earnings per share - (*EPS_STD*), Scope 1,2,3 GHG emissions expressed in absolute and relative term (revenue and asset intensity). Controlling for firm fixed effect. From left to right: analysts' estimates for 1 fiscal year ahead (FH+1) up to 3 fiscal years ahead (FH+3). Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. Considering at least 15 analysts' forecasts for each forecast date. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

	Emission intensity revenues			Emission intensity assets			Log absolute emissions		
	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3
<i>EPS_G</i>	15.7828*** (1.4887)	8.1093*** (0.3517)	11.4338*** (0.1841)	15.2102*** (1.4804)	7.9844*** (0.3516)	11.4045*** (0.1849)	14.141*** (1.4593)	8.1621*** (0.3439)	11.4513*** (0.1852)
<i>EPS_STD</i>	36.1642*** (2.8394)	0.5417 (1.4275)	-11.7913*** (1.3773)	32.2877*** (2.7964)	1.1212 (1.4165)	-12.644*** (1.3882)	29.3903*** (2.827)	0.3254 (1.3806)	-13.2866*** (1.3541)
<i>SCOPE_1</i>	-0.0001*** (0)	-0.0002*** (0)	0.0003*** (0.0001)	0.000*** (0.2886)	0.000* (0)	-0.0001*** (0)	0.1023 (0)	2.4821*** (0.254)	0.5872 (0.4126)
<i>SCOPE_2</i>	0.0011 (0.0063)	-0.0022*** (0.0007)	-0.0008 (0.0013)	0.0089 (0.6802)	-0.0074*** (0.0037)	0.0006 (0.0054)	-1.6785*** (0.0008)	-7.6011*** (0.5963)	-1.0468 (0.9737)
<i>SCOPE_3</i>	0.0000*** (0.0001)	0.0001*** (0)	0.0000 (0)	-0.0001 (0.2966)	0.0001*** (0.0001)	0 (0.0001)	1.1384*** (0)	3.5286*** (0.2605)	0.3725 (0.4301)
R^2	0.0915	0.1853	0.6499	0.0791	0.1886	0.6444	0.088	0.2178	0.6354
N	5026	4739	2859	5131	4820	2895	5205	4878	2922
FE Firm	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table A5: Panel regression considering minimum number of estimates greater than 5. Panel regression of price-earnings ratio, earning per share growth mean forecast (*EPS_G*), earnings per share forecast disagreement - defined as the ratio between the standard deviation of analysts' estimates and the absolute value of the latest earnings per share - (*EPS_STD*), Scope 1,2,3 GHG emissions expressed in absolute and relative term (revenue and asset intensity). Controlling for firm fixed effect. From left to right: analysts' estimates for 1 fiscal year ahead (FH+1) up to 3 fiscal years ahead (FH+3). Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. Considering at least 5 analysts' forecasts for each forecast date. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

	Emission intensity revenues			Emission intensity assets			Log absolute emissions		
	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3
<i>EPS_G</i>	17.1052*** (0.6361)	6.9151*** (0.1191)	11.2296*** (0.1385)	28.3143*** (0.6379)	6.9207*** (0.1183)	11.6557*** (0.1283)	17.8288*** (0.5806)	13.2681*** (0.1197)	14.2242*** (0.1204)
<i>EPS_STD</i>	27.1682*** (1.4348)	-0.0001*** (0.33)	-0.0031*** (0.3855)	-0.0043*** (1.4482)	-0.0009*** (0.3277)	-0.0286*** (0.3886)	24.485*** (1.3179)	5.7348*** (0.3307)	11.7644*** (0.3828)
<i>SCOPE_1</i>	-0.0009* (0.0006)	-0.0086 (0.0002)	-0.0358*** (0.0006)	-0.5352** (0.0023)	-0.0388* (0.0006)	0.0446*** (0.0099)	-40.5824*** (8.1869)	-5.5114*** (2.5809)	-11.0889*** (4.2097)
<i>SCOPE_2</i>	-0.1748*** (0.0138)	0.0001** (0.0048)	-0.0002*** (0.0105)	0.0018*** (0.1002)	0.0006 (0.032)	-0.0015 (0.0663)	9.4041* (5.7907)	0.5639 (1.8858)	8.0049*** (3.0257)
<i>SCOPE_3</i>	0.0017*** (0.0002)	-5.3806*** (0.0001)	-7.684* (0.0001)	7.6564 (0.0014)	-5.6498* (0.0004)	-12.3879 (0.0012)	-1.062 (1.8816)	0.8697 (0.6387)	-1.6532* (1.0151)
Oil & Gas Integrated	-28.6921 (10.7114)	-12.5501* (3.583)	-12.3189 (5.6183)	-19.1706 (11.0083)	-12.1612* (3.5704)	-15.7063*** (6.1507)	553.8283*** (93.3896)	64.5136*** (29.5752)	84.4228** (49.6363)
Oil & Gas Exploration & Production	6.0277*** (5.9428)	-1.6712*** (2.1111)	3.4812*** (3.6648)	30.872*** (5.5961)	-1.7374*** (1.919)	14.6732*** (4.1019)	487.455*** (86.3388)	54.8813*** (27.389)	76.3594** (44.8119)
Oil & Gas Refining & Marketing	-39.2344 (10.6681)	-3.1263 (3.6876)	-6.316 (6.8463)	-46.3015*** (11.3972)	-3.0683 (3.7567)	-12.9933** (8.7145)	536.9284*** (89.6028)	65.6017*** (28.2971)	98.6779*** (46.763)
Oil & Gas Storage & Transportation	-12.2363*** (8.3302)	11.3516 (2.5497)	-11.434 (5.6916)	-12.5959*** (8.996)	11.6155 (2.6562)	-5.2359** (6.8559)	430.0717*** (85.4417)	61.4769*** (27.1637)	72.1224* (43.9035)
Coal & Consumable Fuels	12.8433 (23.433)	13.7574* (7.4975)	16.2278 (11.8621)	12.855 (23.9571)	14.1271* (7.4611)	-5.2359 (12.699)	495.6135*** (89.8103)	78.3061*** (28.4755)	82.7269** (46.4238)
R^2	0.8958	0.983	0.9424	0.8906	0.9830	0.9400	0.887	0.9815	0.9394
N	3424	4009	1351	3443	4048	1353	3513	4121	1371
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Table A6: Panel regression including sub-industries. Panel regression of price-earnings ratio, Scope 1,2,3 GHG emissions expressed in absolute and relative term (USD mln revenues and assets), earning per share growth mean forecast (*EPS_G*), earnings per share forecast disagreement - defined as the ratio between the standard deviation of analysts' estimates and the absolute value of the latest earnings per share - (*EPS_STD*), and Sub-industries. Controlling for firm fixed effect. From left to right: analysts' estimates for 1 fiscal year ahead (FH+1) up to 3 years fiscal years ahead (FH+3). Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

	(1)			(2)		
	FH 1	FH 2	FH 3	FH 1	FH 2	FH 3
<i>EPS_G</i>	4.7607*** (0.4174)	9.653*** (0.1036)	0.0998*** (0.0298)	5.032*** (1.5871)	15.1348*** (0.3077)	18.3934*** (0.3067)
<i>EPS_STD</i>	2.8888*** (0.6759)	7.5983*** (0.1477)	0.1848*** (0.0751)	41.8321*** (1.9537)	9.2057*** (0.7782)	16.7057*** (0.5838)
ESG	-14.2924*** (5.4931)	-4.256 (4.8142)	1.5273 (9.544)	12.5862*** (11.9607)	9.2866*** (10.7321)	18.4701*** (16.8017)
ROE				31.5176*** (12.5583)	12.2061 (10.7171)	7.2309 (22.0175)
Liquidity				0.0304 (0.0666)	0.1579*** (0.0546)	-0.3587*** (0.1727)
Profit Margin				-15.7909*** (6.9868)	-6.1174 (6.1265)	-10.8346 (10.005)
<i>M/B</i>				1.8768* (1.2254)	0.2918*** (1.2897)	6.8752*** (2.8981)
Leverage				-76.5667*** (19.2522)	-0.9529 (17.4137)	-116.5636*** (32.6335)
Cash to Debt				-0.1104 (16.8417)	-100.9435*** (15.3721)	-6.4637 (25.6419)
R^2	0.0587	0.6646	0.006	0.1441	0.4578	0.7506
N	4835	5467	2124	2924	3047	1387
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes

Table A7: Panel regression robustness including ESG ratings. Panel regression of price-earnings ratio, earning per share growth mean forecast (*EPS_G*), earnings per share forecast disagreement - defined as the ratio between the standard deviation of analysts' estimates and the absolute value of the latest earnings per share - (*EPS_STD*), and Refinitiv ESG scores. Controlling for firm fixed effect. From left to right: analysts' estimates for 1 fiscal year ahead (FH+1) up to 3 fiscal years ahead (FH+3). Monthly estimates between January 2010 and December 2019 for 480 fossil-fuel companies. Considering at least 5 analysts forecasts. *** significant at 5% confidence level, ** significant at 10% confidence level, * significant at 15% confidence level. Standard errors in brackets.

	P/E	EPS_G	EPS	ROE	Liquidity	Profit Margin	M/B	Leverage	Cash debt
P/E	1	0.106	0.1	0.02	0.00	0.00	0.00	-0.02	0.02
EPS_G	0.16	1	-0.36	0	0.00	0.03	0.02	-0.01	0.03
EPS_STD	0.10	-0.36	1	-0.08	0.00	-0.04	-0.04	0.07	-0.03
ROE	0.02	0	-0.08	1	0.02	0.38	-0.38	-0.28	0.12
Liquidity	0.00	0.00	0.00	0.02	1	0.1	0.00	0.01	0.10
Profit Margin	0.00	0.03	-0.04	0.38	0.1	1	-0.19	-0.14	0.22
M/B	0.00	0.02	-0.04	-0.38	0.00	-0.19	1	0.29	-0.02
Leverage	-0.02	-0.01	0.07	-0.28	0.01	-0.14	0.29	1	-0.40
Cash debt	0.02	0.03	-0.03	0.12	0.1	0.22	-0.02	-0.4	1

Table A8: Regression variables correlation. Pearson correlation coefficient matrix of variables in empirical analysis. From top to bottom and left to right: price earnings ratio (P/E), analysts earnings growth mean forecast (EPS_G), analysts forecast disagreement (EPS), Return on Equity (ROE), Interest coverage ration (Liquidity), Profit margin, Market to Book ratio (M/B), debt to assets (Leverage) and cash to debt. Monthly data between January 2010 and December 2019 for 480 fossil-fuel companies.

	PD	<i>E_STD_1</i>	<i>E_STD_2</i>	<i>E_STD_3</i>	VIX	GEPU	CPU	EnvPU	OECD	IVOL	IVOLSPX
PD	1	-0.54	-0.78	0.26	0.34	-0.67	-0.52	-0.31	-0.66	-0.52	-0.78
<i>EPS_STD_1</i>	-0.54	1	0.62	-0.21	-0.24	0.37	0.25	0.22	0.44	0.26	0.44
<i>EPS_STD_2</i>	-0.78	0.62	1	-0.34	-0.27	0.44	0.28	0.12	0.33	0.66	0.86
<i>EPS_STD_3</i>	-0.54	0.27	0.62	1	-0.4	0.05	0.02	0.12	0.43	0.34	0.62
VIX	0.34	-0.24	-0.27	0.09	1	0.02	-0.07	0.02	-0.31	0.35	-0.28
GEPU	-0.67	0.37	0.44	-0.27	0.02	1	0.66	0.23	0.42	0.37	0.38
CPU	-0.52	0.25	0.28	-0.01	-0.07	0.66	1	0.52	0.58	0.19	0.27
EnvPU	-0.31	0.22	0.12	0.24	0.02	0.23	0.52	1	0.59	0.13	0.15
OECD	-0.66	0.44	0.33	0.14	-0.31	0.42	0.58	0.59	1	0.09	0.33
IVOL	-0.52	0.26	0.66	-0.36	0.35	0.37	0.19	0.13	0.09	1	0.8
IVOLSPX	-0.78	0.44	0.86	-0.4	-0.28	0.38	0.27	0.15	0.33	0.8	1

Table A9: Indexes correlation. Pearson correlation coefficient matrix among climate uncertainty, general uncertainty indexes and measures of forecast disagreement for FH 1,2,3. Vix of the S&P 500 index retrieved from Fred Database, Global Economic Uncertainty Index (GEPU) of [Bloom \(2009\)](#), Climate Policy Uncertainty index (CPU) of [Gavriliadis \(2022\)](#) used by [Chan and Malik \(2022\)](#), EnvPU from [Noailly et al. \(2022\)](#) and OECD CPU index of [Berestycki et al. \(2022\)](#). Average implied option volatility of fossil-fuel firms in the sample (IVOL) and Average implied option volatility of fossil-fuel firms in the sample minus implied volatility of S&P 500 index (IVOLSPX).

Date	Event
20/04/10	BP Oil Rig explodes
10/12/10	COP 16
11/03/11	Fukushima
01/09/11	Solyndra bankruptcy
09/11/11	COP 17
09/02/12	US NRC approves new Nuclear Power Plants
27/03/21	EPA clean air act
17/04/12	EPA clean air act for natural gas
06/11/12	Obama election
07/12/12	COP 18
25/06/13	Obama climate action plan
20/09/13	EPA new rule to cut emissions from plants
23/11/13	COP 19
13/02/14	Ivanpah, World's largest Solar power generation plant goes online
22/09/14	Rockefellers and over 800 global investors announce fossil fuel divestment
23/09/14	Climate summit 2014
01/11/14	IPCC Fifth Assessment Report
12/12/14	COP 20
03/08/15	Obama announces Clean Power Act
12/12/15	COP 21
08/11/16	Trump election
18/11/16	COP22
28/03/17	Trump sign reversal of Obama Clean power Act
01/06/17	US Withdraws from Paris Agreement
31/07/17	Two nuclear plants abandoned before construction completed in NC
22/12/17	Act opens Arctic Drilling
09/05/18	Solar power to be required by all New California homes by 2020
02/12/18	COP 24
22/03/19	New Mexico Commits to 100% Renewable Energy for Electricity by 2050
02/12/19	COP 25
20/10/19	Three Mile Island to Close

Table A10: Climate Policy Events. List of major climate policy events between 2010 and 2020

Date	Event	Property Damage (2021 USD)	Fatalities
30/04/11	Flooding	7,694,617,566	402
31/05/11	Coastal Flooding	7,997,691,811	202
31/08/11	Hurricane/Tropical Storm	4,083,073,551	113
31/07/12	Heat	755,061,921	121
31/10/12	Heat	24,326,399,473	49
31/05/13	Flooding	2,769,247,857	68
31/12/15	Flooding	406,764,972	61
30/06/16	Heat	206,311,372	62
31/08/16	Flooding	9,735,094,174	25
31/10/16	Coastal Flooding	4,210,043,341	37
31/08/17	Severe Storm/Thunder Storm	94,468,908,739	118
30/09/17	Hurricane/Tropical Storm	25,868,233,259	45
31/07/18	Heat	1,660,779,779	137
31/10/18	Hurricane/Tropical Storm	6,038,462,572	15
30/11/18	Wildfire	19,732,088,872	101

Table A11: Climate Physical Events. List of major climate disasters in the US between 2010 and 2020. Major disaster defined as event which caused either fatalities or property damages higher than the 90th percentile of events in the decade 2010-2020.

Democratic	Republican
BERGEN-PASSAIC, NJ	AUSTIN-SAN MARCOS, TX
BOSTON-WORCESTER-, MD	CHICAGO, IL
DENVER, CO	DALLAS, TX
FLORIDA	FORT WORTH-ARLINGTON, TX
HARTFORD, CT	HOUSTON, TX
JERSEY CITY, NJ	LOUISVILLE, KY-IN
LOS ANGELES-LONG BEACH, CA	MEMPHIS, TN-AR-MS
MIDDLESEX-SOMERSET-HUNTERDON, NJ	NASHVILLE, TN
MINNEAPOLIS-ST. PAUL, MN-WI	OKLAHOMA CITY, OK
NASSAU-SUFFOLK, NY	
NEW HAVEN-BRIDGEPORT	
NEW YORK-NEWARK, NY-NJ-PA	
NEWARK, NJ	
ORANGE COUNTY, CA	
PORTLAND-VANCOUVER,OR-WA	
RICHMOND-PETERSBURG, VA	
SAN DIEGO, CA	
SAN FRANCISCO, CA	
SAN JOSE, CA	
SEATTLE-BELLEVUE-EVERETT, WA	
WASHINGTON, DC-MD-VA-WV	

Table A12: Political orientation. Metropolitan statistical area and State political Orientation. Political orientation defined in terms of election results between 2004 and 2020 (four electoral cycles). Without considering states where election results were mixed in the four electoral cycles considered.

Part IV

Implications for traditional finance models

Model-based financial regulations impair the transition to net zero carbon emissions¹

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Abstract

Investments via the financial system are essential for fostering the green transition. However, the role of existing financial regulations in influencing investment decisions is understudied. Here we analyse data from the European Banking Authority (EBA) to show that existing financial accounting frameworks might inadvertently be creating disincentives for investments in low carbon assets. We find that differences in the provision coverage ratio (PCR) indicate that banks must account for nearly double the loan loss provisions for lending to low carbon sectors as compared to high carbon. This bias is likely the result of basing risk estimates on historical data. We show that the average historical financial risk of the oil and gas sector has been consistently estimated lower than renewable energy. These results indicate that this bias could be present in other model-based regulations, such as capital requirements, and possibly impact the ability of banks to fund green investments.

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The urgency of climate change has not always been matched by the pace of action by governments. But increasing concerns about climate-induced financial instability and stranded assets (Battiston, Guth, Monasterolo, Neudorfer, & Pointner, 2020; D’Orazio, Hertel, & Kasbrink, 2022; Lamperti, Bosetti, Roventini, & Tavoni, 2019; Mercure & et al., 2018; Semieniuk & et al., 2022) has led some academics and financial regulators to advance a set of possible policy changes to help catalyse the green transition (Alessi, Girolamo, Pagano, & Petracco, 2022; Campiglio, 2016; Dafermos & Nikolaidi, 2021, 2022; Diluiso, Annicchiarico, Kalkuhl, & Minx, 2021; Philipponnat, 2020). While various policies aimed at assessing climate related financial risks - which could possibly indirectly stimulate the net zero carbon transition - have become widespread in recent years (e.g., climate stress testing, climate related risk disclosure) (Ameli, Drummond, Bisaro, Grubb, & Chenet, 2020; Ameli, Kothari, & Grubb, 2021; Edwards, Yapp, Mackay, & Mackey, 2020; Goldstein, Turner, Gladstone, & Hole, 2019), financial policies aimed at directly fostering green investments have not always gained traction among policymakers (e.g., differentiated capital requirements). Yet, a largely neglected question in this literature and among policymakers is whether existing financial regulations could be negatively contributing to the net zero carbon transition.

This paper assesses whether widely used model-based risk regulations might create disincentives for financial institutions to divest their portfolios from high carbon assets. Such financial regulations have extensively required banks to use statistical models for assessing firms and investments financial risk for various purposes (e.g., financial stability). For example, capital requirements (e.g., Basel III/IV) aim to force banks to hold higher capital buffers for investments that are estimated to be riskier. Accounting rules (e.g., IFRS9) appraise the “fair value” of outstanding loans on banks’ balance sheet, reducing their net value by the amount of estimated expected losses. These regulatory frameworks affect key metrics of financial institutions which ultimately influence management’s incentives and resources allocation (Aymanns, Caccioli, Farmer, & Tan, 2016; Beatty & Liao, 2014; Glancy & Kurtzman, 2022; Gropp, Mosk, Ongena, & Wix, 2019).

