

Carbon Beta: A Market-Based Measure of Climate Transition Risk Exposure*

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This draft: March 2023

First draft: November 2021

We estimate asset-level climate transition risk exposure by regressing stock returns on a pollutive-minus-clean portfolio. This climate risk measure, ‘carbon beta’, is forward looking, able to distinguish transition winners from losers, and can be calculated for any asset for which returns are observed. We study the interaction of carbon betas with several proxies for realisations in climate risk. Returns to stocks with high carbon betas are lower during months in which climate change is more frequently discussed in the news, during months in which temperatures are abnormally high, and during exceptionally dry months. Variation in carbon betas correlates with green patent issuance and forward-looking measures of climate risk. We find that exposure to climate transition risk is priced in the cross-section of equity returns. The ‘carbon risk premium’ amounts to an additional return of 1.15% annually for each standard deviation increase in carbon beta.

Keywords: Climate change, carbon risk, climate finance, asset pricing.

JEL: G11, G12, Q54.

*We thank David Blitz, Jean-Paul van Brakel, Jeroen Derwall, Meredith Fowlie, Itay Goldstein, Marcin Kacperczyk, Georgi Kyosev, Simon Lansdorp, Christian Leuz, Susanne Preuss, Viorel Roscovan, Laura Starks, Yasmine van der Straten, Laurens Swinkels, Xuan Wang, Utz Weitzel, and seminar and conference participants at *Robeco*, *Vrije Universiteit Amsterdam*, *Maastricht University*, the *NBER Conference on Measuring Carbon Footprints and Climate Risk Exposure*, the *Joint Research Centre at the European Commission*, the *5th Annual Conference of the Global Research Alliance for Sustainable Finance and Investment*, the *2022 Research in Behavioral Finance Conference*, and the *ESSEC-Amundi Webinar on Climate Risk and Portfolio Management* for comments. The views presented in this paper are the authors’ own and do not necessarily represent those of their affiliated institutions.

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1 INTRODUCTION

In the 2015 Paris Agreement, 196 parties committed to holding global average temperature increases to below 2°C above pre-industrial levels. The agreement explicitly calls on the financial industry in helping to make finance flows ‘*consistent with a pathway towards low carbon emissions ...*’ (p. 3, United Nations, 2015). Investors are becoming increasingly aware of their role in mitigating climate change and the potentially enormous societal and economic consequences of failing to do so. As a result, asset owners and investors representing over \$120 trillion in assets have signed up for the UN Principles for Responsible Investment in 2021.¹ Nonetheless, many institutional investors report challenges in addressing climate risks, citing a lack of best practices, problems around data availability, and inherent difficulties with assessing climate change (Krueger et al., 2020; Giglio et al., 2020).

Development of scientific methods and metrics to measure climate risk exposure is urgently needed (Krueger et al., 2020; Giglio et al., 2020). We contribute to this need by introducing a measure of asset-level climate risk exposure, determined by the extent to which an asset’s price correlates with a carbon risk factor. Following the terminology of the asset pricing literature, we refer to this measure as *carbon beta*. Our measure is complementary to other measures of climate risk, of which corporate greenhouse gas emissions and emission intensities are the most prominent examples.² Our approach contributes to the current literature in the following three aspects.

First, due to the market-based nature of our measure, carbon betas potentially reflect market participants’ expectations regarding an asset’s future transition risk exposure. Besides a company’s current greenhouse gas emissions, factors such as the availability of clean technologies, quality of management, innovation ability, competition, and financial health likely affect a company’s ability to deal with transition risks and reduce future greenhouse gas emissions. If market prices incorporate expectations about such aspects, then our carbon beta will reflect those as well. As such, the distinction between greenhouse gas emissions and carbon beta’s is akin to the broader distinction in the asset pricing literature between characteristics and the covariance structure of returns as introduced in Daniel and Titman (1997).

Second, and related to the former, carbon betas allow a clear distinction between assets that are expected to benefit from a low-carbon transition and assets that are expected to lose from such a shift. Corporate emissions, on the other hand, are best at identifying ‘climate losers’ (Sautner et al., 2022), that is, firms that are currently among the heaviest emitters and likely negatively impacted by a

¹See UN PRI Annual Report 2021: <https://www.unpri.org/annual-report-2021/how-we-work/building-our-effectiveness/enhance-our-global-footprint>

²Emission intensities are defined as corporate greenhouse gas emissions divided by revenues.

sudden transition. Moreover, all emissions are assumed equally harmful, while investors might assign greater weight to some emissions over others. For example, for firms whose emissions occur in the production of goods that reduce emissions elsewhere (e.g. solar panels), or that operate in sectors for which abatement is expected to be easier, investors might perceive lower risk exposures. To illustrate this point, note that the annual direct emissions of Tesla, Inc., a manufacturer of electric vehicles, and W&T Offshore, Inc., an independent oil and gas producer, are relatively similar, ranking close to the 80th percentile in our sample. However, the average carbon beta of Tesla is among the *bottom* 5%, while that of W&T is in the *top* 5%. Seemingly, investors can hold widely varying expectations of climate risk exposure as measured by carbon beta even for firms with similar emissions output. In other words, the carbon beta approach allows investors to hedge the carbon risk in their portfolio since it can single out climate winners next to climate losers.

Third and finally, the approach allows us to calculate carbon betas for any asset for which returns are observed. Thus, our procedure allows the estimation of carbon betas for asset classes that have no other carbon-related measures available, for which it is inherently difficult to construct such measures (e.g. commodities), or which are by their nature opaque (e.g. hedge funds for which the holdings data are not publicly available). The estimation procedure is transparent and consistent across assets and asset classes and does not directly rely on the voluntary disclosure of emissions-related information.

Our carbon risk factor is constructed by forming a long-short portfolio. The long leg of the portfolio contains relatively pollutive companies whereas the short leg contains relatively clean companies. To roughly classify companies into pollutive and clean groups, we use companies' relative greenhouse gas emissions. The motivation behind this choice is not that emissions are a perfect indicator of whether a company is *green* or *brown*,³ but rather that as a group, heavy emitters are more likely to be negatively affected by an accelerated low-carbon transition than light emitters are. Our carbon risk factor thus consists of a long position in the stocks of the heaviest-emitting 30% of firms offset by a short position in stocks of the least-emitting 30% of firms, controlling for size as in Fama and French (1993). We refer to this portfolio as the Pollutive-Minus-Clean, or *PMC*, portfolio.

The economic mechanism behind the carbon risk factor follows that of the Pástor et al. (2020, 2022)'s model of an ESG factor. If concerns regarding the climate unexpectedly rise, consumer demand will shift from brown products and services to greener ones. Producers of these products and services will benefit accordingly, which increases their valuation. Simultaneously, investors who care about the climate will substitute brown asset holdings for greener alternatives, either because they derive more utility from holding green assets (for example because they are publicly pressured to do so),

³We use 'brown', 'pollutive', and 'unsustainable' interchangeably to describe firms, products, and services that are contributing to climate change, while we use 'green', 'clean', and 'sustainable' to describe firms, products, and services that contribute much less to, or even help in, mitigating climate change.

or because they anticipate stricter environmental policies. Our proxy for the carbon risk factor is intended to capture such shifts in the valuation of brown firms relative to green firms that occur due to changing concerns around climate change.