We focus on financial accounting rules which are a key driver of the profitability of banks and leverage model-based estimates of risk. A key measure in this framework is Loan Loss Reserves (LLR), which is an allowance for potential future losses from outstanding loans. Due to the structure of double-entry accounting, LLR are liabilities which net the valuation of assets by the amount of their expected losses. Any change in LLR results in Loan Loss Provision charges (LLP), which are a present cost of the future expected credit losses from outstanding loans (ECL). When there is any change in these model-based estimates of risk, banks are expected to account for any estimated financial losses before they occur. In turn, differentials in any of these estimates may influence banks' profitability, management behaviour and resources allocation.

To examine the impact of such financial accounting rules we use data from the European Banking Authority (EBA) transparency exercise which provides the amount of LLR and outstanding loans of supervised banks in the European Union by economic sector (defined as NACE rev2 level 1). We combine these data with the results of the EBA risk assessment exercise, which reports the average exposure towards climate policy relevant sectors (CPRS) 5 within each NACE level 1 section, to classify sectors as "high carbon" or "low carbon". We classify the sectors with a share of CPRS higher than 95% as high carbon and provide a set of robustness analyses. We are particularly interested in the ratio of loan loss reserves over the value of outstanding loans, which is a proxy of banks' estimates of expected credit losses. This measure is oftentimes called provision coverage ratio (PCR).

Our empirical analysis allows us to observe that model-based estimates of risk are lower for high carbon sectors compared to low carbon ones. We then provide an assessment of what are the implications of this observation for some key financial metrics of banks if they had to divest from high carbon assets. Specifically, we utilise the accounting relationships among some of these metrics to show that an active divestment from high carbon assets could be costly for banks. We argue that this, in turn, could create perverse incentives impairing the shift of financial resources from high carbon to low car-

bon assets, possibly including much needed investments in renewable energy. Finally, we provide some possible explanations as to why some of these models may lead to estimates that are negatively correlated to carbon emissions.

1 Results

Our analysis shows that in 2021 the average provision coverage ratio of banks in the EU was substantially lower for high carbon (1.8%) than low carbon sectors (3.4%), as reported in Table 13. Such a difference has substantial implications for banks' return on capital and profitability and therefore heavily influences management incentives and behaviours. Our analysis shows that this result is consistent for banks of different portfolio size and across country of the banks' headquarters, with the only exception being Italy. Looking at the results by the size of banks, this effect is exacerbated for smaller financial institutions in absolute terms, but in relative terms there is no correlation between the difference in provision coverage ratio and the bank size. This finding is also consistent across countries, regardless of the large variation in terms of absolute provision coverage ratio between Nordic and Southern/ Eastern European regions.

These results emerge from banks' statistical models based on historical information as required by the accounting framework. Standard backward-looking risk models can show a high carbon portfolio to be relatively low risk, even if there is a possibility of a rapid transition to green energy (see Section 5). Although it is arguably difficult to take an objective stance on the correct estimate of risk for these investments on a forward-looking basis, our analysis is sufficient to show that the structure of model-based risk frameworks may have an unintended side effect that is potentially in conflict with the purpose of the regulations or other societal goals. By affecting financial institutions' incentives, model-based financial regulations may create perverse outcomes possibly leading to more investments in polluting activities.

		PCR low carbon	PCR high carbon	N Banks
Total sample		0.034	0.018	59
Book size (quartile)	0-25	0.0729	0.0328	14
	25-50	0.0368	0.0201	15
	50-75	0.0282	0.0113	15
	75-100	0.032	0.0194	15
Country	Austria	0.0298	0.0212	3
	Belgium	0.037	0.0227	2
	Denmark	0.0192	0.006	3
	Finland	0.0146	0.0117	2
	France	0.0324	0.0198	9
	Germany	0.0208	0.01	12
	Greece	0.1249	0.0652	4
	Hungary	0.0485	0.0353	1
	Ireland	0.0502	0.0495	2
	Italy	0.0475	0.0487	7
	Netherlands	0.0242	0.0104	4
	Portugal	0.0673	0.0325	1
	Spain	0.0348	0.0242	5
Sweden	0.0071	0.0044	4	

Table 13: Provision coverage ratio for high carbon and low carbon investments for European Banks Exposure weighted average provision coverage ratio (PCR) for sectors classified as high carbon and low carbon for 59 of the largest European banks participating in the EBA transparency exercise, representing 93% of total banking exposure as of June 2021. PCR defined as the ratio of loan loss reserves over value of outstanding loans. The table reports the breakdown by bank size (quartile of total loan outstanding) and country of the bank headquarter

Simulating the effect of a divestments from high carbon activities and a re-investment in low carbon sectors allows us to better understand the effects of such action on banks' financial metrics and the linked management incentives which ultimately affect behaviours and resources allocation. Specifically, as indicated by the accounting rules, we assume that if a bank had to divest from high carbon sectors and re-invest the proceeds in low carbon sectors, the PCR of such investments would need to increase to the higher level of the latter (Table 13). This, in turn, would lead to a higher level of loan loss provisions and higher costs due to the structure of the accounting rules (see Section 3).

1.1 Simulation of a divestment strategy

Due to the model-based risk estimates of PCR required by the accounting regulation, the performance of financial institutions would be substantially impacted if they were to swiftly shift their portfolio away from high carbon to other investments. Our modelling shows that if banks had to stop lending to firms in high carbon-sectors and lend only to low carbon ones, the portfolio average provision coverage ratio would need to increase by more than 100 basis points (1%) across most institutions in the European banking sector (Figure 1). This effect is consistent for most banks in our sample and across various nations, with the exception of a few institutions with low provision coverage ratio for high carbon assets. Banks in countries with the largest difference in PCR between high carbon and low carbon assets would be hit substantially more according to our analysis. Most financial institutions would be affected by this shift regardless of their size, but, in line with our empirical observations, banks in the smaller size quartile would be impacted more than others (2.35% increase compared to 0.9% simple average).

We estimate that a shift in investments away from high carbon to low carbon assets would require a loan-weighted average increase of 35% of LLR for banks in the European Union (Figure 6). This result is consistent after controlling for bank size and country of headquarter. The decision to divest from high carbon assets could lead to more than doubling of provisions for some banks in our sample and could thus have material impacts on the bank's stock market valuations. The increase in loan loss reserves will not only depend on the difference between the estimated expected loss from lending to low carbon and high carbon activities, but also on the share of high carbon loans. The higher the share of current outstanding loans towards high carbon firms, the more pronounced the impact on LLR given a certain level of difference in provision coverage ratio. This relationship further exacerbates the potential impact of a divestment for banks more exposed to high carbon sectors creating greater hysteresis in investing in high carbon sectors and contributing further to the build-up of risk in assets that could become stranded in a green transition.

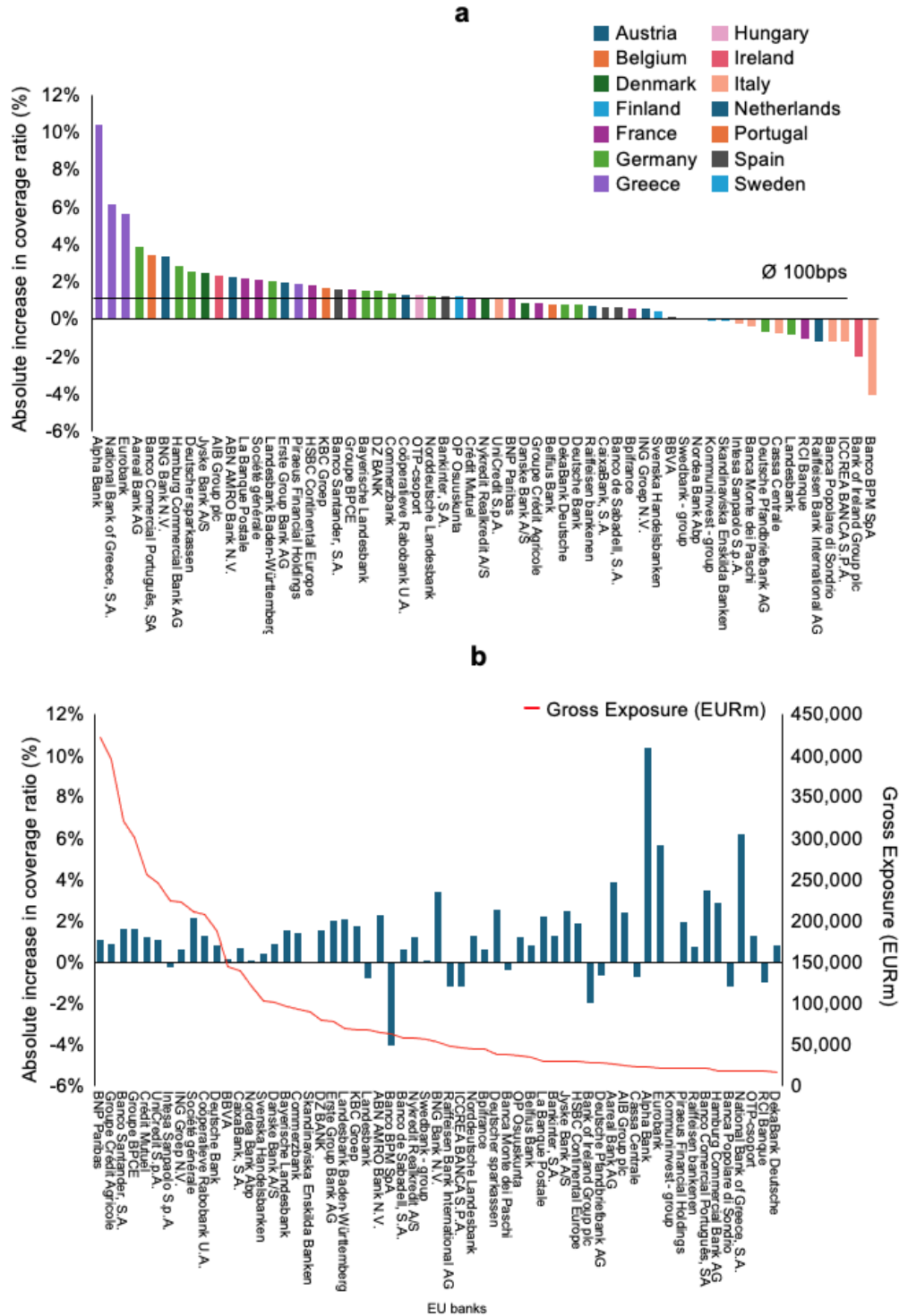


Figure 5: Change in provision coverage ratio increase for 59 largest European banks. Absolute percentage increase in provision coverage ratio (PCR) following a divestment from high carbon assets and corresponding re-investment in low carbon assets, maintaining a constant level of outstanding loans by bank. Colours represent the country of bank's headquarters. The increase in PCR represents the difference between PCR required for low carbon as opposed to high carbon assets, for each bank in our sample. Horizontal line represents average in basis points (bps). a) show the banks ranked by absolute increase in PCR. b) is the same information ranked by gross loan exposure (from largest on left hand side to smallest).

The increased provision coverage ratio, loan loss reserves and the resulting loan loss provision charges driven by a potential divestment strategy could weigh substantially on banks' net profits. An increase in loan loss reserves not only impacts the liability side of the balance sheet, but also the income statement through decreased profits. In order to simulate this effect, we take the absolute increase in loan loss provisions, and we compare it to each bank's cumulative profits from 2016 to 2020. We select 5 years of profits to smooth possible bad years or extraordinary items in the financial reporting and to provide a stable baseline for our counterfactual analysis.

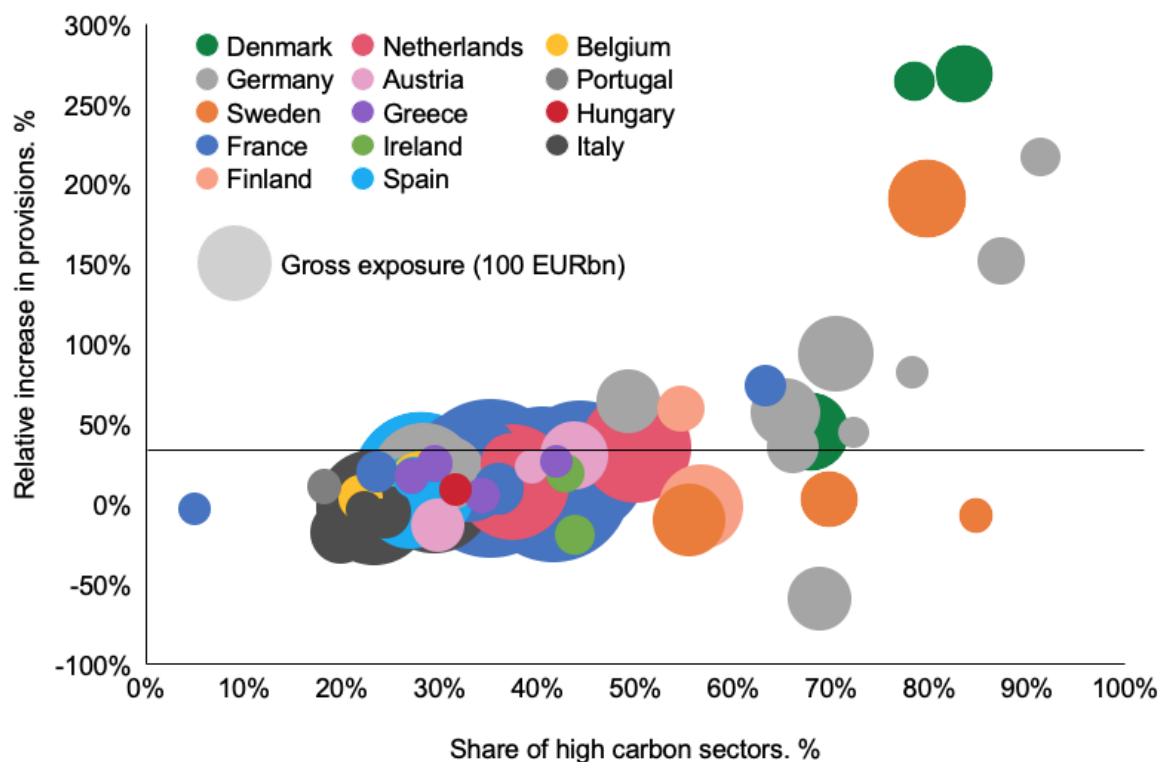


Figure 6: Relative increase in loan loss reserves. Relative increase in loan loss reserves (LLR) following a divestment from high carbon assets and corresponding re-investment in low carbon assets, maintaining a constant level of outstanding loans. Horizontal axis represents current share of high carbon sector outstanding loans (June 2021). Bubbles represent banks in our sample, colour coded based on the country of headquarter. Bubble size represents the total value of outstanding loans. Relative increase in LLR represents the absolute increase in LLR over the level of LLR as of June 2021. Results are gross exposure weighted. Horizontal line is weighted average by gross exposure across banks (35%).

We estimate that for some banks the transition could cost as much as five years of profits over the divestment horizon and, on an outstanding loan weighted average basis, 15% of the previous five years of profits due to a large increase in loan loss reserves (Figure 7). The total sum of banks' lost profits due to the increase in provisions following a divestment from high carbon assets could be of the order of 28 Euro billion (considering the 59 largest banks in the European Union). This is only a rough estimate as it does not account for how such divestment could affect other investments in a network of interconnected banks (indirect effects), whether sufficient alternative investment opportunities are available to the banks, or the impact on the costs and prices of alternative energy generation options resulting from changes in the investments in those options. However, this figure is useful to assess the materiality of our findings. The European Central Bank (ECB) estimates that the impact of physical risk and transition risk could be around 17 and 53 Euro billion respectively in a short-term scenario for the 41 largest banks in the Euro area.

Although, there are a few instances of banks who experience higher profits due to their lower estimate of risk for low carbon than high carbon sectors, our results show consistently that most banks' profits would be negatively impacted by a divestment from high carbon assets. Our findings are also robust to the classification of specific sectors as high carbon. It is the prevalence of the lowest provision coverage ratio among the high carbon sectors, in general terms, that drives our key results. We found that relabelling some selected sectors between high carbon and low carbon clusters does not alter the main outcome of our study, although the magnitude of the impact can change (Section 4). This sensitivity test provides us with confidence that sectors with particularly low (high) levels of PCR among the high carbon (low carbon) sectors are not driving our results.

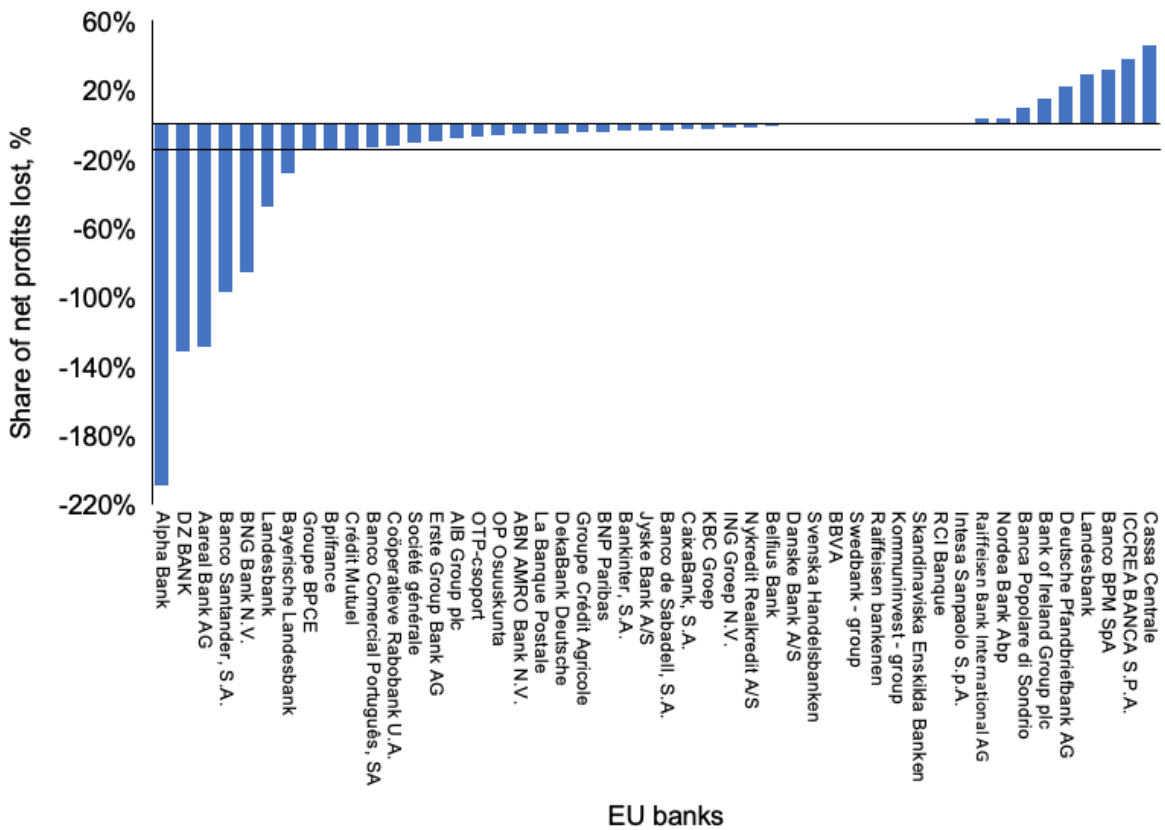


Figure 7: Impact on average 5 years net profits. Impact on net profits following a divestment from high carbon assets and corresponding re-investment in low carbon assets, maintaining a constant level of outstanding loans by banks. Bars represent the share of cumulative 2016-2020 profits lost due to the required increase in LLR. The impact represents the ratio of absolute increase in LLR over the cumulative profits between 2016-2020. The horizontal line represents the average loss of profits (-15%).

We then simulate the impact of allocating each sector partially to the low carbon and to the high carbon cluster depending on their median share of climate policy relevant sectors (CPRS) found among banks in the European Union taking part in the EBA risk assessment exercise. This robustness analysis simulates a partial divestment of only the high carbon portion of investments in each NACE level 1 and allows us to better investigate the heterogeneity of high carbon/low carbon sectors within each NACE level 1 section. This is because the underlying CPRS classification leverages a much more granular sectorial classification (NACE level 4) which better captures whether economic activities are high carbon or low carbon. Once again, we find that our main results

persist. Moreover, our results are robust after controlling for different time periods. If we use quarterly average levels from March 2020 to June 2022 (maximum temporal depth of the data) the impacts are similar (100% increase in PCR, 33% increase in provisions, 14% impact on previous 5 years profits).

The robustness of our results highlights that our findings are not a function of the specific high carbon/low carbon classification used but driven by a lower average estimated risk for high carbon sectors compared to low carbon ones. As long as the structure of the regulation foresees that i. losses are costs that are accounted for as expected as opposed to incurred and ii. provision coverage ratios are proportional to model-based estimates of risk, then divesting from an estimated low-risk asset and re-investing in an estimated high-risk asset mechanically leads to higher costs in the income statement. Indeed, despite not being able to use carbon emissions data directly, in our Discussion and Methods sections, we provide strong evidence for a negative correlation between CPRS / emission intensity of assets and risk estimates (Figure 9). This in turn leads to a confirmation of our conclusion that there likely exists an implicit incentive structure which might inadvertently favour assets involved in high carbon activities.

2 Discussion

The bias shown toward high carbon assets identified in this paper likely emerges from the backward-looking nature of risk estimates. That is, it is the outcome of using models that rely on the historical relationship between a firm's financial performance and past risk as a predictor of future risk. As discussed in the literature and by policymakers, such models are useful but may not be well suited to capturing uncertain macro-economic outcomes when there are structural breaks or non-marginal changes in the system – such as the clean energy transition. In these risk-based models, the creditworthiness of firms is oftentimes estimated through financial ratios measuring profitability (e.g., EBIT/Revenue), solvency (e.g., Debt/Asset, Interest/EBITDA) and liquidity (e.g., short term debt/working capital). If these ratios have been historically favourable for high carbon

firms, as previous research has highlighted (Schmidt, 2014), risk models will likely produce favourable outcomes for this type of investment. This phenomenon might arguably limit investments in green assets if their past risk estimates have been relatively high.

To illustrate this, we use a simple analysis based on a dataset of 228 oil & gas and 235 renewable energy firms worldwide and financial information between 2010-2021, retrieved from Bloomberg (See Section 5). We use this dataset as a representative sample of some of the most relevant sectors in the high carbon and low carbon clusters. We construct some financial ratios that are commonly used in risk assessment to investigate the origins of risk estimates differentials. We then contrast them to infer the likely relative magnitude between these two important sectors in the net zero carbon transition. The average share of interest expenses over Earnings Before Interest, Taxes, Depreciations and Amortizations (EBITDA) for the period 2010-2021 is lower for oil & gas (16%) than renewable energy firms (32%) and the average debt over asset ratio lower for oil & gas (31%) than renewable energy (42%) (Figure 8). Similarly, the outcome of one such models retrieved from Bloomberg shows consistently higher average estimates of risk (expressed in terms of probability of default) for renewable energy than oil & gas between 2010 and 2021 (Figure 8). This highlights how historically investing in the former might have been less risky compared to the latter, due to the higher solvency and lower indebtedness.

These ratios have been a good proxy of the historical creditworthiness of firms and have been used extensively by financial analysts. However, problems arise if these historical metrics are not representative of the future, following a change in the probability distribution of losses (Holscher, Ignell, Lewis, & Stiroh, 2022). For example, we estimate that if there were an increase in the average global level of carbon tax enforced on Scope 1 and 2 emissions to USD \$100 (or climate policies with an equivalent shadow carbon price), the ratio of interest expenses over EBITDA for oil & gas firms might increase substantially above the ratio of renewable energy companies (from 16% to 46% against 32% for renewable energy).

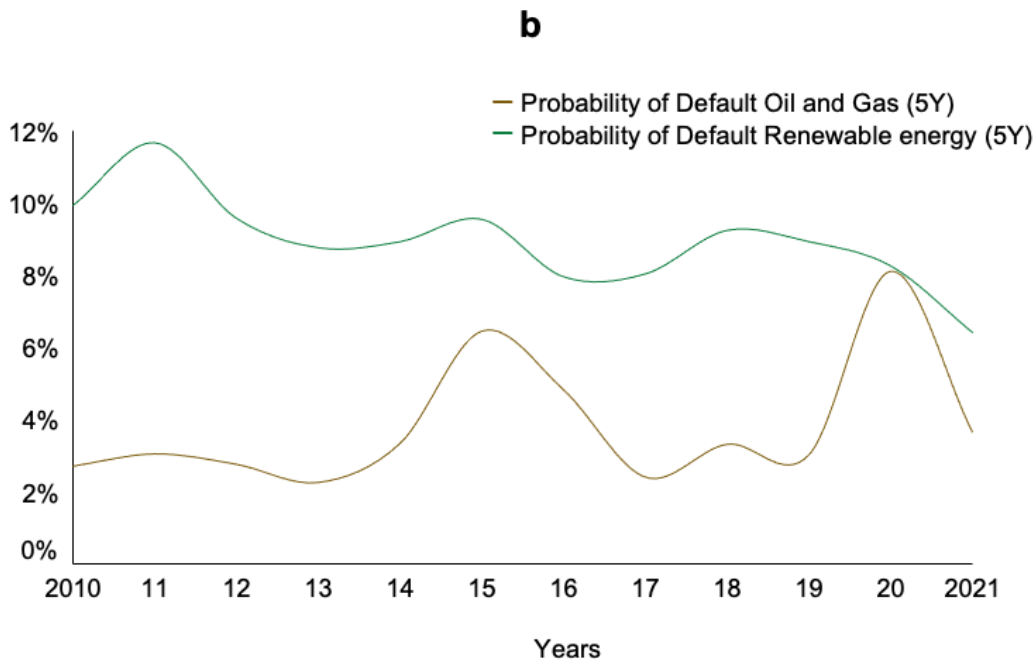
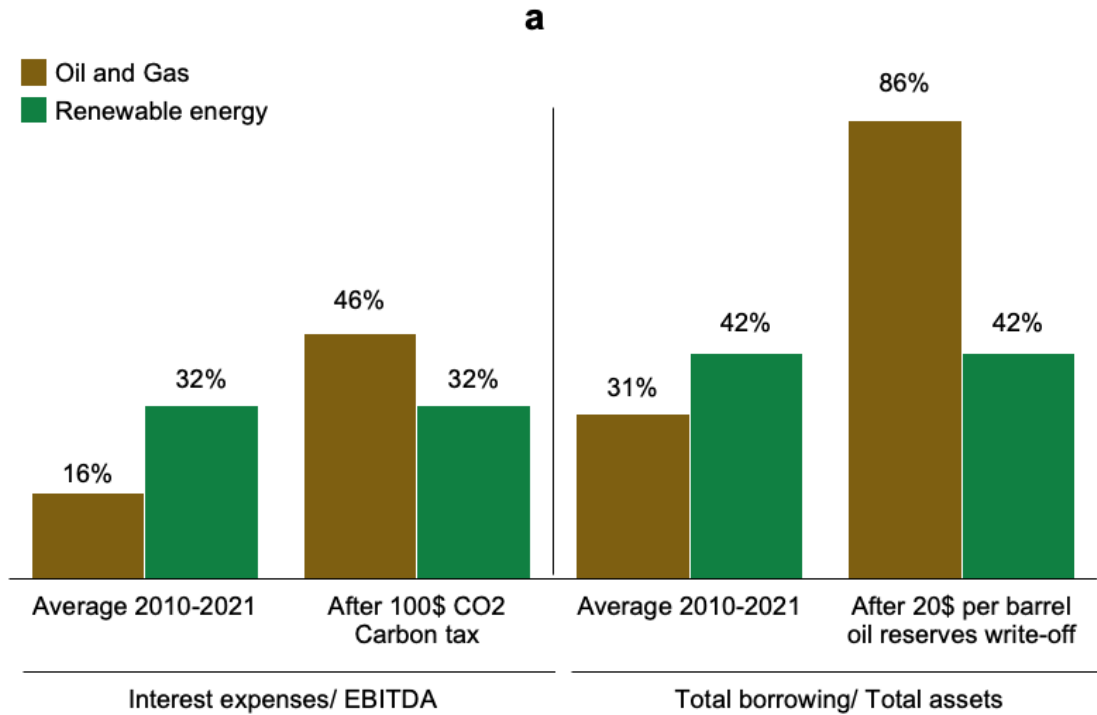


Figure 8: Comparison of financial ratios between oil and gas and renewable energy industries. Average of 5 years Bloomberg Probability of Default (PD), interest expenses over EBITDA and Total Borrowing over Total assets of 228 oil & gas and 235 renewable energy firms in our sample between 2010-2021. Simulation of the impact of USD \$100 carbon tax on EBITDA expressed in terms of average interest expenses over EBITDA ratio (left-hand side). Impact of USD \$20 per barrel write-off of oil reserves on total assets expressed in terms of average Total Borrowing over Total Assets (right-hand side). b): Average Bloomberg PD estimate through time for the companies in the sample.

Similarly, a partial write-off of oil reserves valuations in the balance sheet of oil & gas companies of USD \$20 per barrel, might result in an increase in the debt to asset ratio of these firms, much higher than the average value observed among renewable energy companies (from 16% to 86% against 32% for renewable energy). In such case, financial ratios, and the resulting risk estimates, might become lower for renewable energy investments. A more forward-looking framework including scenario analysis or the consideration of climate related risks in such assessments might be better suited to capturing such unprecedented emerging risks.

In conclusion, our results suggest that model-based financial regulations, and in particular accounting rules, might disincentivise banks to divest from high carbon sectors by directly impacting their profitability. This side effect of the rules might impair the transition towards net zero carbon emissions and in turn contribute to increasing the build-up of transition risk in the financial system. Our comparison of financial ratios between oil & gas and renewable energy firms indicates that this effect might penalise investments in clean energy. Current financial accounting practices might unintentionally hinder the shift of funds required for the green transition, especially in Europe where these investments are oftentimes provided by the banking sector. While the desire to promote a green transition may be based on broader social objectives that lie beyond the remit of financial regulators the deeper problem for regulators is that this transition could represent a potential source of systemic risk. Broader research is needed to determine whether the existing regulations sufficiently account for any such emerging sources of systemic risks that might accompany the green transition. More research is needed to shed light on whether this bias might be present in other similar model-based frameworks (e.g., capital requirements). Finally, regulators and investors should investigate risk models that include forward looking assessments of climate and energy transition risk to ensure those risks are appropriately incorporated in decisions and remove any inadvertent bias.

3 Methods

3.1 Data

We use data from the 2021 European Banking Authority (EBA) transparency exercise which provides portfolio level information of banks' gross exposure and accumulated provisions (Loan loss reserves) by NACE sector level 1 at end of June 2021. We use the most recent data, but we ensure with additional robustness analysis that the results do not change using different years (the reader should note that due to the structure of this modelling the provision coverage ratios oscillate with time in level but the relative difference across sectors is generally preserved). The Nomenclature of Economic Activities (NACE) is a standard classification of sectors in the European Union. It has various levels of granularity from 1 (least granular) to 4 (most granular) and the EBA transparency exercise relies on this classification. The exercise is an annual data collection to foster transparency, and to complement banks' own disclosures. The data published includes 111 EU banks across 25 countries and provides information regarding banks' assets, liabilities, loan loss provisions, and other financial information for each bank.

We use the Legal Entity Identifier (LEI) code in the EBA dataset to complement this information with the historical net profit data from Bloomberg. The data identifiers have been matched with each LEI code in our sample through manual research on the Bloomberg terminal. We start from the largest 60 banks in our sample representing 95% of the total banking exposure, but we exclude one bank because its name and LEI code are missing, which does not allow us to retrieve their income information. This bank represents around 2% of total EU banking assets. After this manipulation our dataset covers more than 93% of total banking loans in the European Union and provide us with loan loss reserves, total lending amount for all NACE sectors (level 1) and cumulative net profits from 2016 to 2021 for the largest 59 banks in the EU. A summary of the sector-level statistics is reported in Table S1.

NACE Sector	Gross exposure	PCR
A Agriculture, forestry and fishing	213318	0.0255
B Mining and quarrying	81359	0.0398
C Manufacturing	815066	0.0332
D Electricity, gas, steam and air conditioning supply	259135	0.0123
E Water supply, sewerage, waste management	48423	0.0157
F Construction	268833	0.0595
G Wholesale and retail trade	680038	0.0354
H Transport and storage	317979	0.0278
I Accommodation and food service activities	156017	0.0574
J Information and communication	147902	0.0175
K Financial and insurance activities	223718	0.0199
L Real estate activities	1383779	0.0145
M Professional, scientific and technical activities	251711	0.0274
N Administrative and support service activities	213488	0.0228
O Public administration and defence	13119	0.0153
P Education	17098	0.0252
Q Human health services and social work activities	101754	0.0171

Table 14: System wide exposure distribution and provision coverage ratio by sector Summary of EU banking system exposure (Euro millions) and provision coverage ratio (PCR) by NACE sectors for banks in our sample. PCR expressed as ratio of Loan Loss Reserves over total outstanding loans by sector.

3.2 High carbon sectors classification

We add to this dataset the information necessary to classify sectors as high carbon (i.e., sectors with high levels of emission intensity). Specifically, we complement the data with the results of the EBA Risk Assessment exercise which provides median values of Climate Policy Relevant Sectors (CPRS) as defined by Battiston et al., (2017) within each NACE level 1. CPRS is a classification used to assess the exposure of investments to transition risks, including carbon taxation, and is a proxy of the level of pollution associated with an investment. The exercise was carried out by the EBA and a sample of 29 volunteer banks from 10 countries representing 50% of the total EU banking assets with the objective to have a preliminary quantification of the exposure of banks to climate related risks, with a particular focus on transition risk. The data annex provided (publicly available) discloses the share of CPRS sectors in each NACE level 1 section according to banks’

classification of their own clients in CPRS. This information is particularly useful because it allows us to have a more granular labelling of low carbon and high carbon sectors than the NACE level 1 (which would not be sufficient to address the heterogeneity of some sectors). The CPRS rely on NACE level 4 which provides a better discrimination between climate sensitive sectors and others (additional information provided in Section 5).

The information at bank level of total gross loan amount and loan loss reserves by NACE code has been grouped into high carbon and low carbon sectors. We define as “high carbon” sectors that have a median share of CPRS higher than 95%, as reported by banks in the EBA Risk Assessment exercise (Figure 18 – Data annex). This gives us the following high carbon sectors and their respective code: A - Agriculture, forestry and fishing, B - Mining and quarrying, D - Electricity, gas, steam and air conditioning supply, E - Water supply, sewerage, waste management, H - Transport and storage, and L - Real estate activities. We acknowledge that our approach has limitations, but we extensively test the robustness of our results to a change in the methodology used to classify low carbon and high carbon sectors (Section 4). Moreover, we compare our classification to more granular data reporting emission intensity to provide transparency about their level of correlation. It should be noted that the banks participating in the climate risk exercise did not include Sweden, Denmark, and Norway, but results do not change if those countries are excluded due to their relatively low materiality in the overall EU banking system.

Data availability prevented us from assigning carbon emissions to loans directly. However, the CPRS classification we use is highly correlated with GHG emissions intensity (Figure 9). The EBA Risk Assessment provides a breakdown of emission intensity by percentiles for CPRS and non-CPRS. They use individual firms’ GHG emissions from the data provider Trucost (representing 30% of total banks’ loan amount) and a proxy based on the average GHG emission intensity at NACE rev 2 level 4 for the remaining loan amount. Each bank loan is classified in percentiles of emission intensity in a range from very low to very high (More details could be found in the EBA 2020 Risk Assessment

Report – Table 19). We use these data to test the correlation between the share of loan amount in the CPRS/non-CPRS and its emission intensity. There is a clear correlation between the share of loan amount of CPRS and the clusters of emission intensity (Figure 9). Around 85% of loan amount classified as having “very high” emission intensity are in CPRS. On the opposite end of the spectrum, only 8% of loan amount of CPRS are in the very low emission intensity bucket. The correlation between the share of loan amount in CPRS (non CPRS) is therefore strongly positive (negative), and around 90% (-90%). In Section 4 we show that this correlation is very unlikely to change with different classifications using a set of robustness analyses.

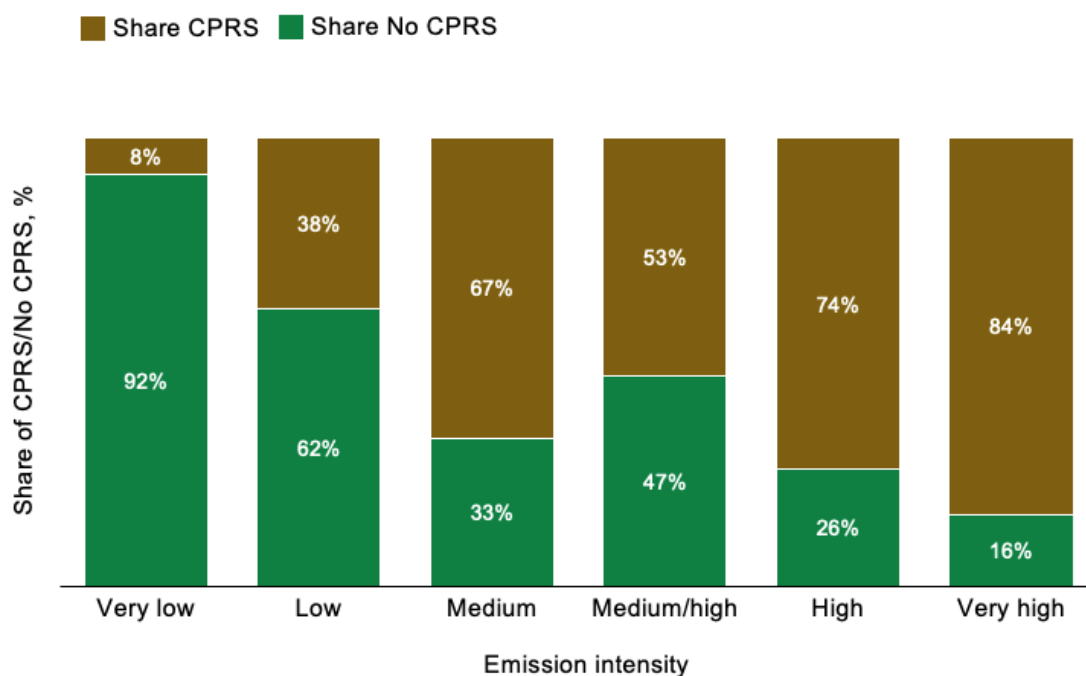


Figure 9: Correlation between GHG emission intensity and CPRS. Share of gross loan amount pertaining to CPRS and non-CPRS sectors grouped by buckets of emission intensity. The buckets of emission intensity range from very low to low and are based on the classification used by the EBA in the 2020 Risk Assessment report. Based on 81% of total gross loan amount with either GHG emissions or CPRS classification available. Very low refers to lower than the 10th percentile, low between 10th percentile and Q1, medium between Q1 and Median, medium/high between Median and Q3, high between Q3 and 90th percentile, very high above 90th percentile.