We perform time-series regressions of equity returns on the carbon risk factor – while controlling for additional factors known to drive returns – to determine stock return sensitivities to carbon risk. We regard the loading on the carbon risk factor, the *carbon beta*, as a firm-level indicator of climate transition risk exposure. Our results corroborate the existing findings on the pricing of greenhouse gas emissions and intensities (Bolton and Kacperczyk, 2021a,b), and add a number of new insights consistent with the complementary characteristics of the carbon beta measure.

Inspired by recent work by Cohen et al. (2020) we explore the relationship between our measure of climate risk and firms' green patents output. Cohen et al. (2020) find that green innovation is largely driven by firms in the Energy sector, yet paradoxically these firms are generally amongst the worst performers on environmental issues. We download all patents issued by the U.S. Patent and Trademark Office (USPTO) from 2010 to 2020 and link their patent classes to green patent classification schemes. Our results indicate a negative and statistically significant association between carbon beta and green innovation, indicating that green innovators are less exposed to climate risk. If we only include Energy firms in the analysis, the effect becomes more pronounced. We do not find similar results when focusing our analysis on carbon intensities or carbon emissions as the indicator of climate risk exposure. These findings suggest that firm differences in green innovation are taken into consideration by market participants and are therefore reflected by carbon betas, illustrating the forward-looking nature of carbon beta.

Assets with positive carbon betas tend to depreciate in value when investors become more concerned about the climate. On the contrary, negative carbon beta assets tend to appreciate in such times. These assets can be regarded as 'climate hedge' assets because they deliver high returns when climate change concerns increase. We devise several tests to uncover such an effect. To start, we construct an index similar to Engle et al. (2020)'s Climate Change News Index. Our index is determined by the textual similarity between daily news articles published in the Wall Street Journal and a corpus of texts on climate change collected from official reports and Wikipedia. We theorise that periods in which climate change is frequently reported in the news tend to coincide with episodes of heightened uncertainty around future climate policies. As this approach is analogous to that in the literature on economic policy uncertainty (see, e.g., Baker et al. 2016), we refer to our index as the Climate Policy Uncertainty (CPU) index. We find that in months when CPU increases, firms with higher carbon beta have lower returns. A standard deviation increase in carbon beta leads to around a 15 bps reduction in returns, *ceteris paribus*, for each standard deviation increase in

climate policy uncertainty. Based on observations that extreme temperature shocks reduce corporate earnings (Addoum et al. 2018; Pankratz et al. 2019) and disproportionately diminish the market values of pollutive firms (Choi et al. 2020), we perform similar analyses using extreme weather events in the United States. We document that during months with abnormally high temperatures, firms with high carbon betas tend to generate significantly lower returns, in both economic and statistical terms. A qualitatively similar pattern is observed in periods of extreme drought, where a standard deviation increase in carbon beta is associated with a 39 bps lower return. These results are consistent with the model of Pástor et al. (2020, 2022), implying that carbon beta is indeed functioning as a measure of climate risk.

A natural question that arises is whether climate risk is priced. If investors dislike states of the world in which the climate deteriorates, they should demand higher returns for holding high carbon beta assets that underperform in such scenarios. Likewise, they should be willing to accept lower expected returns for climate hedge assets with negative carbon betas, in return for these assets' ability to hedge climate risks. On the contrary, in times of increasing concern about the environment, assets with high carbon betas tend to depreciate in conjunction with the PMC portfolio, because these assets are expected to be negatively affected by a low-carbon transition. As such assets are riskier and shunned by investors, they should trade at discounts, and offer higher expected returns. In line with theoretical predictions by Pástor et al. (2020), our asset pricing tests confirm this to be the case. A one standard deviation increase in carbon beta tends to be associated with, *ceteris paribus*, an increase in annualised return by 1.15%-points.

Carbon beta is a relatively simple, flexible, and intuitive approach to assess asset-level climate transition risk exposure. We demonstrate the flexibility of our methodology by applying it to three different asset classes: (i) U.S. equities as the core focus of our paper, (ii) national equity indices in Appendix B, and (iii) U.S. corporate bonds in Appendix D. Theoretically it is possible to apply our approach to any asset class with a sufficient history of returns observations, but further avenues to apply our concept are left for future research. As such, the data created for this paper will be made publicly available by us. Importantly, this means that carbon betas will be distributed and can be used by investors and researchers. Moreover, the CPU index and green patent data will be made available and can be used by other researchers.

Our paper relates to a growing literature on *climate finance*, which studies the interactions between climate change and financial markets. Addoum et al. (2018) examine the effects of extreme temperature shocks on corporate earnings and find that such shocks significantly impact earnings in over 40% of industries. Relatedly, Bansal et al. (2019) estimate stock return sensitivities to long-run temperature shocks and find that temperature-exposed stocks carry a risk premium. Pankratz et al. (2019)

establish a causal negative relationship between heat exposure and firms' operating performance, and observe that financial analysts and market participants incorrectly anticipate the effects of heat on company performance. Bortolan et al. (2022) argue that variation in temperatures affects asset prices, and provide empirical evidence to back their claim. Huynh et al. (2021) observe that mutual fund managers divest from pollutive firms after they experience increased local air pollution. Hong et al. (2019) explore the stock prices of food producers and conclude that they do not efficiently reflect long-run drought risks. Engle et al. (2020) construct portfolios to hedge innovations in climate change news. We adopt their methodology of quantifying climate change news. Choi et al. (2020) study how people update their beliefs about climate change during periods of high temperatures. The authors confirm that attention to climate change spikes during such periods, and that stocks of firms with low carbon emissions outperform their carbon-intensive peers. The effects coincide with selling from retail investors, yet better-informed institutional traders do not exhibit similar behaviour. Painter (2020) and Goldsmith-Pinkham et al. (2022) find that physical climate risks are priced in the U.S. municipal bond market. Goldstein et al. (2022) model how ESG investing affects price informativeness. One of the model's implications is that an increasing share of ESG-motivated investors leads to prices that are more reflective of ESG signals and less reflective of firm fundamentals.