3.3 Simulation of a divestment strategy

Using the data available, we can provide an estimate of the potential impact of a divestment from high carbon assets on EU bank's financials. The primary assumption in this estimation is that the total amount of loans of each bank is left unvaried. In other words, the simulation assumes that banks shift their lending portfolio directly from high carbon to low carbon investments. We also assume that sufficient low carbon investments are available for these transactions. The labelling in our data allows us to calculate the average risk estimate (provision coverage ratio) of low carbon and high carbon sectors for all banks in our sample. We make use of the accounting relationship between provisions coverage ratio, loan loss provision charges and net profits to assess the impact of a divestment from high carbon assets on these metrics (all else being equal). Importantly, we do not rely on an explicit economic model, but on the accounting relationship among these metrics. In turn our results are generated by the structure of the regulation as long as a bank divests from a low PCR asset and re-invests in a high PCR asset.

It should be noted that Loan Loss Provision changes are only the direct effect of this divestment on bank's net profit changes at the time they make the investment. This is an expected loss, not necessarily a loss that will occur in the future. More specifically, three conditions need to be satisfied to generate an increase in costs from a divestment by banks:

- Losses are costs that must be accounted for as expected as opposed to incurred. That is financial firms must account for any change in the portfolio expected losses not the actual incurred losses;
- Provision coverage ratios must be equal to model-based estimates of expected losses. That is, expected losses are proportional to measures of risk;
- Risk estimates of the asset in which a bank is divesting are lower than the asset in which it is making a new investment;

Point 1) and 2) are provided by the structure of the regulation and replicated in the stylized analysis proposed in this paper. Evidence supporting condition 3) is provided in our empirical analysis and further corroborated in the analyses described in the sections 2 and 5. In particular, from the three conditions above, it emerges that the results of the simulation are grounded on PCR differentials. For this reason, we pay particular attention in demonstrating a negative correlation between high carbon sectors and risk measures.

More formally, we define the provision coverage ratio (PCR) as the loan loss reserves (or accumulated provisions in EBA terminology) divided by the gross exposure for the high carbon and low carbon sectors i for each bank j . The provision coverage ratio represents the expected credit loss (of non-default counterparties) and the corresponding loan loss provisions which banks must allocate to lending activities in each sector. This measure is assumed to be the model-based output from each institution risk model, in line with the accounting regulation:

$$PCR_{i,j} = LLR_{i,j} / Exposure_{i,j} \quad (1)$$

We then calculate the change in the level of loan loss reserves following a divestment from high carbon assets. This is performed by assuming that all low carbon loans replacing the high carbon ones would require the average provision coverage ratio of existing low carbon assets. In other words, a divestment from low PCR assets and re-investment in high PCR assets would lead to an increase in the overall average PCR. More formally, the increase/decrease in provision for bank j is defined as follows:

$$LLP_j = \Delta LLR_j = (PCR_{low-carbon,j} - PCR_{high-carbon,j}) * Exposure_{high-carbon,j} \quad (2)$$

This result provides the expected increase or decrease in provisions if a bank had

to shift the totality of its assets from high carbon to low carbon investments. This relationship is an accounting identity defined by the framework. The impact of additional loan loss provisions on a particular bank's income statement is considered a loan loss provision charge (i.e., additional cost) with direct effect on their net profit. In particular, the increase in provisions (i.e., the loan loss provision charges) is directly deducted from net profit, being an additional cost for the bank in the fiscal year of the divestment. This, in turn, provides a direct estimate of the change in net profits following a divestment from high carbon assets. More formally:

$$Profit_{j,t+1} = Profit_{j,t} - LLP_j \quad (3)$$

Where j refers to each bank in our sample, t is the starting point period and $t+1$ is the period post divestments. Importantly, in order to simulate the effect of the divestment we assume it occurs entirely in one fiscal year. This divestment would likely be spread across multiple years, but frontloading the entire impact allows us to better investigate the implicit incentive structure created by the regulation. This simple approach allows us to simulate what would be the impact of a divestment from high carbon assets on banks' balance sheet and income statements testing the hypothesis that a potential divestment strategy might be costly disincentivizing banks in taking such action.

4 Supplementary information 1 - Sensitivity of results

Our analysis provides evidence of the potential negative effects of model-based regulation on the green transition, but our results are susceptible to the inevitable imprecision involved in classifying an investment as high carbon or low carbon. As highlighted by the fact that this is still a highly controversial issue in the case of the EU green taxonomy. The classification of climate policy relevant sectors (CPRS) provided by (?) has been used extensively in the literature and by policy makers but it is only one of the many alternatives available. To ensure that our findings are not affected by the labelling methodology, we perform a sensitivity analysis on our classifications. We find that our results are driven primarily by the prevalence of high provision coverage ratio estimates among low carbon sectors and we show here that this correlation is very unlikely to change with alternate green classifications. While the data refers to 2021, similar results have been found in previous years. In this section, we discuss this regarding some key sectors and provide transparency on how the results would change were we to reclassify industries among the two clusters.

We first simulate the impact of allocating each sector partially to the high carbon cluster depending on their median share of climate policy relevant sectors (CPRS) found among banks in the European Union that took part in the EBA Risk Assessment exercise. For example, considering that the median share of CPRS in the Manufacturing sector reported by banks is 73%, we can allocate only this portion of the portfolio to the high carbon bucket. In other words, we assume that each NACE level 1 is composed of a share of CPRS/non-CPRS loans and we simulate the divestment only of that part of the portfolio. In this case, the increase in the provision coverage ratio is still positive (30bps) including the effect on loan loss reserves (+25%). The average impact of a divestment strategy on profits in this case is lower (-4%) but still negative and with high variance among the banks in our sample (minimum -187%, maximum 287%).

We then investigate the sensitivity of our results to the reclassification of sectors

from high carbon to low carbon activities. In particular, we ensure that sectors with particularly low (high) levels of PCR among the high carbon (low carbon) sectors are not the main driver of our results. The real estate sector is one of the largest investments of banks in our sample and one with the lowest PCR in the high carbon cluster. It is therefore relevant in shifting the average results. For this reason, we recalculate the aggregate level impact relabelling the real estate sector as low carbon. As expected, in this case the effect of a divestment from high carbon sectors is still substantial (44bps PCR increase). Similarly, we relabel some low carbon sectors with a relatively high coverage ratio and emissions in the high carbon sectors. The construction sector in this case could significantly impact our results because of its high PCR. In fact, relabelling it as high carbon would lead to an overall lower increase in the coverage ratio following a divestment strategy (44bps coverage ratio increase), but still high enough to generate the bias discussed in our main results.

We then consider the effect of reclassifying sectors which could be particularly heterogeneous. For example, the power generation sector is particularly difficult to classify as high carbon and low carbon because of its sub-industry heterogeneity. Our sensitivity analysis provides reassuring results for this sector, as relabelling Electricity, gas, steam and air conditioning supply as low carbon would still impact the profits of banks willing to divest (74bps PCR increase). Similarly, the manufacturing sector may have heterogeneous activities and could include firms with various levels of carbon intensity. For this reason, it is worth investigating the impact of including it in the high carbon cluster. In this case, the impact of a divestment strategy would still lead to an increase in the overall coverage ratio among the banks in our sample (89bps). This analysis further reassures that the sectorial heterogeneity of some sectors does not substantially affect our results.

The relabelling of some selected sectors between the low carbon and high carbon clusters provides some comfort that the main outcome of our study is not sensitive to the classification applied, although the impact varies. To further understand the effect of the classification of some specific sectors in driving the overall results, and to provide

transparency on how the results would change if we reclassified some sectors, we carry out a similar analysis for all NACE labels (Table 15). Recursively re-classifying sectors to the opposite cluster (e.g., high carbon to low carbon clusters) shows us that our main results are not sensitive to the classification of individual industries as high carbon. Thus, we conclude that the prevalence of the highest provision coverage ratios among the predominantly low carbon sectors is a key driver of our results.

NACE Sector	Impact on profits	LLR Increase (%)	PCR Increase (bps)
Baseline model	-14.7%	34.9%	104
A Agriculture, forestry and fishing	-14.1%	32.9%	106
B Mining and quarrying	-16.9%	38.9%	114
C Manufacturing	-14.9%	33.3%	89
D Electricity, gas, steam and air conditioning supply	-9.8%	26.7%	74
E Water supply, sewerage, waste management	-13.5%	31.5%	100
F Construction	-6.8%	32.1%	44
G Wholesale and retail trade	-14.9%	27.6%	77
H Transport and storage	-14.9%	34.8%	104
I Accommodation and food service activities	-13.9%	33.6%	82
J Information and communication	-17.5%	37.0%	116
K Financial and insurance activities	-16.7%	38.4%	111
L Real estate activities	-1.9%	0.82%	44
M Professional, scientific and technical activities	-15.2%	36.4%	103
N Administrative and support service activities	-16.3%	37.1%	107
O Public administration and defence	-15.1%	35.1%	105
P Education	-14.9%	35.3%	104
Q Human health services and social work activities	-17.3%	45.8%	115
R Arts, entertainment and recreation	-14.2%	34.5%	98
S Other services	-15.7%	34.8%	88

Table 15: Sensitivity analysis of the impact of a divestment from high carbon assets and corresponding re-investment in low carbon assets, maintaining a constant level of outstanding loans by bank, on the system level provision coverage ratio (PCR), loan loss reserves (LLR) and net profit. Values refer to the impact of a reclassification of the sector represented in the row to the opposite cluster. A Agriculture, forestry and fishing, B Mining and quarrying, D Electricity, gas, steam and air conditioning supply, E Water supply, sewerage, waste management, H Transport and storage, H Transport and storage classified as high carbon in the baseline setting of the model. All other sectors classified as low carbon in the baseline setting of the model. The sensitivity analysis tests the impact of a reclassification of the sector in the high carbon cluster.

5 Supplementary information 2 – Additional analyses

We first retrieve data about oil gas and renewable energy companies worldwide available on Bloomberg. This represents 228 oil gas and 235 renewable energy firms and their respective information between 2010-2021. This includes common financial metrics (e.g., assets, revenues, earnings), but also data about their total GHG emissions (scope 1,2,3) and their proved oil reserves (barrels of oil). We calculate two commonly used financial ratio: i. total interest expenses over Earnings Before Interest, Depreciation, Amortization (EBITDA) and ii. total borrowing over total assets.

Our analysis simulates two possible effects emerging from the transition to net zero carbon emissions on these financial ratios. The first effect pertains an increase in carbon taxation enforced globally on total emissions emerging from a possible increase in the stringency of climate regulation. The second effect represents a devaluation of fossil fuel reserves in global markets due to an increased recognition of the possibility of stranded assets. The simulation assumes that the devaluation of reserves is reflected in the valuation of firms' total assets.

We then recalculate the two financial ratios assuming that carbon taxation decreases the EBITDA of the companies in our sample and the devaluation of oil reserves leads to a corresponding lower value in the total assets of the respective firm. We take arbitrary but conservative values in terms of carbon taxation and possible devaluation of oil reserves in our scenario. The values of EBITA and assets after considering the effect of the net zero transition drivers discussed above are used to recompute the two financial ratios for each company in our sample. We extend this analysis by retrieving data from Refinitiv about carbon emissions and Refinitiv credit risk model which, similarly to Bloomberg, reports an estimate of the probability of Default for different firms and it relies on similar metrics used by banks' models. We use a large sample of around 4800 firms across all NACE sectors. We compare their emission intensity (expressed in terms of emissions over assets) with the average probability of default estimate. Coherently with the main findings in

the “Discussion” section we find a negative correlation between average emission intensity and estimates of Probability of Default emerging from Refinitiv’s model. This further corroborates the evidence provided about a possible negative correlation between emission intensity and models’ estimates of risk.

NACE Sector	Emission Intensity Assets			Emission Intensity Revenues			PD(%)	N
	Scope 1	Scope 1, 2	Scope 1, 2, 3	Scope 1	Scope 1, 2	Scope 1, 2, 3		
A Agriculture, forestry and fishing	42.4	46	81	21,270	23,536	42,321	1.02	14
B Mining and quarrying	100.6	114	938	13,974	16,241	62,732	0.44	174
C Manufacturing	23.3	36	240	9,246	13,399	58,414	0.66	1441
D Electricity, gas, steam and air supply	262.1	290	519	4,532,186	4,549,155	14,519,981	0.56	81
E Water supply, sewerage, waste	65.8	70	107	11,074	12,031	22,152	0.57	27
F Construction	11.7	13	81	1,592	1,901	24,017	0.48	62
G Wholesale and retail trade	5.5	11	97	2,412	6,777	15,726	1.01	308
H Transport and storage	189.3	195	499	67,757	69,749	149,404	0.8	137
I Accommodation and food service	7.9	23	221	1,543	3,842	28,130	1.04	72
J Information and communication	1.2	6	12	354	1,939	4,377	1.06	659
K Financial and insurance activities	2.6	3	22	2,154	2,527	15,423	0.62	756
L Real estate activities	1	4	513	1,080	3,947	2,496,514	1.17	201
M Professional, scientific activities	0.1	0	1	20	54	206	0.77	642
N Administrative and support service	4.2	5	24	1,267	1,480	7,540	0.61	98
O Public administration and defence	0	0	0	0	0	0	2.43	2
P Education	0.1	1	1	29	123	180	0.33	40
Q Health services and social work	0.5	1	29	81	182	4,868	1.94	77
R Arts, entertainment and recreation	0.6	2	3	40	175	184	1.92	38
S Other services	6.2	8	19	457	742	1,147	0.74	13
Correlation with PD	-30%	-31%	-29%	-17%	-17%	-15%		

Table 16: Average emission intensity and Probability of Default. The table shows the correlation between the average emission intensity of assets (expressed in terms of tonnes of CO2 emissions over million dollars of total assets), the average emission intensity of revenues (expressed in terms of tonnes of CO2 emissions over million dollars of revenues) and Refinitiv credit risk model's probability of default estimate for 4842 firms in the Refinitiv universe grouped at the NACE level 1. Data refers to 2023.

6 Supplementary information 3 – Descriptive statistics

Sector	Median share of CPRS
A - Agriculture	100%
B - Mining and Quarrying	96%
C - Manufacturing	73%
D - Electricity, Gas, Steam	100%
E - Water supply, sewerage, waste management	100%
F - Construction	85%
G - Wholesale and Retail	18%
H - Transportation and Storage	97%
I - Accommodation and Food	62%
L - Real Estate	100%
M - Professional	1%
N - Administrative	23%

Table 17: Percentage of climate policy relevant sector by NACE code. Percentage of climate policy relevant sector by NACE code according to EBA 2020 Risk assessment (Data annex, figure 18) based on banks participating to the 2020 EBA analysis of climate risk and classification provided in Battiston et al. (2017)

Sector	CO ₂ Emissions (Tonnes)	Banks' Exposure (EURm)
Electricity, gas, steam and air conditioning supply	695,249,449	259,135
Manufacturing	694,258,047	815,066
Transportation and storage	369,796,104	317,979
Agriculture, forestry and fishing	98,943,702	213,318
Wholesale and retail trade; repair of motor vehicles and motorcycles	62,106,757	680,038
Construction	49,379,561	268,833
Water supply; sewerage, waste management and remediation activities	34,943,731	48,423
Public administration and defence; compulsory social security	24,925,976	13,119
Mining and quarrying	22,464,410	81,359
Human health and social work activities	20,966,844	101,754
Professional, scientific and technical activities	17,028,217	251,711
Administrative and support service activities	17,018,320	213,488
Accommodation and food service activities	12,980,932	156,017
Other service activities	11,247,794	170,396
Education	10,880,959	17,098
Information and communication	7,957,810	147,902
Arts, entertainment and recreation	6,937,446	33,059
Financial and insurance activities	6,260,460	223,718
Real estate activities	5,070,313	1,383,779
Activities of households as employers	97,717	0
Activities of extraterritorial organisations and bodies	324	0

Table 18: Carbon emissions by sector Eurostat Total European Union (EU27) and Banks' exposure. Carbon emissions in 2020 as reported by Eurostat and gross loans in our sample (EURm).

Part V

Climate change risk and uncertainty

A re-evaluation of the financial risks of the net zero transition

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Abstract

This paper examines the potential impact of climate change on financial risk and the uncertainty surrounding the outcomes of different mitigation scenarios. We use a consistent climate stress test model to evaluate the effect of three possible net zero scenarios on companies' valuations and financial investments. We find that the impact of the transition to net zero emissions could vary greatly for the same target (below 2°C) based on how the transition may unfold. We suggest that a wider range of scenarios and assumptions could help to better understand the uncertainty of the effects of climate change and the net zero transition on the financial system and discuss some of the implications.

JEL Codes: Q51, Q43, G21, G32

Keywords: Sustainable finance, Climate change, Stress testing, Scenario analysis, Risk management, Financial risk

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1 Introduction

The evidence is quite clear that climate change will have large effects on the global economy, even if we manage to reach the Paris goals of 1.5° of warming above pre-industrial levels. Finance will play a vital role in providing the large amount of funds required to transition to a low carbon economy (Campiglio, 2018; D’Orazio et al., 2022). However, there is increasing evidence that the act of preventing the worst physical risks of global warming by rapidly transitioning to clean energy sources, could have serious consequences for the financial system, including financial instability (Caldecott et al., 2021). Climate-related financial risks might emerge not just from scenarios where global warming leads to increased extreme weather events (physical risk), but also from scenarios where climate change is rapidly mitigated through a set of decarbonisation policies implemented in line with the Paris Agreement (transition risk). The recognition of this transition risk is growing, and the literature that has assessed the potential impact of a rapid transition to net-zero on the stability of the financial system is becoming increasingly influential in shaping policy and investment decisions (Battiston et al., 2017; Battiston & Martinez-Jaramillo, 2018; Roncoroni et al., 2021; Stolbova, Monasterolo, & Battiston, 2021; Vermeulen et al., 2021).

Despite the growing research, our understanding of the resilience of the financial system to transition risk is still limited, due to the complexity and the uncertainty of the problem (Hansen, 2021). Some key issues requiring attention are: firstly, that many of the complex modelling exercises into the impacts of climate policy are characterised by opaque assumptions about how economic systems might adapt to such a major transition (Farmer, Hepburn, Mealy, & Teytelboym, 2015). Secondly, many of the factors underlying the potential economic impacts of a rapid transition are deeply uncertain, such as future socioeconomic conditions, behavioural change, technological progress, and other endogenous and exogenous factors (Rekker, Ives, Wade, Webb, & Greig, 2022; Welsby et al., 2021). This deep structural uncertainty has been studied extensively in the envi-

ronmental economics literature², but has yet to be sufficiently assessed in the branch of research concerned with climate-induced financial instability.

Previous studies that focused on the potential of climate change to generate financial instability have not adequately addressed the full extent of uncertainty associated with future climate scenarios (Monasterolo et al., 2019). As a consequence, researchers and supervisors might understate financial risks emerging from both physical risk (Mahul, Ranger, & Monasterolo, 2021) and transition risk (Baer, Kastl, Kleinnijenhuis, Thomae, & Caldecott, 2021)³. This literature generally investigates the resilience of financial institutions by looking at the tail of the distribution of financial losses conditional on the financial stress associated with a given future scenario. It usually categorises climate-related financial risks based on when and if the transition to net zero carbon emissions will occur. However, it rarely examines how climate-related financial risks may depend on the path by which such scenarios unfold. Although there is a broad acknowledgement that a sudden transition to meet the goals of the Paris Agreement may result in financial instability, there is limited research on the various ways in which this transition might affect the financial system.