Görge et al. (2020) are the first to consider the concept of a carbon risk factor. Their factor is constructed from several ESG variables provided by MSCI, Sustainalytics, the Carbon Disclosure Project (CDP), and Thomson Reuters. The authors find that Fama and French (1993) and Carhart (1997) asset-pricing models perform significantly better after the inclusion of the carbon risk factor. They find no evidence of a carbon risk premium in the cross-section of returns. After conducting a Campbell and Vuolteenaho (2004) decomposition, the missing premium is attributed to carbon risk being associated more with unrewarded cash flow risk than with discount rate risk.⁴ Görge et al. (2020)'s paper is different from ours in several ways. First, Görge et al. (2020) primarily adopt an asset pricing perspective of the carbon risk factor as a driver of stock returns, while we focus more on firm-level sensitivities towards such a factor as a measure of carbon risk. Second, the construction of Görge et al. (2020)'s carbon factor relies on a number of ESG variables designed to capture differences in a firm's climate change adaptability, its value chain, and the public's perception. Considering the many variables available to choose from and given that ESG data are notoriously inaccurate (see, for example, Chatterji et al. (2016), Kotsantonis and Serafeim (2019), and Berg et al. (2022)) and costly to obtain, we refrain from making additional assumptions on how firms are

⁴Campbell and Vuolteenaho (2004) predict that cash-flow risk should be priced at a larger premium than discount rate risks, as the latter is more transitory. Görge et al. (2020) however observe the reverse to be the case in their sample period. Explanations for this finding could lie in the time-varying component of the price of cash-flow risk and in the fact that after the global financial crisis, cash-flow shocks have been predominantly upward (Maio, 2013; Campbell et al., 2013).

exposed to climate risks, other than that such exposure is roughly proxied for by carbon emissions. Our paper fits into a relatively recent literature that examines forward-looking, firm-level measures of climate risk. Sautner et al. (2022) and Li et al. (2020) construct measures of corporate climate risk from textual analysis of earnings call transcripts. Both studies use a similar methodology that quantifies climate risk via the share of the earnings call conversations devoted to climate-related topics. Sautner et al. (2022) go to great lengths to validate their Climate Change Exposure. The measure indicates higher exposure for companies listed in countries with stronger climate regulations. Compared to more traditional measures of carbon risk, a greater fraction of the variation in Climate Change Exposures occurs at the firm level rather than at the sector, year, or country level. Based on climate risk disclosures in annual reports, Kölbel et al. (2020) conclude that transition risks have statistically and economically significant effects on the spreads in CDS markets, while physical climate risks do not. Huynh and Xia (2021) consider the covariance between corporate bond returns and the Engle et al. (2020) Climate Change News Index. Bonds with high climate news betas are more expensive, consistent with their potential to hedge against climate risks. Similarly, Alekseev et al. (2022) evaluate climate hedging portfolios formed by going long (short) the stocks that are disproportionately bought (sold) by mutual fund managers after they have experienced local extreme heat events.

Finally, our work adds to recent findings on the stock return implications of corporate carbon emissions. Two of the most comprehensive works on this topic are Bolton and Kacperczyk (2021a) and Bolton and Kacperczyk (2021b) who focus on the pricing of corporate carbon emissions in respectively U.S. and global equity markets. In the former study, the authors conclude that more emissions are associated with higher returns, yet only the indirect emissions display explanatory power beyond the industry effect. The latter research utilises levels and percentage changes in firms' emissions as a proxy for long-term and short-term transition risks. A transition risk premium is mostly present in the cross-section of North American, European, and Asian stocks. In Australian, African, and South American stock markets, transition risk does not seem to be priced. Additionally, the global carbon premium increased markedly following the 2015 Paris Agreement. A related study by Monasterolo and De Angelis (2020) finds that the systematic risk of low-carbon assets has decreased after the Paris Agreement, while carbon-intense assets have become riskier. Using information from option prices, Ilhan et al. (2021) report larger downside tail risks for stocks with higher carbon intensities. Moreover, the costs of protection against these tail risks are higher at times of heightened attention to climate change. Hsu et al. (2023) examine the existence of a pollution premium in the cross-section of U.S. stock returns. Their focus lies on mandatory toxic emissions disclosures, rather than on greenhouse gas emissions. A long-short portfolio sorted on toxic emissions generates a return spread

of 5.52% annually. The authors explain this ‘pollution premium’ through higher regulatory risks faced by pollutive firms and provide empirical support for this hypothesis.

The remainder of this paper is organised as follows. Section 2 introduces our main sources of data and our dataset construction procedure. In Section 3, we describe the construction of the pollutive-minus-clean portfolio and the estimation of carbon betas. Results follow in Section 4, including the validation of our estimates and main analyses. Section 5 concludes.

2 DATA

2.1 STOCK MARKET AND CORPORATE DATA

For the main analysis of this paper, we combine U.S. stock market data from the Center for Research in Security Prices (CRSP) with financial statements data from S&P Capital IQ Compustat. We utilise the Wharton Research Data Services (WRDS) Linking Table to match observations from CRSP’s Monthly Stock File with observations from Compustat’s Fundamentals Annual at the end of June of the previous year.⁵ To mitigate survivorship bias resulting from Compustat’s data collection procedure (Banz and Breen, 1986), we only include firms after they have appeared in Compustat for two consecutive years.

We proceed by calculating several variables from the combination of fields in CRSP and Compustat. To compute book-to-market ratios, we divide the book value of equity by the market capitalisation at the end of January of the associated year. We divide the following items by total assets: book leverage; capital expenditures; property, plant, & equipment; and research & development expenses, resulting in the accounting ratios debt-to-assets, investment-to-assets, PP&E-to-assets, and R&D-to-assets. We calculate return on equity by dividing net income by total shareholder’s equity. All accounting variables are winsorised at the 1% and 99% cutoff points to mitigate the effect of outliers and potential data errors. We calculate momentum by compounding a stock’s return over the past 12 months, excluding the most recent month to account for short-term reversal (Jegadeesh, 1990). We utilise daily returns obtained from CRSP’s daily security file to estimate CAPM-implied market betas and idiosyncratic return volatilities. Estimations are based on rolling windows containing three years of daily return observations. We obtain data on U.S. factor returns from Kenneth French’s data library, which we use in the estimation of CAPM-betas, idiosyncratic volatilities, and carbon betas.⁶

⁵We only make use of the linking information if the link type is any of *LU*, *LC*, *LS*, *LX*, *LD*, *LN*, or *LO* and if the link primary is *P* or *C*. At the time of matching, the link must be valid according to the link date and link end date.

⁶https://mba.tuck.dartmouth.edu/pages/faculty/ken.french/data_library.html

2.2 EMISSIONS DATA

We collect information on greenhouse gas emissions from S&P's Trucost, a leading provider of corporate emissions data. Trucost data are either reported or estimated by Trucost's proprietary models. Reported emissions originate from various sources, including the Carbon Disclosure Project (CDP), MSCI, Sustainalytics, Bloomberg, ISS, and corporate sustainability reports. The extent to which non-reported emissions are estimated varies. Some values are partial estimates, for example, derived from a company's usage of fossil fuel. Other estimates might be derived from partial disclosure in corporate sustainability reports or private conversations with company representatives. A majority of estimations result from Trucost's proprietary model, which utilises an extensive input-output model that associates business activities with environmental impacts. Trucost reports emissions according to the standards set forth by the Greenhouse Gas Protocol.⁷ The Greenhouse Gas Protocol decomposes emissions into three 'scopes'. Scope 1 emissions include the direct emissions occurring in a company's production process. Scope 2 emissions are the indirect emissions associated with the purchase of electricity, heat, or steam. All other emissions taking place in a company's value chain are accounted for as scope 3. As our database does not contain the complete data for scope 3 emissions, we only include scope 1 and scope 2 emissions in our analyses.⁸ We sum scope 1 and scope 2 to a combined scope 1 & 2, and calculate emission intensities for the combined and separate scope 1 & 2 emissions by dividing each of the total emissions by the associated firm's revenues as reported by Trucost. In the remainder of this paper, we refer to the combined scope 1 & 2 emissions when using the terms *emissions* or *total emissions*, and we refer to the combined scope 1 & 2 emissions scaled by revenues when we use the terms *emission intensity* or *intensity*.