In this paper, we focus on the uncertainty around transition risks across rapid climate mitigation scenarios. We investigate how such uncertainty might impact the valuation of financial investments depending on the speed and manner in which the world decarbonises the energy system. In doing so, we concentrate on whether the "tail" risk of financial losses associated with a rapid transition to net-zero is adequately covered in the stress tests employed by financial institutions and regulators. We compare three Paris aligned net-zero scenarios from internationally recognised institutions, namely: the International Energy Agency (IEA); the global consortium of central banks called the Network for Greening the Financial System (NGFS); and the Institute For New Economic Thinking (INET) at the University of Oxford. We employ a consistent, bottom-up asset-level stress testing methodology, developed by Baer et al. (2021), to determine the impact of these

²See for example Cai and Lontzek (2019); Weitzman (2011)

³See for example UK gov Financial Services And Markets Bill

scenarios on energy companies. We believe that the impact on firms' valuations is a suitable indicator to assess the diverse effects each scenario could have on the financial risk of different companies which, in turn, could propagate in the financial system.

Our results reveal a significant level of variability in the impact of different net zero transition scenarios on the valuation of financial assets. The average change in valuation between scenarios ranges from -20% to 2%, demonstrating the substantial difference in outcomes. The correlation of the impacts on firms across the different scenarios ranges from 90% to as low as 60% while the distribution of the changes in companies' valuations conditional on a net zero transition shock is also substantially different. Moreover, we find geographical variation depending on the underlying scenario narrative. Some countries that are early adopters of renewable energy may even benefit from the transition, while others, heavily reliant on coal, could be negatively impacted. Additionally, our findings indicate that the level of scenario uncertainty increases when considering the heterogeneity of firms. The impact on an individual firm may vary greatly depending on its degree of alignment with the scenario assumptions, such as its energy technology mix. These are likely conservative estimates of the variability of different transition scenarios on financial assets as we do not consider firms that might fail in the transition. Nevertheless, our findings highlight the importance of considering a broader range of assumptions when evaluating the potential impacts of tail events such as a disruptive net zero transition on the financial system.

We highlight the significance of incorporating uncertainty in the examination of the relationship between climate transition risk and financial stability. Our contribution to the existing literature is twofold. Firstly, we demonstrate that uncertainty is pervasive in the results of climate stress testing studies and provide a new perspective on the potential outcomes of a transition to a net zero carbon economy on the financial system. Instead of solely focusing on *whether* the transition will occur, we also examine the financial risk implications associated with *how* it could unfold. Secondly, we offer a novel approach to explore some of the uncertainties involved in the net zero transition. By comparing

different scenarios using a consistent climate stress testing framework, we are able to differentiate the variability associated with modelling choices and parameter uncertainty arising from different climate scenarios. To the best of our knowledge, this is the first study to compare scenarios in this manner, showing that in principle, very different scenarios can be compared consistently.

A growing body of literature has been published on climate stress testing and scenario analysis in recent years ([Battiston et al., 2017](#); [Battiston & Martinez-Jaramillo, 2018](#); [Roncoroni et al., 2021](#); [Stolbova et al., 2021](#); [Vermeulen et al., 2021](#)). This manuscript is not the first to challenge the narrative of climate scenarios used in stress testing. [Battiston, Dafermos, and Monasterolo \(2021\)](#) argue that the most widely used scenarios do not consider the possible feedback loop between the financial system and the real economy and focus mostly on carbon pricing. Our review is not as substantial as other studies (e.g., [Monasterolo \(2020\)](#)), but instead aims to expand the breadth of narratives considered in the climate stress testing literature by introducing a scenario with a much faster uptake of renewable energy. By doing so we hope to demonstrate the importance for climate stress testing of *how* the net zero transition may evolve. Our paper is not the first to stress the importance of asset-level data in understanding climate-induced impacts, but it shows that the uncertainty represented by different scenarios magnifies the relevance of bottom-up asset-level assessments.

The remainder of the paper is structured as follows: in [Section 2](#), we review the main sources of uncertainty which could lead to the high variability in the results of climate stress testing. In [Section 3](#), we outline our approach of sensitivity analysis of stress testing. In [Section 4](#), we show some key results suggesting the heterogeneity of possible future outcomes associated with a range of future scenarios. In [Section 5](#), we discuss some of the implications and some of the challenges of consistently integrating scenarios developed by different institutions.

2 A short review of the climate scenarios assessed

In this section, we perform a brief review of the climate scenarios used in this analysis, examining both their qualitative and quantitative aspects. Our goal is to understand how the varying assumptions in these scenarios can lead to substantial differences in their outcomes, driven by the inherent uncertainty of some key climate-economy system components. Our focus is on net zero transition scenarios, but the same analysis could be applied to other types of scenarios. We specifically analyze three Paris-aligned mitigation scenarios that keep global warming well below 2°C above pre-industrial levels, with a focus on the energy sector, as it is one of the largest contributors to CO₂ emissions⁴. These scenarios are the International Energy Agency’s (IEA) Sustainable Development Scenario (SDS) (IEA, 2021), the Network For Greening the Financial System’s (NGFS) Net zero 2050 scenario (NGFS, 2021), and the Fast Transition scenario of the Institute for New Economic Thinking (INET) at the University of Oxford (Way, Ives, Mealy, & Farmer, 2022). The latter scenario is chosen specifically due to its focus on consistent technology trends and for its contrast with the former two more widely used scenarios. Despite sharing a similar goal of limiting global warming to well below 2°C, these scenarios exhibit quite varying structural transformations of the energy system, leading to distinct outcomes when used in climate stress testing research. In this section, we will discuss the key assumptions that drive these differences⁵.

Starting with the qualitative review, the IEA Sustainable Development Scenario (IEA, 2021) assumes all countries gradually achieve net zero emissions pledges, starting with advanced economies by 2050, China by 2060, and the rest of the world by 2070. It assumes that electricity will be universally available by 2030, including in emerging economies. To limit energy demand, policies for energy performance standards for electronic appliances, cooling systems, and buildings are introduced. All new buildings are expected to be net

⁴<https://ourworldindata.org>

⁵The targets are not perfectly aligned but in broad terms, they project an increase in global warming well below 2°C and above 1.5°C (50% probability)

zero by 2030, with increased support for energy efficiency in existing buildings. Alternative fuels such as hydrogen and biogas are promoted, and carbon capture and storage (CCS) is implemented across all sectors. The lifetime of nuclear plants is extended, and some new reactors are planned, while carbon-intensive energy-producing technologies are still present but complemented with CCS to reduce emissions. In addition, carbon prices are expected to be introduced in the near future, reaching \$160 in advanced economies and \$95 in other countries by 2050.

In the NGFS Net Zero 2050 scenario (NGFS, 2021), more stringent climate policies are immediately implemented to drive innovation and taxes on CO₂ (and rise to around 720\$ in advanced economies, 650\$ in China, and 450\$ in the rest of the world by 2050 at 2010 prices⁶). In this scenario, the majority of advanced countries are expected to reach net zero emissions by 2050. This results in a 60% reduction in the energy intensity of the global economy from 2020 to 2050, driven by a transition to clean energy sources and by increased energy efficiency measures. Electrification is assumed to be widespread, including in the electric vehicle sector, and more than half of the energy used in buildings, industry, and transportation is assumed to be electric by 2050. Any fossil fuels used by 2050 are assumed to be carbon neutral through the implementation of carbon capture and storage (CCS) technologies. This scenario expects the removal of 5 gigatons of CO₂ per year (14% of the 35Gt CO₂ emissions in 2020⁷) in a cost-effective manner. Finally, the agriculture, forestry, and other land use (AFOLU) sector is expected to reach net zero by 2030.

The Fast Transition scenario developed by the Institute for New Economic Thinking (INET) at the University of Oxford (Way et al., 2022) is different in many respects compared to the two described above. It only models carbon emissions from the energy system and assumes the world will replace the largest part of fossil fuel energy by 2050, largely through technological progress in clean energy generation. It also does not make assumptions about energy efficiency and it assumes carbon capture and storage will be

⁶GCAM 5.3 model

⁷<https://ourworldindata.org>

negligible. In terms of energy demand, it allows for a 2% growth per year (which is equivalent to the high economic growth of the IPCC SSP5 Baseline scenario). In this INET scenario, a significantly larger decline in the cost of electricity generation from renewable sources is projected, especially for solar, due to predicted learning rate improvements from continuing growth in the deployment of these technologies. This scenario assumes that the current exponential growth rate in key clean energy technologies continues until 2030 before gradually slowing down to the economy-wide 2% growth rate, resulting in a much larger share of renewable energy in 2040 than the other two scenarios.

Turning to the quantitative review. The first notable difference which emerges from the comparison of the three scenarios is the markedly different projected structure of the energy system. This arises from the different qualitative assumptions translated into alternative modelling approaches and parameter values. In 2040, the share of energy produced from renewables is 42 and 55% in the IEA and NGFS scenarios respectively, while it reaches over 85% in the INET scenario. The energy generated from gas ranges from 18-7% by 2040 in the IEA and NGFS pathways, while it falls to around 5% in the INET scenario. In contrast, the IEA and NGFS scenarios still include a substantial portion of energy generated from coal and oil (around 14% and 5% respectively), whereas both energy sources are expected to account for a minimal share of energy in the INET scenario. Furthermore, the energy generated from nuclear plants is around 10% in the IEA and NGFS scenarios, while it is assumed to not grow much beyond current capacity in the INET scenario due to its comparative high cost compared to renewables plus storage (Fig. 10)

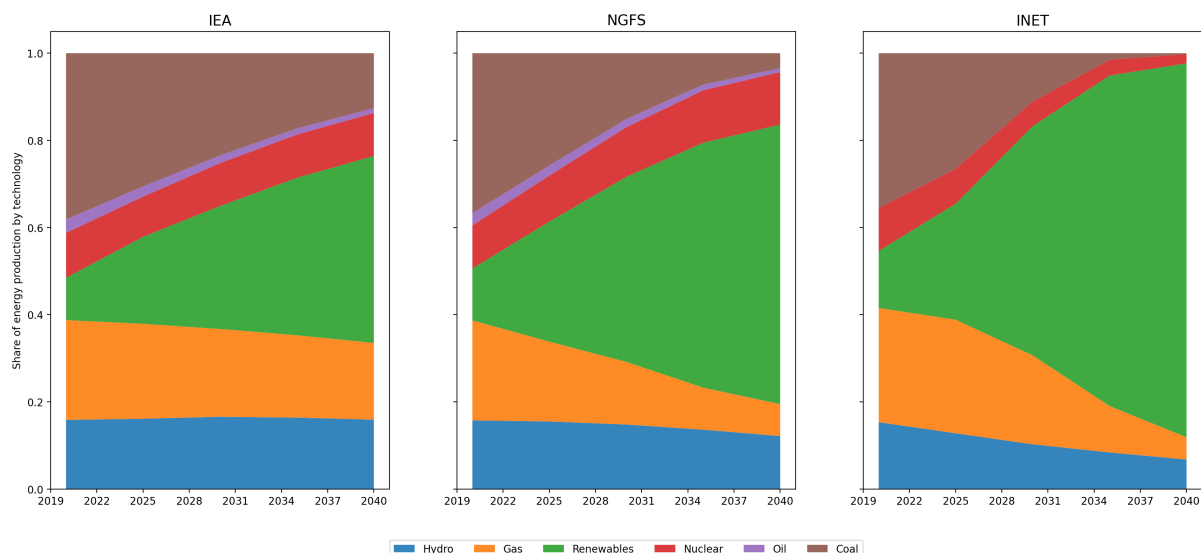


Figure 10: Comparison of projections of the share of energy produced by technology for some of the most widely used scenarios for climate stress testing and a scenario based on empirically grounded technological forecast.

Carbon prices are also substantially different across the scenarios (excluding INET which does not provide carbon prices explicitly). In the IEA scenario, the cost of emitting one tonne of CO₂ in 2030 is around 100 USD in advanced economies while carbon taxation is not expected to be introduced in developing and emerging countries by 2030. On the contrary, the NGFS scenario already foresees carbon prices between 75 and 201 USD per tonne of CO₂ in 2030 at 2020 prices⁸. The difference is even higher in 2050 where IEA prices range from 95 to 160 dollars per tonne of CO₂ while the levels are significantly higher for the NGFS scenarios, reaching between 586 and 934. This difference is the result of a much steeper increase in carbon taxation from 2040 to 2050 in the NGFS scenario, which does not occur in the IEA scenario. Carbon prices are one of the outputs of these modelling exercises, but they are also usually the main policy instrument for achieving a defined emission target⁹.

Cost assumptions regarding key technologies, such as renewables, constitute a third difference between the three scenarios assessed. The IEA scenario reaches a Levelised

⁸Assumes a global increase in prices of 30% from 2010 to 2020. Source: World Bank <https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG> (Accessed: September 2022)

⁹In the NGFS scenario, the carbon price is framed as a "shadow price"

Cost of Electricity (LCOE) of approximately 30 dollars per MWh in 2040, while the INET scenario projects a LCOE of 15 dollars per MWh (Fig. 11.)¹⁰. The INET scenario forecasts a steeper decrease in the cost of electricity generation from wind in a fast transition. Both scenarios predict stable or slightly increasing costs for carbon-intensive generation technologies, such as coal and gas. Importantly, as [Way et al. \(2022\)](#) highlight, most energy-economy models consistently failed to capture the much steeper drop in the costs of renewable energy technologies that have occurred in the past. In their model, they use empirically grounded forecasting to project forward the cost reductions associated with different levels of ambition in renewable energy deployment. The main driver in their model is Wright’s Law, which provides predictions of declining costs in the learning-by-doing associated with increased deployment of solar, wind, and energy storage technologies.

		Year 2030	Year 2040	Year 2050
IEA	Developed	100	140	160
	Other	-	35	95
NGFS	Developed	201	305	934
	Other	75	189	586
	China	150	218	814

Table 19: Comparison of shadow carbon prices from 2030 to 2050 in International Energy Agency (IEA) and Network for Greening the Financial System (NGFS) scenarios. Values expressed in dollars per tonne of CO₂ (USD/tCO₂). Expressed in terms of 2020 prices. NGFS CO₂ levels restated at 2020 from 2010 using average global Consumer Price Index (CPI).

A fourth difference between the scenarios is their projected reliance on negative emissions technologies. While there is limited consensus on the economic feasibility of such technologies ([K. Anderson, 2015](#)), the IEA and NGFS scenarios both incorporate extensive use of Carbon Capture and Storage (CCUS) and Carbon Dioxide Removal (CDR) technologies to reach their net-zero emission objectives. This assumption allows for an

¹⁰This drop in energy production cost has already been observed in some regions. Portugal has recently approved the development of a project at 11.4 Euro per MWh

extended use of fossil fuel energy production as emitted CO_2 is either taken from the power generation process or from the atmosphere and sequestered deep underground. In contrast, the INET scenario does not require the use of technologies for negative emissions, but relies primarily on the high uptake of renewable and storage energy technologies resulting from their forecast cost declines.

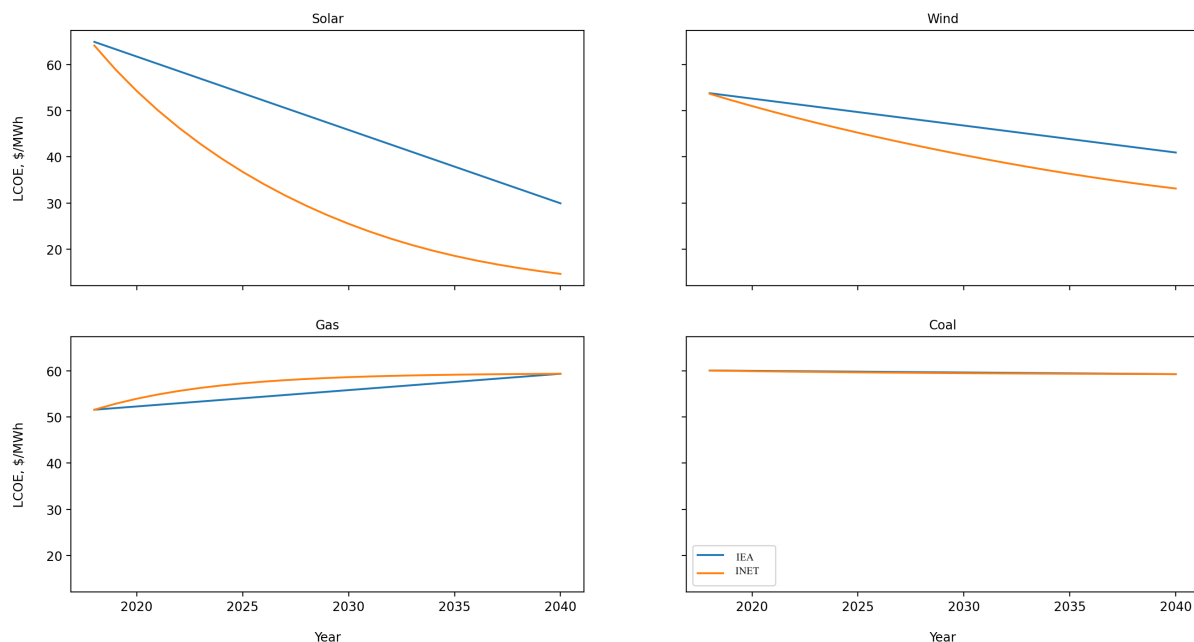


Figure 11: Projection of the Levelised Cost of Electricity (LCOE) by technology and scenario for the IEA (IEA, 2021) and INET scenario (Way et al., 2022). The INET scenario assumes that the current trends in the costs of electricity continue for the next 10 years. LCOE expressed in dollars per MWh at 2020 levels. See Ives et al. (2021) for a comparison of LCOE between the IEA and INET scenarios for all energy generation technologies

Lastly, the three scenarios differ in their levels of global energy demand. The NGFS and IEA scenario assume increasing measures of energy efficiency which provide a significant decrease in the energy intensity of the economy. The IEA and the NGFS scenario project an absolute decrease in the total energy demand from 2020 to 2050, although the NGFS scenario still allows energy demand from electricity to grow at around 3% per year. In the INET scenario, the demand for *useful* energy increases at 2% per year, but significant efficiency reductions in *final* energy demand are gained through the electrification

of heat and transport.

The assumptions discussed above are just a few of the most critical elements that shape the differences between these climate scenarios. Factors such as cost of capital, technological development, innovation breakthroughs, energy demand, and carbon prices substantially influence the outcome of the scenarios and, in turn, the impact on individual companies and the results from climate stress testing. Not surprisingly, different criticisms have been raised about the significant drawbacks of integrated assessment models and large energy models (Creutzig et al., 2017; Farmer et al., 2015; Victoria et al., 2021). As we will show later, these differences may cause high variation in the results of climate stress testing. This demonstrates the need to assess a wider range of scenario narratives, to understand the impact that such key methodological differences could have on the potential for financial instability associated with the net zero transition.

3 A sensitivity analysis of climate stress testing

Stress testing is one of the most popular tools for assessing the resilience of the financial system, financial institutions and portfolios (Aymanns, Farmer, Kleinnijenhuis, & Wetzler, 2018). It has recently been extended to the context of climate change and the net zero transition to assess the potential for climate-related transition risks to generate financial instability (Baer et al., 2021; Battiston et al., 2017). The methods applied in the literature have emerged from various disciplines and strains of research, providing a broad understanding of the issue at hand, but also limiting comparability across methods and preventing a consistent treatment of scenario uncertainty¹¹. In this section, we outline our approach to sensitivity-testing climate stress testing which is designed to improve our understanding of the magnitude of the uncertainty around the net-zero carbon transition. Although we do not model financial institutions portfolios, our analysis sheds light into

¹¹For example, some methods emerged from traditional risk modelling (Dietz et al., 2016; Jung et al., 2021), while other approaches came from agent based modelling (Dafermos et al., 2018; Monasterolo & Raberto, 2018) and network analysis (Battiston et al., 2017; Roncoroni et al., 2021; Stolbova et al., 2021)

the effects of uncertainty on the financial risks emerging from a net zero transition (or transition risks) which are a key driver of financial instability. In order to effectively isolate the variation in financial outcomes emerging from the methodological heterogeneity of the various scenarios, and to assess the fundamental differences in their assumptions, we contrast three markedly different scenarios using a single comprehensive climate stress testing framework based upon the asset-level climate stress test - the TRISK model - by [Baer et al. \(2021\)](#).