2.3 CLIMATE POLICY UNCERTAINTY INDEX

We follow Engle et al. (2020) in creating an index for climate news risk. The index levels are determined by the textual similarity of news articles in the Wall Street Journal with a corpus of climate change terms constructed from authoritative sources. We theorise that periods of high climate change news are indicative of increased uncertainty around climate change regulation. Following similarly constructed indices for Economic Policy Uncertainty (see Baker et al. 2016), we refer to this index as the Climate Policy Uncertainty (CPU) index.

The CPU index is constructed as follows. First, we collect documents on climate change. Our corpus includes the five Assessment Reports written by the UN Intergovernmental Panel on Climate Change

⁷<https://ghgprotocol.org>.

⁸Our Trucost data only includes the downstream scope 3 emissions, which are the indirect emissions that occur further 'down' a company's value chain. These are emissions by a firm's customers, but not by its suppliers.

(IPCC). Because these reports are technical (see Sautner et al. 2022; Li et al. 2020), we extend the climate change corpus with articles in the ‘climate change’ category on Wikipedia.⁹ We assume that the writing in Wikipedia articles is more representative of the language used in newspapers than the writing in official reports on climate change. We refer to the collection of texts from the IPCC reports and the Wikipedia articles as the *climate change corpus*, denoted by \mathbb{C}_{CC} . We collect texts of daily articles published in the Wall Street Journal starting from 1997. The collection of each daily archive’s texts is referred to as $\mathbb{C}_{WSJ,t}$. We determine the CPU index as follows. We start by applying several text preprocessing steps commonly used in Natural Language Processing.¹⁰ We then perform a term frequency - inverse document frequency (TF-IDF) transformation to convert our collection of text articles into numerical vector form.¹¹ We apply the same TF-IDF transformation to the climate change corpus \mathbb{C}_{CC} and each day’s collection of news article texts $\mathbb{C}_{WSJ,t}$, yielding TF-IDF vectors denoted by \mathbf{v}_{CC} and $\mathbf{v}_{WSJ,t}$. Finally, for each day we compare $\mathbf{v}_{WSJ,t}$ with \mathbf{v}_{CC} by cosine similarity.¹² The intuition behind this approach is that when news articles use climate change terms in similar proportions as the texts related to climate change, the index indicates a high level of climate change news risk (Engle et al., 2020). We lower the frequency of our measure from daily to monthly by taking monthly averages of daily index levels. For ease of interpretability, we scale index values such that the mean of the index equals 100.

Figure 4 plots the Climate Policy Uncertainty index through time. Along the horizontal axis, various events related to climate change are reported. As can be seen, the CPU index generally rises when such events occur. The index peaks in December 2009, when the 15th Conference of the Parties (COP) was held in Copenhagen. COP15 was one of the first international conferences to bring climate change to the highest political level. As a result of the conference, the Copenhagen Accord was signed. The Accord expressed clear political intent to limit carbon emissions and respond to climate change. The CPU index reached its second-highest level in November and December 2015, during COP21 in Paris. At this conference, the Paris Agreement was negotiated. Around the end of 2019, the index remained at elevated levels. This period marked a series of mass protests to demand action on climate change. These strikes coincided with the Climate Action Summit in New York.

⁹https://en.wikipedia.org/wiki/Category:Climate_change

¹⁰These involve, in the following order: removing punctuation, tokenising (splitting sentences into words), removing stop words, lemmatising (reducing words to their word roots, e.g. the words ‘climate’ and ‘climatology’ both become ‘climat’), and converting terms into bigrams (two-word collections of consecutive words).

¹¹The TF-IDF algorithm converts words, in our case bigrams, into scores determined by the word’s frequency within a document, penalised by its frequency across documents. Hence, a word occurring often in one document but rarely in other documents receives a high score, as it is regarded as being informative for that certain document.

¹²Formally, the cosine similarity between two vectors is defined as the cosine of the angle between them, or equivalently by the inner product of the vectors normalised to have unitary length. The cosine similarity reaches its maximum of 1 when the angle between \mathbf{v}_{CC} and $\mathbf{v}_{WSJ,t}$ equals 0°.

2.4 OTHER DATA

We collect data from various additional sources. In this section, we briefly describe the datasets used, the data collection procedure, and the purpose of collecting the data.

1. Sautner et al. (2022) Firm-Level Climate Change Exposure. We compare our estimates of carbon beta with Sautner et al. (2022) Climate Change Exposures (hereafter SvLVZ CCEs). This measure is determined by the extent to which climate change-related words are used by the company's management and analysts during earnings calls. Besides general Climate Change Exposure, Sautner et al. (2022) determine separate vocabularies for risks, opportunities, and regulations related to climate change.¹³ We use the three components, as well as general climate change exposure in our analysis. We cross-sectionally standardise all SvLVZ CCE exposure values to make their scales comparable.

2. Temperature and drought statistics. We collect monthly temperature anomalies for the United States from the U.S. Climate Reference Network.¹⁴ A month's temperature anomaly is defined as the temperature deviation from its 30-year average reference temperature. We download the Palmer Z-Index, a derivative of the Palmer Drought Severity Index (PDSI; Palmer 1965) as a measure of drought severity.¹⁵ The PDSI uses precipitation, temperature, and geographic data to model available quantities of water to a location of interest. As the PDSI is inaccurate over short frequencies (see, e.g. Karl (1986)), we use the Palmer Z-Index which is designed to be more responsive on a monthly frequency. Negative values of -4 indicate extreme drought, values between -1 to 1 indicate regular conditions, and values of +4 indicate unusually wet periods.

3. MSCI Climate-Value-at-Risk and MSCI Emissions Data. We obtain Climate-Value-at-Risk (CVaR) data from MSCI for about 2,200 firms in our sample. CVaR has been designed to capture firm-specific forward-looking valuation assessments regarding climate risk and opportunities.¹⁶ The measure includes a wide array of information, including - but not limited to - corporate emissions data, green patent issuance, exposure to physical climate risks, green revenues, and modeled outcomes in different policy and technology scenarios. Values for CVaR are bounded by -100 and 100, where -100 (100) indicates that a company is expected to be harmed by (benefit from) climate change. We reverse the sign of CVaR to align it with traditional Value-at-Risk, and cross-sectionally standardise it to enable comparison with other metrics. In additional robustness checks, we base the construction of the PMC portfolio on MSCI's corporate emissions data rather than Trucost's.

¹³The data are available at <https://osf.io/fd6jq/>

¹⁴<https://www.ncdc.noaa.gov/temp-and-precip/national-temperature-index/time-series/anom-tavg/1/0>

¹⁵<https://www.ncei.noaa.gov/access/monitoring/historical-palmers/>

¹⁶<https://www.msci.com/documents/1296102/16985724/MSCI-ClimateVaR-Introduction-Feb2020.pdf/f0ff1d77-3278-e409-7a2a-bf1da9d53f30>

4. MSCI Country Indices. For tests on international carbon betas, we download daily returns on 48 national equity indices from Refinitiv (formerly Thomson Reuters) Eikon. All index prices are denominated in U.S. dollars. We collect data from January 2015 to December 2020. We use national equity indices to estimate carbon betas on the country level, which we use for our validation tests in Appendix 6.

5. Green Patents. Following Cohen et al. (2020), we download U.S. patents through the U.S. Patent and Trademark Office's (USPTO) Bulk Data Storage System.¹⁷ The USPTO provides text files for all patents issued in the United States from 1976 onwards. We download patents granted from 2010 up to and including 2020. We rely on two techniques to link patent issuance to our dataset. First, we download the patent-to-company mapping from the Compustat Link table of WRDS' newly released US Patents (Beta) product.¹⁸ This patent-company linkage is available for the 2011-2019 period. For this period, our patent database and that of WRDS cover almost the same patents.¹⁹ A small difference (less than 1%) in patent coverage is likely the result of retrospective changes in USPTO's data or an occasional error in our or WRDS's retrieval of patent files. Second, we map the stated assignees in patent grants to the company names in our Compustat sample by applying an approximate-string matching algorithm based on a cosine similarity comparison utilised in section 2.3. We only match records if the confidence level exceeds 85%. At this level, manual inspection of matching outcomes yields very few incorrect matches, yet this conservative approach comes with the risk of overlooking valid links. We assume, however, that such valid links are covered by WRDS's linking table. When our matching algorithm disagrees with that of WRDS, we follow the link proposed by WRDS, as we believe the linking table by WRDS is better able to deal with company subsidiaries and name changes. For patents outside the 2011-2019 window, we first extrapolate the WRDS linking table and otherwise rely on our linking procedure. To check the robustness of our green patent construction procedure, we also download information on green patent shares from MSCI.

To identify green patent issuance, we follow guidelines by the OECD as described by Haščić and Migotto (2015). These guidelines describe the patent classifications that are related to a wide variety of green technologies, for example, environmental management, water pollution abatement, waste management, climate adaptation, biodiversity protection, renewable energy, greenhouse gas capture and storage, and fuel efficiency. We supplement the guidelines of the OECD with the International Patent Classification (IPC) Green Inventory.²⁰ In our analyses, we proxy for green innovation by

¹⁷<https://bulkdata.uspto.gov/>

¹⁸Available at <https://wrds-www.wharton.upenn.edu/pages/analytics/wrds-us-patents/>

¹⁹We obtain over 99% of the patents in the WRDS database for the 2011-2019 period for which WRDS has patent data available.

²⁰See <https://www.wipo.int/classifications/ipc/green-inventory/home>

Green Share; the number of green patents as a percentage of the total number of patents issued to a company (Cohen et al., 2020). We download over 750,000 unique patents, matched to over 3,000 firms. A little under 10% of total patent issues are classified as green. Top green patent issuers, by the total number of green patents, are IBM, Ford, General Electric, Intel, Apple, and Raytheon.

3 METHODOLOGY

3.1 THE POLLUTIVE-MINUS-CLEAN PORTFOLIO

We regard the pollutive-minus-clean (PMC) portfolio as an observable proxy for carbon risk. The PMC portfolio captures differences in the returns to a portfolio of polluting firms relative to the returns to a portfolio of cleaner firms. The working of our carbon risk factor follows the mechanism of the Pástor et al. (2020, 2022) model for ESG risk. In this model, ESG risks materialise via two channels, the *customer* and the *investor* channel. A similar mechanism applies to carbon risk. When climate concerns unexpectedly rise, for example, because the predicted path of temperature warming worsens, *customer* demand shifts from ‘brown’ to ‘green’ products and services. Lower demand negatively shocks the profitability of pollutive companies, and hence reduces these companies’ market values, while the opposite occurs for clean companies. The second channel involves investors’ preferences. Investors derive more utility from sustainable investments in times of climate stress, either because they care about the climate or because they face public pressure to divest from brown assets. Indeed, Choi et al. (2020) report that stocks with high carbon intensity underperform stocks with lower carbon intensities during abnormally warm months. Their findings are mainly driven by retail investors selling carbon-intensive stocks. Furthermore, investors may anticipate governments imposing stringent climate change policies, as the likelihood of policy interventions increases in times of heightened environmental concerns (see Pástor and Veronesi (2013) for political risk in general). Selling pressure and increased discount rates induced by heightened climate concerns cause pollutive firms to depreciate, and clean firms to appreciate, in value. As the PMC portfolio holds a net long (short) position in brown (green) stocks, both channels lead to a reduction in the PMC portfolio’s value in response to a climate shock. The opposite occurs when concerns regarding climate change unexpectedly lessen so that the return on the PMC portfolio becomes positive.

We similarly construct the PMC portfolio as the Fama and French (1993) HML portfolio. PMC is a self-financing portfolio that takes a long position in the most polluting 30% of firms and a short position in the least polluting 30% of firms. We perform this sorting on scope 1 & 2 emissions, which include both estimated and reported emissions. We do not consider scope 3 emissions for several

reasons. First, our data only includes downstream scope 3 emissions, which measures the emissions further ‘down’ a company’s value chain.²¹ As different firms operate at different levels in the value chain, downstream emissions are less comparable between companies. Second, scope 3 emissions data are by definition estimated rather than reported. There are considerable complexities in accurately modeling emissions associated with all activities in a company’s value chain. As a result, when comparing firms’ emissions, Busch et al. (2018), Berg et al. (2022), and Kalesnik et al. (2022) report much lower pairwise correlations for scope 3 emissions than for scope 1 & 2 emissions. Third, because scope 3 emissions are double-counted for firms active in the same value chains (see Kalesnik et al. 2022), they are much larger in magnitude than scope 1 and 2 emissions. Hence, combined scope 1, 2 & 3 emissions tend to be dominated by their scope 3 component and are relatively similar to scope 3 emissions in isolation. While constructing the PMC portfolio, we adjust for the size bias that results from sorting on corporate emissions. We do so by explicitly forming separate portfolios for firms valued below and above the median NYSE firm, following Fama and French (1993). We define breakpoints for polluting and clean firms at the 70th and 30th percentiles. For each year we form four value-weighted portfolios; small/polluting (SP), big/polluting (BP), small/clean (SC), and big/clean (BC). The return on PMC is then given by:

$$r_{PMC,t} = \frac{r_{SP,t} + r_{BP,t}}{2} - \frac{r_{SC,t} + r_{BC,t}}{2}, \quad (1)$$

where $r_{PMC,t}$ is the return on the PMC factor on day t and $r_{SP,t}$, $r_{BP,t}$, $r_{SC,t}$, and $r_{BC,t}$ are the returns, respectively, on the Small / Polluting, Big / Polluting, Small / Clean, and Big / Clean portfolios on day t . Figure 1 displays the cumulative log return on the PMC portfolio. The mean return on PMC has been substantially negative over the 2007 to 2021 period. Returns to the PMC portfolio are significantly lower in months where climate policy uncertainty increases and in months that have abnormally high temperatures, as Panel B of Figure 1 shows. Table 1 compares the PMC factor to the Fama and French (1993) factors and the Carhart (1997) momentum factor. Returns to the PMC portfolio are negatively correlated with the market factor, indicating that the pollutive leg on average holds firms with lower systematic risk. The PMC portfolio correlates positively with value. This is expected, as the most pollutive firms tend to be value firms, while cleaner firms tend to be growth firms. The procedure we follow to ensure size neutrality seems to work, as indicated by the insignificant association between the carbon risk and size factors. To verify the robustness of some of our portfolio construction choices, we alternatively construct PMC portfolios on other sorting variables besides Trucost’s reported and estimated emissions. Figures A1 and A2 and Table

²¹E.g. for a gas station, downstream emissions include emissions from the cars consuming the station’s gasoline, while upstream emissions include the emissions involved with the extraction of crude oil or refining of oil into gasoline.