For our sensitivity analysis, we assess individual firms' net present values under the different scenarios. The way in which the model is constructed allows to simulate a tail event affecting the valuation of these companies. In the model, some climate-adjusted economic parameters affect the physical production of firms, induce additional costs, and shift market shares according to the alignment of firms with decarbonisation pathways. This alters the firms' cost structure and production mix across technologies and business units (e.g., electricity produced from solar or coal power plants) and impacts their income and profitability. Asset and firm-level impacts are translated into equity valuation changes, through a discounted cash flow model. The model takes into consideration the comparative advantage of firms throughout the transition based on stipulated forward-looking production plans and scenarios around demand and unit cost developments. We use this model to neutralise the methodological differences and focus on the scale of climate uncertainty. For a more comprehensive review of the TRISK methodology refer to [Baer et al. \(2021\)](#).

The model represents heterogeneous firms in the power generation sector. We assume that parent company production levels are aggregated relative to the parent company's equity stake in its subsidiary. We rely on data from the provider Asset Resolution for companies current and planned production and investments (AR)¹². A unique feature of the AR data is that it contains information on the 5-year production plan of firms. This allows us to represent a forward-looking dimension that depends on the transition

¹²<https://asset-resolution.com>

plan of each firm, stipulating how it might reduce and shift its production composition towards sustainable technologies. Firms that do so will see their production levels and associated carbon emissions fall, and will be less vulnerable to a demand change, policy-induced phase-out, or other climate policies that could harm their profits. AR captures asset-level information for climate-critical sectors (i.e., oil, gas and coal extraction, power, steel, cement, aviation, shipping and car manufacturing) that account for nearly 80% of global carbon emissions. In this paper, we focus on firms in the power generation sector. Our model includes a set of 135 public power firms, owning around 8,000 physical assets across 30 countries, for a total market capitalisation of around 1.9 trillion US dollars at the end of 2022¹³

In the model, transition risk is represented by a set of climate-adjusted economic parameters, based on a set of transition scenarios. More specifically, the set of transition scenarios \mathcal{S} is defined as $\mathcal{S} = \{s_1, \dots, s_N\}$, where s denotes the applied scenario and N is the total number of scenarios. Each scenario s consists of the specification of two climate-adjusted variables over time: (1) production $P_h^{s,t}$ and (2) technology unit cost $c_h^{s,t}$, where s is the scenario, h is the technology and t is time (years). The model assumes that firms continue to produce according to the respective baseline scenario, until the introduction of a “climate action” shock¹⁴. The shock shifts the production of energy by each firm onto a Paris-aligned path to, in aggregate, comply with the production trajectories and carbon budgets described in each shock scenario. We apply aggregate technology-specific rates of change of the production in line with the scenario to each individual company pro-rata. The mechanisms of the model works in a way that reflects how and when transition policies are implemented. Energy firms whose decarbonisation plans are the

¹³One estimate the total market capitalisation of the 192 largest power generation firms worldwide is 2.5 trillion dollar (companiesmarketcap.com). While our analysis is not representative of the whole power sector, it contains sufficient information to reveal the potential impact of the variations in the different scenario assumptions and their narratives. Our results are therefore only of limited external validity, and should not be extrapolated to analyse the absolute risk levels of firms.

¹⁴Note that the shock year can be varied for sensitivity purposes to reflect varying degrees of a disorderly transition. The baseline scenario describes a counterfactual scenario where there is no transition to net zero carbon emissions. The model estimates the difference in terms of companies’ valuation between the baseline and the net zero scenarios or shock scenario

most misaligned with the scenario when the shock occurs suffer the steepest adjustment in their production levels.

To accommodate variations in the transition-related financial risk stemming from the uncertainty around particular scenario narratives, we need to input different climate scenarios in the model. More specifically, we aim to isolate the effect of scenario uncertainty while keeping constant other methodological variations. We focus on two key scenario variables which are the input of the TRISK model: (1) the production decarbonisation trajectories per energy generation technology ($P_h^{s,t}$) that is required in each scenario to achieve their respective climate mitigation outcomes; and (2) the evolution of the levelized cost of electricity (LCOE) for each technology ($c_h^{s,t}$), which represents the comparative cost advantages across firms' production based on their technology mix¹⁵. Loosely speaking, we analyse the impact of transition risk for each of the firms under different scenario assumptions around the associated speed and level of disruption created in the global energy mix, as well as different manifestations of the evolution of energy technology costs that impact the market share and cost structure of the analysed firms. Our analysis focuses on the three scenarios described in the previous section, namely the IEA's Sustainable Development Scenario (IEA), the NGFS Net Zero 2050 scenario (NGFS) and INET's Fast Transition scenario (INET).

More formally, consider each firm i 's asset value, $A_i^{s,t}$, at time t in scenario s , which is given by the sum of the values of its physical assets a , $A_{i,a}^{s,t}$, across its ownership structure and subsidiaries:

$$A_i^{s,t} = \sum_{a \in \mathcal{A}} A_{i,a}^{s,t} \quad (1)$$

where the value of physical production assets $A_{i,a}^{s,t}$ at time t in scenario s is given by the discounted sum of the profit generated by the asset a

¹⁵The asset-level data of physical production infrastructure and scenarios allow for a differentiation of impact on firms profitability across the following technologies: electricity generated from coal, oil, gas, hydro, nuclear and renewables

$$A_{ia}^{s,t} = \sum_{t \in \mathcal{T}} \exp^{-\rho(t-T)} \mathbb{E}_t[\pi_{i,a}^{s,t}] + \Omega_{iar}^{s,T}, \quad (2)$$

where $\mathbb{E}_t[\pi_{i,a}^{s,t}]$ refers to the assets' expected profits in scenario s at time t . Future profits are discounted at the average risk premium plus risk free rate $\rho = 7\%$. We assume that after the time horizon of the stress test future profits grow according to a terminal value (perpetual growth) $\Omega_{iar}^{s,T}$, which is given by

$$\Omega_{iar}^{s,T} = \frac{\pi_{ia}^{s,T}(1+r)}{\rho-r}, \quad (3)$$

where r is the long-term growth rate. Hence, the asset value $A_i^{s,t}$ of firm i represents the sum of the net present values $A_{ia}^{s,t}$ of its assets a derived from a discounted cash flow model. The profits $\pi_{ia}^{s,t}$ of firm i 's asset a at time t are given by its revenues $R_{ia}^{s,t}$ minus its costs $C_{ia}^{s,t}$

$$\pi_{ia}^{s,t} = R_{ia}^{s,t} - C_{ia}^{s,t}, \quad (4)$$

where the revenue $R_{ia}^{s,t}$ of firm i 's asset a is given by its production $P_{iha}^{s,t}$ across different energy producing technologies h multiplied by the energy sale price p_h^s

$$R_{ia}^{s,t} = \sum_{h \in \mathcal{H}} P_{iha}^{s,t} p_h^s, \quad (5)$$

and the cost structure of firm i 's asset a is represented by

$$C_{ia}^{s,t} = \sum_{h \in \mathcal{H}} P_{iha}^{s,t} c_h^{s,t} \quad (6)$$

where $c_h^{s,t}$ refers to the unit cost of energy producing technology h of asset a of firm i . From equation 5 and equation 6 it becomes clear that the profit margin pm_{ih}^t of firm i across its technologies h is time-varying and dependent on the unit cost and price differentials in the given scenario

$$pm_{ih}^t = 1 - \frac{c_h^{s,t}}{p_h^s} \quad (7)$$

In this way, the model captures changes in profit margins due to the comparative advantages of individual firms and incorporates the changing costs of transitioning to a green business model in anticipation of, and response to, the shock scenario. This can result in an increase/decrease in profits for firms due to the changing cost structures for the energy sector. For example, consider a firm with a renewable energy asset. The valuation of this asset is the present value of its future profits, which are defined as the difference between revenues and costs. Costs and revenues change in line with the scenario. Further, extend this example to two assets. Each asset will generate different levels of profits depending on the scenario cost projections. The total firm's profits will depend on the share of energy it produces from each asset in the scenario. The share of energy produced by each technology is projected by the shock scenario. These two technology-specific components, energy technology cost projections and energy technology share have an impact on each firm's total energy production at each point in time, and hence determine their total net present valuation.

Subsequently, defines the transition risk, $TRISK_i^{NPV}$, as the difference in the net present value of firm i after a shock and their net present value in a baseline scenario. In this way, the model captures the expected change in companies' valuations following a sudden shift to a Paris-aligned (or "shock") scenario from an inertial (or "baseline") scenario. The shock is assumed to represent a tail event which impacts the valuation of the power generation firms in our sample allowing us to better explore the uncertainty in the tail of the distribution of valuations.

$$TRISK_i^{NPV} = A_i^{stress} - A_i^{baseline}. \quad (8)$$

We run the model three times, each time with a different scenario, to assess the variation in TRISK emerging from different scenarios. The full specification of baseline and shock scenarios are reported in Table 20. Besides the sets of input parameters mentioned above, all other model parameters are kept constant throughout the exercise to isolate the effect of changes in the scenario inputs on financial risk outcomes. However, we perform a sensitivity analysis on some key scenario-independent parameters, such as the discount rate and the year in which the net-zero path 'shock' is introduced. This allows us to test the robustness of our results to these parameters. We initially focus on the variation in the TRISK outcomes on the firm level, but in principle, our approach can be extended to also show differences in the expected losses in financial portfolios. This allows a better understanding of the uncertainties and financial risks at a systemic level and tests the resilience of the real economy, and consequently the financial sector, to different scenario narratives.

There are some distinctive features of the TRISK framework that make it particularly suitable for our study. The bottom-up nature of the framework, the calibration on asset-level data, and the representation of transition risk at the firm-level, allow us to examine the implications of the heterogeneity of firm's transition risks. This is relevant for the scaling-down scenarios that are aggregated at the industry level. The TRISK model translates the scenario trajectories into firm-specific trajectories by assuming that the required production change across technologies must be implemented by the firms in the industry according to their changing market share¹⁶. Further, the TRISK framework represents the strategic direction that firms claim to be taking, stipulated through their five-year production plans across key energy technologies. This incorporation of forward-

¹⁶In this study we only scale down global industry scenarios to the firm-level. A regional differentiation of the scenarios could further improve the model, but for the purpose of showing the variations in the outcome, a global analysis suffices.

looking plans allows the TRISK approach to capture the potential adaptive capacity of firms in the transition and to identify climate laggards.

Time horizon $[t, T]$ of TRISK	<ul style="list-style-type: none"> • $t = 2020, T = 2040$
Shock Year	<ul style="list-style-type: none"> • 2030
Stress Scenario	<ul style="list-style-type: none"> • Run A (IEA): $P_{iha}^{s,t}$: IEA SDS Scenario (IEA, 2021); $c_h^{s,t}$: IEA SDS Scenario (IEA, 2021) • Run B (NGFS): $P_{iha}^{s,t}$: NGFS Net Zero 2050 (NGFS, 2021); $c_h^{s,t}$: IEA SDS Scenario (IEA, 2021) • Run C (INET): $P_{iha}^{s,t}$: Oxford Fast Transition (Way et al., 2022); $c_h^{s,t}$: Oxford Fast Transition (Way et al., 2022)
Baseline Scenario	<ul style="list-style-type: none"> • Run A (IEA): $P_{iha}^{s,t}$: AR Production Plan data $[t;2025]$ + IEA Current Policy (CPS) Scenario $[2025, T]$; $c_h^{s,t}$: IEA CPS scenario • Run B (NGFS): $P_{iha}^{s,t}$: AR Production Plan data $[t;2025]$ + Current Policy Scenario NGFS $[2025, T]$; $c_h^{s,t}$: IEA CPS scenario • Run C (INET): $P_{iha}^{s,t}$: AR Production Plan data $[t;2025]$ + No Transition Scenario; $c_h^{s,t}$: No transition scenario
Discount rate, ρ_j	<ul style="list-style-type: none"> • 7%, including average risk premium
Long-term growth rate, r	<ul style="list-style-type: none"> • 2%
Profit margin, pm_i^t	<ul style="list-style-type: none"> • Firm-specific, EIKON data, adjusted by firm-specific cost evolution for $t > 1$
Prices, $p_h^{s,t}$	<ul style="list-style-type: none"> • We assume that the unit end-price for each technology $p_h^{s,t}$ at time t in scenario s depends on the average unit costs for the technology $\bar{c}_h^{s,t}$
Set of Firms	<ul style="list-style-type: none"> • 135 public firms, $a = 8025$ assets • Total market capitalisation of sample firms 1.87 trillion US\$ (11/2022) • Geographical region $g \in \mathcal{G} = 30$ Countries

Table 20: The table reports the baseline settings of the model used for the main results presented in the paper. Additional calibrations have been tested in the robustness analysis

Moreover, the explicit representation of technology costs in the firm’s profit function allows the impact of the cost improvements of key renewable and storage technologies to be modelled over a longer time horizon, resulting in a more realistic representation of how the firm’s valuations and production levels might change based on cost declines for some generation technologies (e.g. changing firm profitability from electricity generated from renewables as opposed to coal-fired power plants). Finally, the TRISK approach is not particularly dependent on the direct pathway of a carbon tax but rather relies on the manifestation of any type of decarbonisation policy across all technologies. In the model, transition risk is not exclusively a function of current and back-ward looking carbon emissions, but rather a function of the strategic misalignment of firms with the relative costs of generation technologies in alternative scenarios.

4 The degree of uncertainty in climate stress testing

In applying our modified TRISK framework to our three chosen net zero scenarios: IEA, NGFS and INET we aim to better understand the impact of the uncertainty associated with different climate scenarios on energy companies' valuations and, as a result the financial system¹⁷. We compare the change in valuation emerging from an abrupt shift to a net zero transition (shock scenario) from an inertial trajectory (baseline scenario) for a set of publicly listed power generation firms across our three selected scenarios. We define the change in valuation as the difference between the net present value conditional to a shock scenario and a baseline scenario. We contrast the results at different levels of granularity and provide some explanations about the differences emerging from the various narratives.

We find that the impacts on firms' valuations across the three net zero scenarios are generally substantially different (Tab. 21). The average impact on the valuation of power generation firms is the highest for the NGFS (-20%) and the IEA (-11%) scenarios. It is slightly positive (2%) for the INET scenario. The difference between the three scenarios is statistically significant at a 5% confidence level (ANOVA Test). Interestingly, the standard deviation of the impact on companies' valuation is also different, especially for the INET scenario. The standard deviation for the INET scenario (54%) is roughly twice as much as the IEA (20%) and the NGFS scenarios (27%). The former projects a much broader difference between the companies that are positively and negatively affected by the low-carbon transition. This, in turn, results in a much larger portion of companies positively affected by the INET scenario. Nevertheless, in line with previous research, we find that the stress of an abrupt transition to net zero on some investments might be large.

Similar results can be observed in the shape of the distribution of impacts on firms'

¹⁷We are not modelling financial institutions' portfolios, but we are assuming the level of financial risk associated with investments in power generation companies could be a first approximation of the magnitude of the net zero transition on the financial system

valuations across the three scenarios (Fig. 12). In a context where a rapid transition unfolds (INET scenario), companies strategically well-positioned would benefit more from the transformation of the energy system. This leads to a markedly longer right tail in the distribution of impacts for the INET scenario compared to the other two. In contrast, energy producers exposed to fossil fuels would remain significantly negatively impacted in all scenarios, either because cheaper renewable energy replaces carbon-intensive sources, or because carbon taxation makes these technologies more expensive. Nevertheless, the differences in impacts vary substantially across the three scenarios.

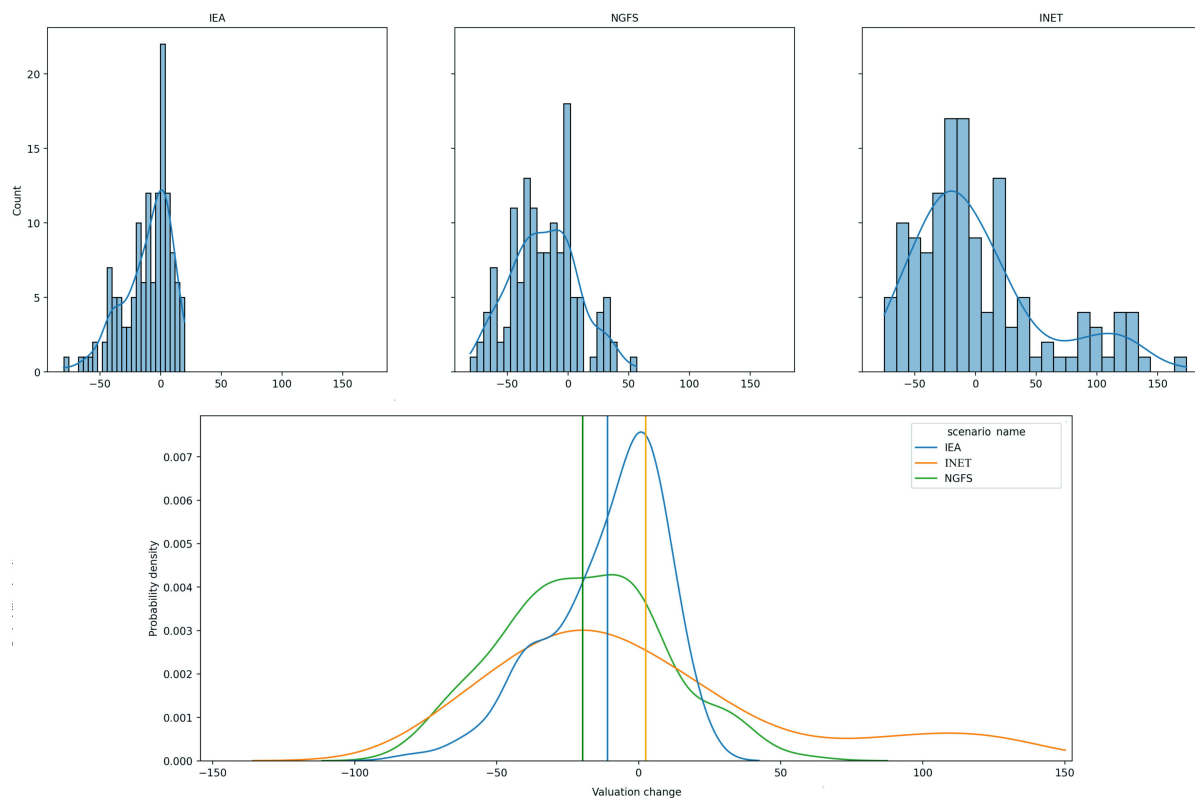


Figure 12: The top three charts represent the distribution of impacts on firm valuations for the three different climate scenarios. Starting from the left hand side IEA Sustainable Development scenario, NGFS Net Zero 2050 scenario, and INET’s Fast Transition scenario. The bottom chart displays the density plots from the three scenarios on the same graph. Vertical lines represents the mean of each scenario distribution. The change in valuation represents the change in net present value of future profits in percentage terms compared to the baseline scenarios

We find that for every year the transition is delayed, the impact on the valuation of

companies is higher. If we look at how the distribution of the impact on companies' valuation changes based on how much the transition is delayed, we notice that the standard deviation also increases (Fig. A4). The more the transition is delayed the greater the difference between the winners and losers. Thus, a delayed and sudden shift to net zero followed by a faster uptake in clean energy technology in line with the INET scenario would greatly magnify the difference between laggards and leaders compared to the IEA and NGFS scenarios. This highlights how the further the transition is delayed, the higher the variability of the impact across different scenarios on the financial system might be if the Paris agreement goals are to be realised.