A3 in Appendix A report evidence that portfolios constructed by (i) using only reported emissions; (ii) using only estimated emissions; (iii) using emissions intensities; and (iv) using emissions provided by MSCI yield relatively similar portfolio returns.

3.2 ESTIMATING CARBON BETAS

To estimate carbon betas – i.e. return sensitivities to the PMC factor – we run time-series regressions of the corresponding firm’s daily stock returns on PMC while controlling for the Fama and French (1993) market, size, and, value factors and the Carhart (1997) momentum factor. We estimate:

$$R_{i,t} = \alpha_i + \beta_i^{RMRF} RMRF_t + \beta_i^{SMB} SMB_t + \beta_i^{HML} HML_t + \beta_i^{UMD} UMD_t + \beta_i^{PMC} PMC_t + \epsilon_{i,t}, \quad (2)$$

where $R_{i,t}$ is the excess return on stock i on day t , α_i is the stock’s risk-adjusted outperformance, β ’s denote sensitivities to the factors, $RMRF_t$, SMB_t , HML_t , UMD_t , and PMC_t are respectively the daily returns on the market, size, value, momentum, and carbon risk factors, and $\epsilon_{i,t}$ is the residual term. Our interest lies in β_i^{PMC} , which denotes the stock i ’s carbon beta. We use a 36-month estimation window, which thus contains about 750 daily return observations.²² In later tests, we cross-sectionally standardise estimates of carbon beta when comparing them to other measures of carbon risk. In all cases, we winsorise estimates at the 1% and 99% levels to mitigate the impact of outliers.²³

4 RESULTS

4.1 SUMMARY OF VALIDATION EXERCISES

To verify that our estimates of climate risk exposure align with expectations, are not overly governed by industry effects, or are driven by spurious correlations, we subject firm-level estimates of carbon betas to a battery of validation tests. The goal of these exercises is to make sure that variation in carbon betas aligns with prior expectations from related studies on other climate risk measures and with commonly held views on climate exposures. We first compare carbon betas across industry

²²Besides considering several alternative carbon risk factor definitions (as shown in Figure A1 and Table A3 in Appendix A), we have further included the Fama and French (2015) profitability and investments factors, performed the regression on monthly instead of daily return observations, utilised an industry-neutral carbon risk factor, and considered a carbon risk factor based on carbon intensities. Our validation results remain qualitatively similar.

²³Our results are virtually unaffected by omitting to winsorise and by increasing the extent of winsorisation to 2% and 98% cutoff points.

sectors. Figure 2A shows that we find the highest carbon betas in the Energy, Materials, and Utilities sectors. These sectors are collectively responsible for over 70% of scope 1 & 2 emissions in our sample, so their high loadings on the carbon risk factor are expected. On the contrary, we observe that firms in the IT, Financial, and Health Care sectors tend to exhibit the lowest average carbon betas. The negative carbon betas of the stocks in these industries indicate a tendency for high stock returns in times of increasing climate concerns. Continuing our validation tests, we investigate how firm characteristics correlate with estimates of carbon beta. We theorise that smaller, more capital-intensive, lower-valued, less profitable, and less innovative firms are more exposed to climate risks. These predictions largely turn out to be true. As demonstrated in Table 3, firms with higher climate transition risk exposure tend to have, *ceteris paribus*, lower market capitalisation, higher property, plant & equipment on their balance sheets, higher capital investments, lower research & development expenses, lower profitability, and higher greenhouse gas emissions. We next turn to comparisons of carbon beta with alternative measures of climate risk. Correlation Table 4 reveals robust associations with emissions, emission intensities, Sautner et al. (2022) Climate Change Exposures, MSCI Climate-Values-at-Risk, and MSCI Green Scores. These associations go in a direction that is *ex-ante* in line with expectations. Appendix B describes our validation tests in greater detail and provides additional validation efforts.

4.2 CARBON BETA AND REALISATIONS OF CLIMATE RISK

In this section, we investigate equity return dynamics during times in which climate change risks materialise. We evaluate two proxies for aggregate climate risks. First, we consider shocks to an index that captures how frequently climate change is reported in the news, where we assume such shocks coincide with uncertainty regarding future climate policies. Second, we consider extreme weather events in the contiguous United States. Research shows that during extreme weather events, investors become more concerned about climate change (Alekseev et al., 2022; Huynh et al., 2021; Choi et al., 2020; Bansal et al., 2016). Our interest lies specifically in the interaction effect between carbon beta and the proxy for materialising climate risk on stock returns. Specifically, we seek to answer the question of how market responses to materialising climate risks are different for firms with high versus low carbon betas.

To answer this question, we adopt the framework of Daniel and Titman (1997) and Bolton and Kacperczyk (2021a,b). We utilise specifications of the form:

$$R_{i,t} = \beta CB_{i,t-1} + \lambda X_{i,t-1} + c_i + \mu_t + \epsilon_{i,t}, \quad (3)$$

where $R_{i,t}$ is firm i 's excess stock return in month t , $CB_{i,t-1}$ is the carbon beta at the end of month $t-1$, $X_{i,t-1}$ is a vector of lagged control variables including the natural logarithm of firm i 's market capitalisation, its book-to-market, return on equity, book leverage, investment-to-assets, PP&E-to-assets, and stock i 's CAPM beta, idiosyncratic volatility, and momentum, c_i is a sector fixed effect, and μ_t is a time fixed effect. Alternatively, we replace $CB_{i,t-1}$ with other measures of climate risk, in which case we cross-sectionally standardise both measures to enable comparison. We include industry sector and time-fixed effects to mitigate possible bias resulting from unobserved effects that vary across sectors respectively in time. Robust standard errors are clustered at the firm level to adjust for possible serial correlation of residuals within firms.

4.2.1 CARBON BETA AND CLIMATE POLICY UNCERTAINTY

As a first proxy for realisations in climate risks, we utilise the Climate Policy Uncertainty index. We study the effects of innovations in the CPU index and its interaction with carbon beta on stock returns. Our specification is the following variation on Equation (3):

$$R_{i,t} = \alpha + \beta CB_{i,t-1} + \gamma CB_{i,t-1} \times \Delta CPU_t + \theta \Delta CPU_t + \lambda X_{i,t-1} + c_i + \mu_t + \epsilon_{i,t}, \quad (4)$$

where $R_{i,t}$ is the excess return on the company i 's stock in month t , $CB_{i,t-1}$ denotes the stock i 's carbon beta at the end of month $t-1$, ΔCPU_t is the standardised percentage change in the CPU index from month $t-1$ to month t , $X_{i,t-1}$ is a vector of lagged control variables including the natural logarithm of firm i 's market capitalisation, its book-to-market, return on equity, book leverage, investment-to-assets, PP&E-to-assets, and stock i 's CAPM beta, idiosyncratic volatility, and momentum, c_i is the sector effect, and μ_t is the year-month effect. We are primarily interested in γ , as it signifies the incremental monthly return associated with a one standard deviation increase in carbon beta for each standard deviation with which the CPU index increases. We estimate similar regression models where we replace carbon beta and its interaction term with standardised log-transformed scope 1&2 emissions or standardised emission intensities to uncover any potential differences in market responses to CPU shocks.

Table 6 reports our findings. Our results show that in months where the CPU index increases (decreases), stocks with higher carbon betas tend to have lower (higher) returns. This finding is economically sizeable: for two firms that differ only by a one standard deviation difference in carbon beta, the firm with the higher carbon beta will tend to underperform the other firm by 15 bps (equivalent to 1.80% annualised) for each standard deviation with which the CPU index increases. To provide a more precise comparison with emissions intensities and emissions, column (2) reports

regression estimates for the subsample of observations that have available emissions data. Within this smaller subsample, the coefficient roughly halves, but the effect remains economically meaningful and statistically significant at the 1% level. Turning to column (3), we repeat the analysis for emissions and emissions intensities instead of carbon betas. We do not find a similar effect when interacting innovations in the CPU with companies' emissions intensities. Column (4), on the contrary, does reveal a similar pattern for emissions. The effect however is subsumed by the inclusion of the carbon beta interaction in column (5), in which the interaction effect of carbon beta remains statistically significant. Our findings suggest that carbon betas are able to sort stocks according to their exposure to climate policy uncertainty. The evidence is also consistent with an explanation of carbon betas being able to identify green firms that act as hedging assets against sudden realisations of climate change risks, to the extent that such realisations are reflected by our CPU index.

4.2.2 STOCK RETURNS AND EXTREME WEATHER EVENTS

Bansal et al. (2016) and Choi et al. (2020) theorise and empirically validate that pollutive firms tend to exhibit poorer returns during extreme weather since the effects of climate change are more salient in such periods. In our first test, we use temperature anomaly observations from the U.S. Climate Reference Network above the 90th percentile of past 30-year observations to classify months in which temperatures are abnormally high. Our second test focuses on drought events. We utilise values of the Palmer Z-Index (Palmer, 1965) below the 10th percentile of past 30-year observations to classify periods of extreme drought. The 10th percentile equates to a Z-Index of just below -2 in our sample, which according to Palmer (1965) indicates moderate drought conditions. We estimate the model:

$$R_{i,t} = \sigma EW_t + \eta CB_{i,t-1} + \phi EW_t \times CB_{i,t-1} + \lambda X_{i,t-1} + c_i + \mu_t + \epsilon_{i,t}, \quad (5)$$

where $R_{i,t}$ is firm i 's excess stock return in month t , EW_t is an extreme weather dummy equal to 1 if the temperature anomaly or drought severity of month t ranks among the 10% most extreme months, $CB_{i,t-1}$ is the carbon beta at the end of month $t-1$, $X_{i,t-1}$ is a vector of lagged control variables including the natural logarithm of firms i 's market capitalisation, book-to-market, return on equity, book leverage, investment-to-assets, PP&E-to-assets, and stock i 's CAPM beta, idiosyncratic volatility, and 12-month-minus-1-month momentum, c_i is a sector fixed effect, and μ_t is a time fixed effect. Our coefficient of interest is ϕ , which can be interpreted as the additional return associated with a one standard deviation increase in carbon beta, ceteris paribus, in times of an extreme weather event.

We find that firms with higher carbon betas experience lower returns during abnormally warm

months. The results are presented in Table 7. We repeat the analysis for two alternative firm-level indicators of carbon risk: Scope 1 & 2 emissions intensity and the natural logarithm of Scope 1 & 2 emissions. These variables do not show a similar pattern in extreme temperature months. In months with temperature anomalies above the 90th percentile, a standard deviation increase in carbon beta tends to be associated with about a 33 bps lower monthly excess return.

In Table 8, we turn our attention to drought spells. Again, we find that carbon beta is the only proxy that shows a significantly negative interaction effect with equity returns. These findings can be explained in several ways. For one, it could be the case that during extreme weather events, investors are more aware of the consequences of climate change, leading them to disproportionately sell holdings they perceive as contributing to a changing climate. This could follow a similar mechanism as in Huynh et al. (2021), who find that fund managers divest from carbon-intense investments after they experience local air pollution. In our case, carbon beta might partially capture investors' perception of firm-specific contribution to climate change. Second, investors might regard extreme weather events as realisations of climate risk, and therefore buy stocks that they deem a 'hedge' against such risk. Here, negative carbon betas proxy for such hedging potential. Yet we cannot rule out a potential third explanation, in which extreme weather directly affects the earnings of high carbon beta companies more so than the earnings of lower carbon beta companies.

4.3 CAPTURING FORWARD-LOOKING ASPECTS OF CARBON RISKS

4.3.1 GREEN INNOVATION

Cohen et al. (2020) report a striking disconnect: firms operating in the Energy sectors are responsible for a large share of greenhouse gasses and are amongst the worst performers on environmental issues, yet they are the most active in patenting low-carbon technologies. As 'green innovators' are likely to be less exposed to climate-related risks and might even benefit from a low-carbon transition, we expect carbon beta to partially pick up differences in green innovation output. Especially in the Energy sector, we expect this result to appear, as here the 'ESG-innovation disconnect' is most pronounced. To test whether active issuers of green patents have lower carbon beta, we exploit the main measure of green innovation used by Cohen et al. (2020): *Green Share*, determined by the number of green patents granted to a company at time t as a fraction of total patents granted to that company. Specifically, we estimate:

$$S_{i,t} = \sigma GreenShare_{i,t} + \lambda X_{i,t-1} + c_i + \mu_t + \epsilon_{it}, \quad (6)$$

where S_{it} is either firm i 's cross-sectionally standardised carbon beta, scope 1 & 2 emissions intensity, or the natural logarithm of total scope 1 & 2 emissions in month t ; $X_{i,t-1}$ is a vector of lagged firm characteristics that includes the natural logarithm of the firm's market capitalisation, its book-to-market ratio, return on equity, book leverage, investments-to-assets, PP&E-to-assets, and R&D-to-assets; c_i is an optional sector fixed effect; and μ_t is a time fixed effect.