	IEA	NGFS	INET
Average	-11.07%	-19.73%	2.41%
Median	-5.65%	-20.27%	-4.15%
Standard deviation	20.07%	27.55%	54.06%
5th Percentile	-45.06%	-63.54%	-64.28%
95th Percentile	13.62%	29.85%	121.57%
N	135	135	135

Table 21: Descriptive statistics of the impact of different net zero transition scenarios on companies valuation defined as the net present value of future profits. Reported figures represent key statistics for the impact of each scenario on the valuations of individual firms.

This heterogeneity of results is also present across space. The valuation of companies located in different regions may be impacted differently depending on the scenario considered (Fig. A3). Global leaders in the post-carbon transition, such as countries in Western Europe, could potentially benefit from a realisation of the INET scenario, but also laggards could be less affected due to offsetting benefits brought on by much cheaper renewable energy. In contrast, regions highly reliant on coal, such as South East Asia, would still be significantly affected. The impact in North America is the most disperse across the scenarios. A faster transition, as projected by the INET scenario, could potentially generate slight benefits for US energy firms while the NGFS and IEA

scenarios would generate large losses. We are cautious with this conclusion given the low number of energy companies considered in each particular geography (especially developing countries) and we limit our observations to macro-regions rather than individual countries¹⁸.

The main driver behind the aforementioned variations in impacts is the different magnitude of the shocks to various energy technologies depending on the scenario considered. Individual companies are impacted differently depending on their energy mix and their specific five-year net zero transition plans across key energy technologies. The NGFS and INET scenarios lead to a very large impact on coal energy production (higher than 50%) while the IEA scenario projects a much milder effect. In the INET scenario, the sharper drop in renewable energy costs leads to a large increase in the valuation of renewable energy technologies. In contrast, the IEA and NGFS scenarios show a significantly lower positive shock to the valuation of clean energy technologies. The INET scenario also projects a sharper decline in future gas generation while the impact of the NGFS scenario on gas is in the low single digits range. The IEA scenario projects the largest increase in the valuation of gas energy mostly due to the much broader deployment of this type of technology for energy production. The scenarios are roughly consistent in terms of Hydro and Nuclear power, although these technologies are only a small component of the overall energy mix.

It is worth focusing briefly on one of the main features of the INET scenario, namely the large decline in levelised cost of electricity (LCOE) for renewables and storage technologies to ensure we have a like-for-like comparison with the other two scenarios which both use IEA LCOEs. In order to test this assumption we run the model with a new scenario consisting of IEA LCOE for each technology but with the deployment rates of the INET scenario. Although this scenario is not consistent with the application of Wright's Law used for the INET scenario, it allows us to disentangle the impact emerging

¹⁸The firm level change in valuation has been aggregated at country-level depending on the location of the company headquarters. We are aware that a company's headquarters is an imperfect proxy for the location of its productive plants but this analysis could help provide a better understanding of the geographical and geopolitical implications of our study

from these two separate factors. The average impact on firms valuations in this hybrid scenario is similar to the IEA scenario (-8%) suggesting that the drop in the cost of electricity production is the leading driver behind the milder impact of the IEA scenario on firm valuations. However, the standard deviation is almost as high as the INET scenario showing how different deployment rates are sufficient to drive a wider variability across firms. Even after neutralising the effects of more aggressive projections of cost declines, the impact on firms' valuations is different across scenarios and the variation emerging from the different assumptions in climate scenarios persistent¹⁹.

	IEA	NGFS	INET
Coal	-46.47%	-72.06%	-72.01%
Gas	13.72%	-8.23%	-43.64%
Hydro	02.53%	1.22%	18.50%
Nuclear	0.83%	2.15%	-4.16%
Renewables	12.24%	32.48%	134.86%

Table 22: Reported figures represent the average change in valuation of different energy producing technologies under the different climate scenario considered. From left to right, IEA Sustainable Development Goal Scenario IEA, the NGFS Net Zero 2050 scenario, and the INET Fast Transition scenario (INET).

Finally, we compare the results across the different scenarios using the NGFS as a benchmark (Fig. 4). The motivation for this choice is that the NGFS has become the standard among policymakers and the private sectors and it is therefore important to assess the contrast provided by alternative scenarios. The correlation of the impact on the valuation of power companies between the benchmark scenario and the IEA is around 90%, but it decreases to around 80% when compared to the INET scenario. The correlation decreases to as low as 60% when comparing the IEA and INET scenarios. The firms are less impacted in the IEA scenario compared to the NGFS scenario, both

¹⁹It should be noted that we are assuming the price of electricity is scenario-independent (revenue side). The LCOE projection affects profit margins, but some of the lower costs could possibly be passed-through to consumers in the long run, leading to different profit margin dynamics for energy companies in the various scenarios.

positively and negatively. On the contrary, the variance of impact is greater in the INET scenario compared to the NGFS scenario, especially for those firms benefiting from the net zero transition. Similarly, the valuation of companies negatively impacted by the transition decreases less in the IEA scenario compared to the INET scenario, but the possible increase in valuation is lower in the former compared to the latter scenario.

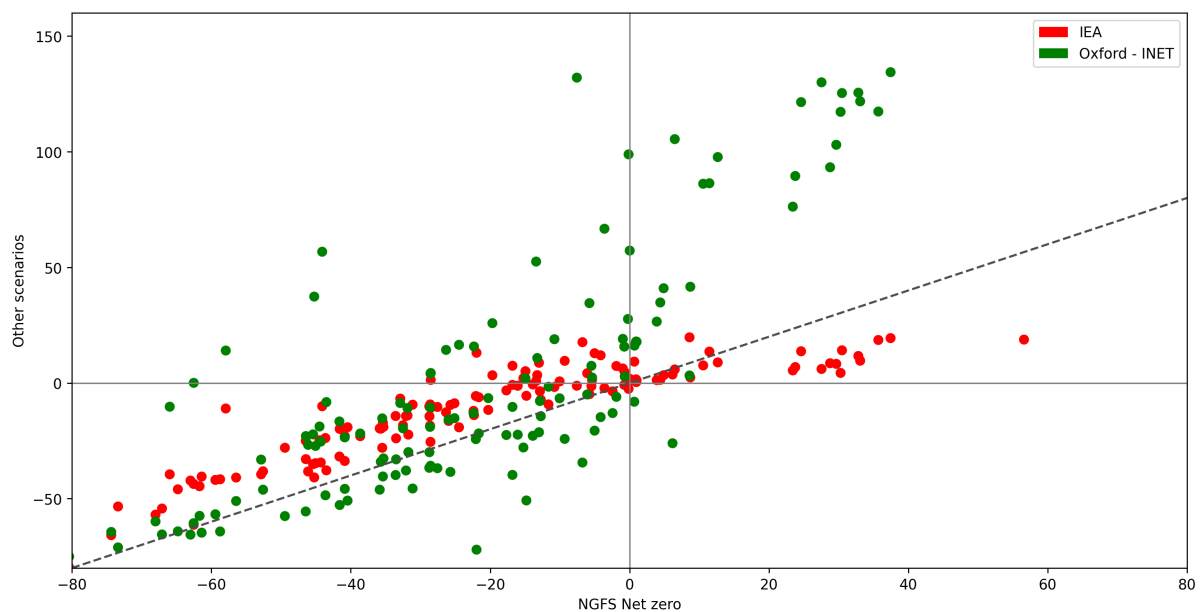


Figure 13: The figure represents a comparison of the change in firms valuation following a sudden shift from a baseline to a net zero scenario. Values are compared to the NGFS Net zero 2050 scenario on the horizontal axis. Vertical axis represents two scenarios: the IEA SDS scenario (Red) and the INET fast transition scenario (Green) colour coded. Each dot represents a firm and the respective impact conditional to the NGFS or the colour-coded scenario. 45° Diagonal line represents perfect correspondence between the benchmark and other scenarios

4.1 Robustness Analysis

In order to test the strength of our findings against some alternative calibrations of the model we run a robustness analysis on two of the key parameters that affect our results: the discount rate and the starting year of the transition 'shock'. We focus on how the distribution of companies' valuation across the different scenarios changes as these parameters change. The discount rate affects the valuations of companies today

because future net profits are discounted at this rate. The year of the shock refers to when the companies in the stress test model shift from the baseline path to the scenario considered. The further in time this begins, the more severe the impact because firms begin their transition later but need to meet the same carbon emissions budget. In particular, we are interested in ensuring that changing these parameters does not lead to less variation between the scenarios. More formally we are interested in assessing that the average impact is still significantly different between scenarios but not significantly different within each scenario (changing discount rate and year of shock).

As reported in Table 23 the mean impact remains significantly different. We reject the null hypothesis that the means are equal between scenarios, but we cannot reject the null hypothesis of equal means between years of shock and discount rate (within each scenario) in a two factor ANOVA test with 5% confidence level. This result is reassuring because it shows that the impact across the scenarios remains significantly different - in line with our hypothesis - even after changing some key model parameters. On the contrary, the magnitude of the impact of each scenario does not materially change with an alternative model set-up.

To further investigate the robustness test on the three scenarios, we divide the companies in our sample into quartiles depending on their current share of coal and renewable energy. We find that regardless of the share of coal or renewable energy, the impact on firms is statistically different between the scenarios within each quartile in an ANOVA test with 5% confidence level. This result gives confidence that the difference is not emerging from possible biases in our sample towards some specific types of companies. Moreover, we find that the projected impact on companies depends on their current share of coal or renewable energy. In line with expectations, companies that today generate a higher share of power from coal are more highly impacted in the three net zero scenarios. On the contrary, the impact on companies' valuations is negatively related to the share of electricity from renewable energy (Fig. A2 and Fig. A1), but the steepness of these relationships is also different across the scenarios. The INET scenario leads to a steeper

relationship between the share of coal/ renewables energy and the impact on companies' valuations compared to the IEA scenario, with the NGFS scenario in between, in line with the expectations and the narratives of these scenarios.

	IEA			NGFS			INET		
	3%	5%	7%	3%	5%	7%	3%	5%	7%
Discount rate									
Average	-15%	-14%	-13%	-20%	-20%	-19%	3%	2%	2%
Standard deviation	21%	20%	20%	29%	27%	26%	57%	54%	51%
5th Percentile	-54%	-51%	-49%	-68%	-65%	-63%	-67%	-64%	-62%
95th Percentile	13%	13%	13%	32%	30%	29%	131%	122%	117%
Year of Shock	2025	2030	2035	2025	2030	2035	2025	2030	2035
Average	-10%	-14%	-19%	-14%	-20%	-23%	4%	2%	6%
Standard deviation	16%	20%	28%	22%	27%	39%	41%	54%	79%
5th Percentile	-37%	-52%	-72%	-50%	-65%	-82%	-50%	-64%	-81%
95th Percentile	11%	13%	23%	23%	30%	55%	91%	123%	183%
N	135			135			135		

Table 23: Top table: average impact of transition risk scenario on company valuations by discount rate. Bottom table: average of impact of transition risk scenario on company valuations by year of shock. Two factor ANOVA test rejects the null hypothesis that means are equal between scenarios (P-value <0.05) but does not reject the null hypothesis of equal means between year of shock and discount rate within each scenario (P-value >0.05)

5 Discussion

Our results suggest that the impact of the net zero transition on companies' valuations may vary for the same emission target (well below 2°C) depending on the underlying scenario assumptions. Thus, calling into question the adequacy of the research conducted to date on the impact of transition risk on financial stability. Researchers in this space should consider dealing more extensively with this uncertainty in order to better understand climate-related financial risks. The three scenarios considered in this study are roughly consistent in terms of total carbon emissions and temperature targets in 2050, but the difference in how the world may meet this net zero objective drives significant

variation in the impact on firms, and the respective financial investments. This in turn may lead to different levels of financial stability.

Moreover, to the best of our knowledge, no other study has assessed how a faster uptake of renewable energy technology could potentially lead to significant differences in the financial risk firms face from the net zero carbon transition. Most of the existing literature focuses on a narrow set of possible future trajectories which inadequately cover the plausible range and ultimately restrict policy options. The results of our study show that the current narratives on the net zero transition could also have repercussions on policy decisions (e.g., on setting additional capital requirements) which might be biased by the assumptions of climate and stress test models. Without properly considering the wider spectrum of future possible outcomes, climate stress testing could only give a false sense of control over the potential threats to financial stability emerging from the net zero carbon transition.

Finally, we have shown that, in principle, many climate scenarios could be made consistent and thereby included in climate stress testing. The integration of alternative scenarios has so far been challenging due to the fragmented landscape of climate scenarios research (e.g. many disparate institutions creating scenarios such as the IPCC and other academic scenarios, the IEA, NGFS, fossil fuel companies, and non-governmental organisation) and different choices around the granularity and specificity of parameters. However, we have demonstrated here how scenarios can be made consistent without losing much of the underlying information, by finding the least common denominator across coverage, specificity, and granularity. Further research should aim to include a greater variety of transition scenarios to reflect a wider range of decarbonization efforts across sectors, different assumptions across technological change, costs of technologies and carbon taxes. Integrating such multiple scenarios will better reflect the different ways that the transition might manifest.

This paper has limitations in that we only focused on the power generation sector and considered only a limited sample of firms. We have also not investigated how a broader

set of scenarios might lead to more or less diverse results. Nevertheless, using asset-level data about energy firms in our sample and three different scenarios has allowed us to demonstrate an approach for better understanding the magnitude of uncertainty around the impact of climate-related risks on financial assets, providing an alternative perspective to the extant literature. Future research should thus focus on expanding the breadth of climate scenarios considered in assessing climate-related financial risks. In this paper, we only covered three scenarios and the power generation sector, but future research could expand this study to other sectors (e.g., agriculture, transport) or to a broader set of climate scenarios to capture an even greater set of uncertainties. For example, business-as-usual scenarios that foresee an increase in physical hazards emerging from global warming may show even higher levels of uncertainty, as highlighted by some research (Mahul et al., 2021). Thirdly, research effort should begin to focus on developing probabilistic methods which allow projecting the inertial trajectory of the system leveraging, for example, the empirically grounded technological forecasting methods employed by Way et al. (2022). This would solve one of the key challenges of these assessments: the ambiguity about the likelihood of climate policy action and the transition. The common thread is that research should explore more broadly the weaknesses and limitations of current methods and work towards improving our understanding of climate-induced financial instability.

6 Conclusions

The transformation required by the net zero carbon transition might pose substantial challenges to the stability of the financial system. Previous studies at the intersection of climate change and financial stability might have not dealt sufficiently with climate uncertainty. In this paper, we have found that the variations in scenario narratives and assumptions may lead to substantially different levels of financial risk emerging from a transition to net zero carbon emissions. We have shown that the impact of a sudden shift towards a transition to net zero carbon emissions on the valuation of power

generation companies, and investments in these firms, varies substantially for the same long-term emission target (below 2°C) depending on the various assumptions underlying the development of climate scenarios (e.g., energy demand, technological innovation, cost projections). This, in turn, may lead to different magnitudes of impacts on the financial system. These results indicate that the degree of uncertainty in financial stability research in the context of climate change might be substantial and that the existing literature might be susceptible to the assumptions and narratives of the climate scenario considered.

This paper shows that the tools that financial supervisors deployed to date might not adequately assess some of the financial risks emerging from climate change. In this manuscript, we have used a consistent climate stress test model to compare three very different net zero scenarios, namely: the International Energy Agency (IEA), the global consortium of central banks named the Network for Greening the Financial System (NGFS) and scenarios developed by the Institute For New Economic Thinking (INET) at the University of Oxford. This approach has allowed us to isolate the variability emerging from scenario assumptions, and neutralise any differences between alternative stress testing approaches. This study provides strong evidence that financial institutions and regulators need to consider a broader set of climate scenarios in stress-testing research which could have profound implications for policymakers.

7 Appendix

7.1 A review of climate stress testing methods

This section reviews the current methods and tools used in the literature for the assessment of climate related financial risks and the implications for financial stability²⁰. The literature at the intersection of climate change and financial stability emerged from various backgrounds which evolved in different methods and approaches. These added a more nuanced view to the impacts of climate change on financial stability, but also limited the comparability of the different outputs. The heterogeneity of methods employed in the literature is one of the fundamental drivers that leads to the significant variability in the output of this research. The methods used emerged from different fields from financial economics, network analysis, agent based modelling as well as supervisory and industry practices. This research has yet to settle on a commonly shared approach.

The climate stress testing literature firstly emerged from the branch of research on financial stability and stress testing ([Aymanns et al., 2018](#)). It extended some of the concepts of the topology of the network of the financial system to empirical observations about the exposure of banks to climate relevant sectors ([Battiston et al., 2017](#)). A network approach allows to study the interconnectedness of the financial system and the potential propagation mechanisms among banks. These methods allow to identify climate related losses which might emerge from both direct and indirect exposures of financial institutions to Climate Policy Relevant Sectors (CPRS). Propagation effects could also extend beyond the second order effects and generate higher order losses including other market participants ([Roncoroni et al., 2021](#)). Losses could also propagate outside of the financial system and generate feedback loops between the real economy and the financial sector which might generate other types of amplification dynamics ([Stolbova et al., 2021](#)). This first strand of research demonstrated to be particularly useful in understanding the propagation dynamics of climate change, but it simplifies the impacts on financial firms

²⁰For a review refer also to [Acharya et al. \(2023\)](#)

through the real economy.

On the opposite, the literature that emerged from financial economics allowed a more tractable assessment of the direct impacts of climate related risks on financial institutions. In this regards, a Merton model has been adapted to Mortgages and Corporate exposures of the Dutch financial sector to assess the effects of market valuation shocks emerging from different climate scenarios on banks capital buffers (Reinders, Schoenmaker, & van Dijk, 2023). Such approach shows that losses could amount to a significant part of banks' capital requirements in case of a large and sudden increase in carbon taxation, even without accounting for second round effects. More traditional financial metrics such as "expected shortfall" conditional to the materialisation of a climate scenario have been proposed in this strand of literature. Jung et al. (2021) measure the relationship between a stranded asset portfolio and the largest global banks' stock market valuations (climate beta). They then calculate the expected equity loss of a 50% drop in the stranded assets portfolio to assess the potential impact of sudden market re-pricing of climate change. Similarly, an early study from Dietz et al. (2016) calculates the value at risk (VaR) of global financial assets. This paper does not explicitly focus on the implication of climate change on financial stability but is one of the first in using traditional risk measures and applying them to the context of climate change.

The benefits of the approaches discussed in the previous paragraph are their simplicity and similarity to more traditional risk measures. On the negative side, these papers might not be able to capture the full extent of the complexity of climate change. For this reason, more granular climate stress testing methods have been employed for both transition and physical risks. Baer et al. (2021) pose a larger focus on the differentiation of firm-level transition impacts and the heterogeneity of the effects of climate change on companies. Similarly, Bressan, Duranovic, Monasterolo, and Battiston (2022) develop an asset-level climate physical risk assessment. They develop a methodological approach to translate the impacts of acute and chronic climate change to assets and subsequently on financial holdings' expected shortfall. These methods are usually data-driven, combined with more

traditional discount models and relying on different estimates of the impact of climate change on specific firms/assets locations or technologies.

Due to the complexity of assessing the impacts of climate change on the stability of the financial system, Agent Based Macroeconomic Modelling (ABM) has also been employed in this literature. [Lamperti et al. \(2019\)](#) use an ABM calibrated on stylised facts of the financial system and climate impact functions to investigate the effects of climate change on the possibility of an increasing likelihood of banking crisis. Arguably these models could allow for a better understanding of the aggregated effects of climate change starting from the bottom-up impact of various economic agents. Similarly, Stock Flow Consistent models (SFC) have been used to investigate the interaction between financial policies and financial stability ([Dafermos et al., 2018](#); [Monasterolo & Raberto, 2018](#)). These methods allow to endogenously model some of the possible behaviours of the banking sector's reactions to changing sentiments and policies about climate change. These models also allow to investigate some of the transmission channels among different financial agents relying on accounting identities between different economic actors ([Dunz et al., 2021](#)).

Some studies leverage adaptations of existing macroprudential stress test models, mostly available to central banks and supervisors, to assess the impact on the financial system of a sharp increase in carbon prices, unanticipated energy technology breakthroughs or a combination of both ([Vermeulen et al., 2021](#)). Central banks have been a relevant contributor to this literature through internal research and financial supervision. The European Central Bank (ECB) show that using granular bank and firm level information in a climate stress testing allows for a better understanding of the sectoral and geographical heterogeneity of the impact of climate related risks ([Alogoskoufis et al., 2021](#)). Similarly other central banks have proposed different studies with various levels of granularity and drivers of climate related risks.

7.2 Additional robustness analyses

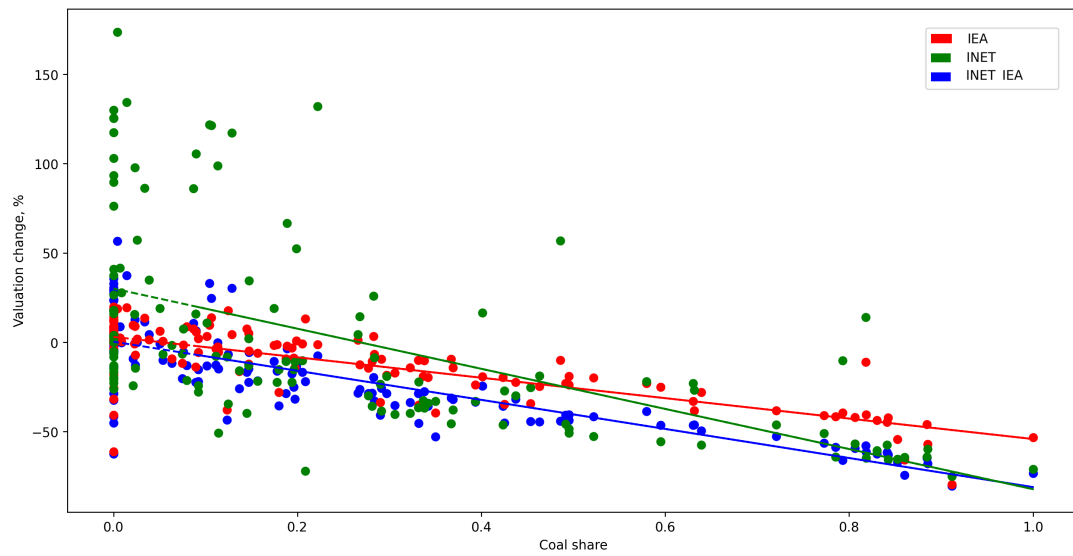


Figure A1: The chart represents the impact on power generation companies valuations of a sudden shift from a business as usual trajectory to a net zero scenario for three different net zero scenarios: IEA, NGFS, INET (vertical axis). The horizontal axis represents the share of energy produced by coal over the total energy produced.

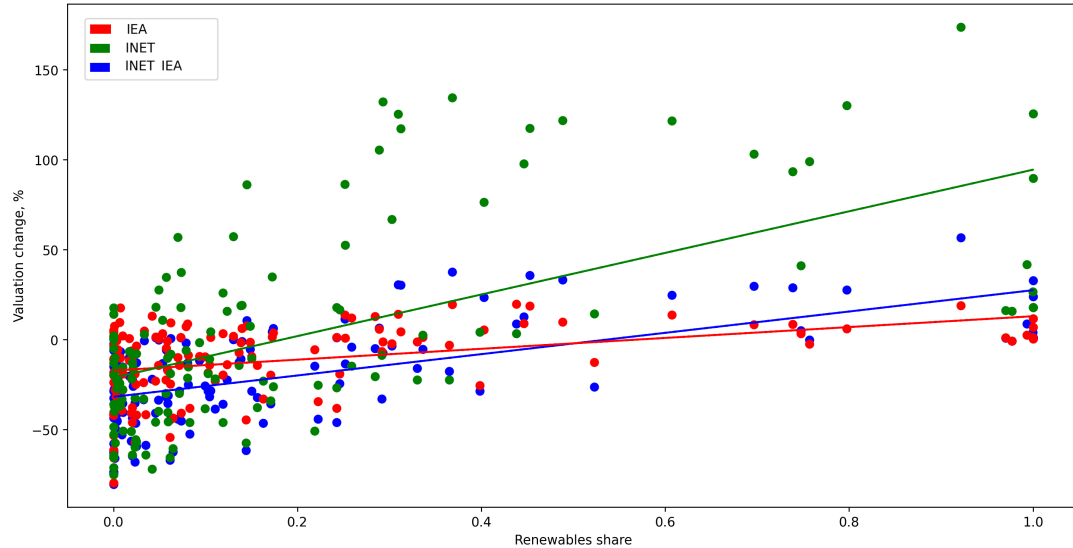


Figure A2: The chart represents the impact on power generation companies valuations of a sudden shift from a business as usual trajectory to a net zero scenario for three different net zero scenarios: IEA, NGFS, INET (vertical axis). The horizontal axis represents the share of energy produced by renewable energy over the total energy produced.

Scenario	Coal Energy share quartile	Average	Standard Deviation	N
IEA	1	-0.5	13.56	83
	2	-18.18	10.38	30
	3	-29.33	7.32	7
	4	-46.81	14.98	15
NGFS	1	-3.87	20.91	83
	2	-34.87	7.81	30
	3	-45.9	4.64	7
	4	-65.02	6.75	15
INET	1	25.88	53.65	83
	2	-24.09	24.76	30
	3	-40.52	16.04	7
	4	-54.46	24.02	15

Table A1: The table reports the impact on power generation companies valuations shock for the IEA, NGFS, INET. The results are divided by quartile of share of energy produced by coal over the total energy produced by each firm.

Scenario	Renew Energy share quartile	Average	Standard Deviation	N
IEA	1	-17.02	19.85	98
	2	5.33	10.77	20
	3	4.24	10.14	5
	4	3.83	6.12	12
NGFS	1	-30.38	21.71	98
	2	4.77	21.66	20
	3	12.33	23.83	5
	4	13.01	18.27	12
INET	1	-20.13	31.41	98
	2	57.71	60.66	20
	3	74.61	45.05	5
	4	64.25	56.4	12

Table A2: The table reports the impact on power generation companies valuations shock for the IEA, NGFS, INET divided by quartile of share of energy produced by renewable energy over the total energy produced by each firm.

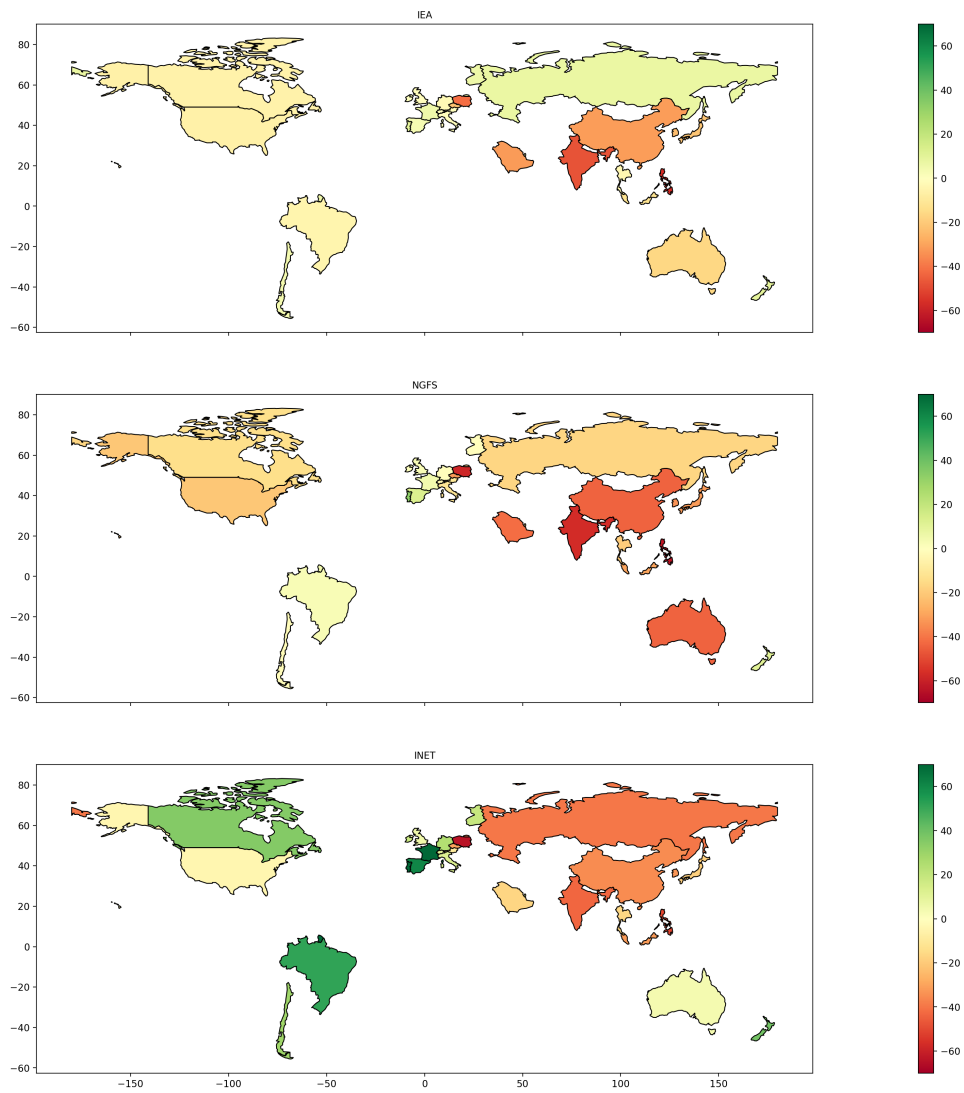


Figure A3: The figure represents the average valuation change of firms headquartered in the respective country for the three scenarios: IEA, NGFS and INET

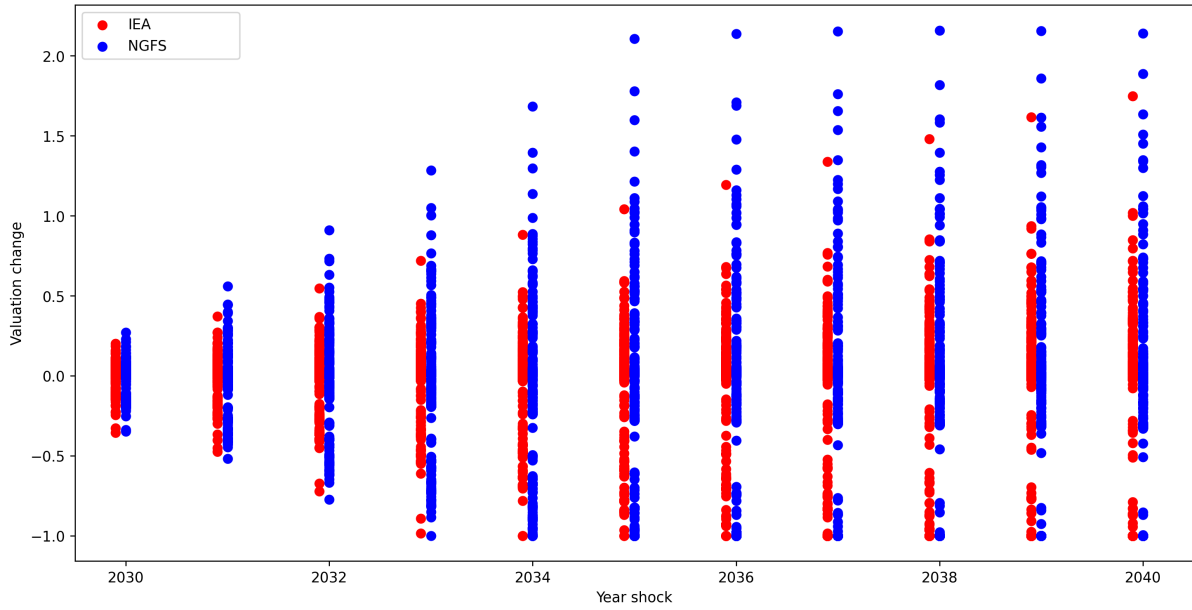


Figure A4: The figure represents the difference in companies discounted net profits between baseline and net zero scenarios for the NGFS and the IEA scenarios (vertical axis). The horizontal axis shows the year in which firms are required to align with the respective net zero scenario (Year of shock). Each dot represents a power generations firm in our sample

Part VI

Conclusion

The financial system carries out various important societal functions such as the allocation of financial resources across space and time, the transfer and pooling of risks, and the mitigation of agency costs (Crane et al., 1995). Financial economists have studied for years the functioning of these activities. Some core tenets have emerged from this field such as the time value of money, the relationship between risk and return, the role of informational asymmetries, and the presence of agency costs. This thesis has shown that some of these societal functions and tenets can be affected by climate change justifying a broader appreciation of this systemic problem by financial economists. In this thesis, I have shown that climate change is already having a profound impact on how we value assets, how we assess financial risks and, in turn, how we might need to restructure our financial regulations.

Financial economists have started to recognise the impact of climate change on the financial system. In Chapter II, I have shown an increase in research in the field of Climate Finance. This literature is rapidly growing and discussing issues touching every aspect of finance such as Asset Pricing, Financial Intermediation, Corporate Finance, and Household Finance¹. In Chapter III, I have discussed some asset pricing implications of climate change showing that it is unlikely that financial markets price a high likelihood of a transition to net zero carbon emissions. I have argued this may be due to the uncertainty around whether we will be able to prevent global warming, but also because the financial sector may not be well equipped to assess systemic change. Indeed, in Chapter IV, I have shown this issue may also impact how the financial sector assesses financial risks. I have found that banks are unlikely to assess high-carbon activities as higher risk than low-carbon ones, despite the increasing number of pledges to achieve net zero carbon emissions. This has potential consequences for the net zero transition

¹I am not the first to review this rapidly evolving literature (Giglio et al., 2021; Hong et al., 2020)

given how strongly the assessment of assets' risks by the financial system influences the allocations of resources between different economic activities.

Novel methods that are better suited to assessing the impacts of climate change have started to emerge, but they remain at the fringe of financial economics. In Chapter [V](#) of my thesis, I have discussed the properties and limitations of climate scenario analysis which allows for the introduction of climate related risks in financial assessments. I have shown that, as they currently stand, they fail to provide a comprehensive picture of the possible financial risks associated with the net zero carbon transition. But newer approaches to scenario analysis and stress testing ([Acharya et al., 2023](#)), could nevertheless prove to be useful for financial economists. For example, in Chapter [III](#), I have leveraged similar methods to assess the valuation of fossil fuels firms conditional on a set of climate scenarios. This has allowed me to explore more broadly the distribution of the valuations of some of the most carbon-emitting activities. In Chapter [IV](#), I have used a simple stylised scenario to show the extent to which banks' risk estimates may fail to capture the risk of a transition to net zero carbon emissions for fossil fuels firms.

The reconsideration of these tenets is important for ensuring our global economy functions within planetary boundaries. The financial system is a necessary condition for a successful transition to a net zero carbon world ([McCollum et al., 2018](#)). For example, transitioning from fossil fuels to renewable energy will require a massive shift from opex to capex, making the role of finance even more important for our energy systems. The findings in this thesis suggest that the financial system, as it is currently organised and regulated, may not be well suited to deliver on this transition. Our risk models are generally lacking a consideration of climate related financial risks and uncertainties, and, in turn, financial regulations are agnostic about the endogeneity of the environment in our economies and financial system. All these factors, impair the ability of the financial system to carry out its important societal functions in the era of climate change and to contribute to mitigate global warming. Financial economists have a role to play to change this status quo.

My thesis has made some contributions in this direction, but much more needs to be done. I provide a better understanding of whether financial markets are pricing climate related risks and the net zero carbon transition contributing to the asset pricing literature (Baker et al., 2022; Bolton & Kacperczyk, 2023; Engle et al., 2020; Flammer, 2021; Hsu et al., 2022; Pástor et al., 2022). I provide a novel and so far neglected perspective to this literature, but more research is required to better isolate climate change uncertainty from general uncertainty. In Chapter III, I show various analyses that suggest a predominance of climate change uncertainty over general uncertainty for fossil fuel firms. Nevertheless, there remain inherent identification challenges. Further research could utilise different methods to better link climate change uncertainty with the valuation of carbon intensive assets.

Further avenues of research could incorporate environmental externalities into asset pricing from a normative perspective. Rather than focusing on whether financial markets are pricing these risks, one may ask what should be the price of such instruments in light of their environmental effects and the inherent climate risks. More research would also be helpful on the asset pricing of "green" assets in light of the possible imbalance between supply and demand of these investments. The largest focus of the literature has so far been on "brown" assets, but the research in this thesis suggests the structural change of the transition may also affect the pricing of low carbon activities.

There is also a need to better understand the role of financial regulations in creating adverse incentives for financial institutions to invest in low carbon solutions. In Chapter IV of this thesis, I have shown that accounting rules may create disincentives for financial institutions to invest in low carbon projects (Gasparini et al., 2024). These issues likely arise from the structure of risk models that are commonly used in the financial system and regulations. A deeper study into the relationship between regulations and investments in low carbon solutions is sure to bare valuable insights. For example, it is likely that capital requirements present a similar challenge to transition-friendly investment as was presented in this thesis for accounting rules. Further research could also improve the link

between risk estimates and broader environmental metrics. Due to the lack of available data, this thesis relied on proxies to assess the exposure of banks to various sectors and their emission intensities. The use of a more complete dataset could establish a better connection between financial firms' risk estimates and carbon emissions providing new insights into the likelihood of perverse incentives.

More research should be carried out around climate risks management and the tools utilised for their assessment. For example, this thesis and other literature² show the challenges of quantifying climate related financial risks and the strong limitations of the tools at our disposal in light of the deep uncertainty surrounding climate change. Despite the limitations of the transition risk model used in Chapter V of this thesis, I have shown the challenges inherent in such assessments. Differently from other papers (e.g., [Barnett et al. \(2020\)](#)), I have provided a first rough estimate of the impact of such uncertainty on the assessment of transition risks. I also utilised a probabilistic scenario about the "most likely" future outcome to benchmark currently used assessments (e.g., those from the Network for Greening the Financial System). Nevertheless, novel methods could be explored to cope with the limitations I encountered and empower the financial system to better assess those risks.

Finally, more research should also be carried out to better understand some old and novel instruments and activities. For example, there is a growing recognition that Environmental Social Governance (ESG) mutual funds may be impacted by advertisement and "greenwashing". This may limit the flow of resources towards more sustainable investments. Some novel activities also deserve attention. The emergence of climate alliances, especially among financial institutions, and their work on setting net zero carbon emission targets may be a useful tool for driving change in absence of strong government intervention. In conclusion, this thesis has shown how fruitful research in this field could be for academics and for the environment. But also that more research needs to be done and deserves broader attention from financial economists.

²See for example [Battiston et al. \(2017\)](#); [Battiston and Martinez-Jaramillo \(2018\)](#); [Jung et al. \(2021\)](#); [Monasterolo \(2020\)](#); [Roncoroni et al. \(2021\)](#); [Vermeulen et al. \(2021\)](#)

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