Table 9 reports our estimates for the specification in Equation (6). In column (1), we regress carbon beta on green innovation and firm-level control variables using our complete sample. In this sample, which includes firms in sectors other than the Energy sector, an economically small yet statistically significant negative relationship is observed between green innovation and carbon beta. That is, firms that are more active in issuing green patents tend to have lower climate risk exposure as indicated by carbon beta. The effect is small, however, as a unit (theoretically, the maximum increase possible in green innovation) increase in green innovation is only associated with a reduction of about 7% of a cross-sectional standard deviation in carbon beta. In column (2), we focus our analysis on the Energy sector, where we expect green patenting to be most important based on Cohen et al. (2020)'s findings. The negative relationship between carbon beta and green innovation is much more pronounced within the Energy sector. A unit increase in green share is associated with about 0.3 of a standard deviation reduction in carbon beta. Moving to emission intensity in column (3) and the natural logarithm of emissions as the dependent variable in column (4), we do not find a similar effect. As a robustness check, we repeat the analysis using MSCI Green Patent Share as the measure of green innovation. Table A2 in Appendix A presents the results. Here, the coefficient on green innovation for all sectors is not significant at the 10% level. When focusing the analysis only on the Energy sector, we do however find the same pattern. That is, within the energy sector, firms that are more active in patenting green technologies have lower carbon betas yet are not significantly different in terms of emissions or emission intensities. Coupled with Cohen et al. (2020)'s observation that much of green innovation is driven by the Energy sector, our findings hold important implications for investors. Our results suggest that divestment from the Energy sector also cuts funding to green innovators, while a divestment strategy that targets high-carbon beta firms operating in the Energy sector still allocates to those firms most productive in researching low-carbon innovation.

4.3.2 UNOBSERVED FACTORS OF FORWARD-LOOKING CLIMATE RISK

Climate-Value-at-Risk (CVaR) is a measure developed by MSCI that incorporates forward-looking and corporate valuation assessments of the impact of climate change and related policies on asset prices. MSCI includes a wide variety of aspects in the estimation of CVaR. Firm emissions and green patent innovations are its main determinants. The measure also incorporates various proxies

for physical climate risks, transition scenario analyses, low-carbon revenues, and abatement policies. The objective of our analysis is to investigate whether or not carbon betas correlate with forward-looking aspects of carbon risk as modeled by CVaR. We are specifically interested in the components of CVaR unrelated to emissions and green innovation. To achieve this objective, we estimate:

$$CVaR_{it} = \alpha + \sigma GreenShare_{it} + \lambda \ln(Emissions)_{it} + \gamma CB_{it} + c_i + \mu_t + \epsilon_{it}, \quad (7)$$

where $CVaR_{it}$ is MSCI's Climate-Value-at-Risk; $GreenShare_{it}$ is a firm's share of green patents relative to total patents; $\ln(Emissions)_{it}$ is the natural logarithm of scope 1 & 2 emissions; CB_{it} is a firm i 's carbon beta at time t ; and c_i is an optional industry fixed effect. Note that we make use of the information provided by MSCI rather than our manually collected data on green innovation. We do so because the measure of green innovation provided by MSCI is used as one of the inputs to the estimation of CVaR, and thus is most suited for orthogonalising CVaR to green innovation.

Regression estimates are presented in Table 10. The specification in column (1) does not include sector-fixed effects while the specification in column (2) does. Emissions and green innovation are positively, respectively negatively, associated with CVaR. This result is by construction, as emissions and green innovation are used in the evaluation of CVaR by MSCI. In both specifications, the coefficient on carbon beta is positive and statistically significant. Our findings indicate a strong association between components of CVaR unrelated to emissions characteristics and green innovation and between carbon beta. Even while controlling for industry effects, the coefficient on carbon beta remains statistically significant, indicating that the information captured by carbon beta does not only vary at the industry level and must thus partly be firm-specific. As column (2) in Table 10 reports, increasing carbon beta by one standard deviation, while keeping emissions, green innovation, and industry membership constant, is associated with about a 7.7% standard deviation increase in CVaR. This indicates that carbon beta correlates with factors included in CVaR other than emissions and green innovation, for example, exposure to low-carbon technologies, exposure to carbon abatement policies, or green revenues.

4.4 PRICING OF CARBON RISK

In this section, we provide evidence on the asset-pricing implications of climate transition risk exposures as proxied for by carbon beta. We employ a similar specification as in our other return regressions:

$$R_{i,t} = \alpha + \theta CB_{i,t-1} + \lambda X_{i,t-1} + c_i + \mu_t + \epsilon_{i,t}, \quad (8)$$

where $R_{i,t}$ is the excess return on the company i 's stock in month t , $CB_{i,t-1}$ denotes the stock i 's carbon beta at the end of month $t-1$, $X_{i,t-1}$ is an optional vector of lagged control variables including company size, book-to-market, return on equity, book leverage, investment-to-assets, PP&E-to-assets, and stock i 's CAPM beta, idiosyncratic volatility, and momentum, c_i is the sector effect, and μ_t is the year-month effect. We are interested in θ , the carbon risk premium, which can be interpreted as the additional return associated with a one standard deviation increase in carbon beta. As carbon betas are estimated imprecisely – due to estimation errors – their use as explanatory variables creates an errors-in-variables (EIV) problem. This biases the estimated coefficient toward zero. If the ‘true’ carbon premium would be positive, then it would be underestimated by regression Equation (8). We employ Jegadeesh et al. (2019)’s approach to correct this issue. Jegadeesh et al. (2019) propose an instrumental variable methodology that adjusts for the EIV bias by estimating betas on disjoint sample periods. In practice, this amounts to estimating carbon betas separately using only the (daily) returns in odd or even months. As the measurement errors are thus by definition uncorrelated, the EIV bias is then resolved by a two-stage least-squares regression estimation where the prior month beta is used as an instrument. The procedure is outlined in detail in Appendix C.

Table 11 reports our results. In column (1), where we do not additionally control for other factors known to affect returns and exclude industry-fixed effects, the carbon risk premium shows negative. This “carbon risk discount” is consistent with the underperformance of the PMC portfolio displayed in Figure 1. Including control variables in column (2) takes away some of the negative coefficient suggesting that the negative premium observed in column (1) is partly driven by factors attributable to characteristics that were negatively rewarded over the sample period and positively correlated with carbon beta, or *vice versa*. Our analysis also reveals that the perceived underperformance of high carbon beta firms is driven by an industry effect: firms with high (low) carbon betas tend to operate in sectors that have shown below (above) average returns over the sample period. Including industry fixed effects to correct for this pattern, as column (3) does, turns the carbon risk premium insignificant from zero. We believe that both controlling for additional factors and including industry-fixed effects results in the most credible and precise identification of a carbon risk premium. The coefficients estimated according to this specification, reported in column (4) of the Table, uncover that a standard deviation increase in carbon beta tends to be associated with an additional 9.6 bps monthly return, *ceteris paribus*, or about 1.15% annualised. Table C1 in Appendix C presents the results without the application of Jegadeesh et al. (2019)’s correction. In this case, the (underestimated) carbon risk premium equals about 5.6 bps a month, or 0.6% annualised, suggesting the size of the EIV bias

amounts to about half of the carbon risk premium.

4.5 CORPORATE BOND CARBON BETAS

Appendix D extends the concept of carbon beta to corporate bonds. We download information on U.S. corporate bond trades from the FINRA's Trade Reporting and Compliance Engine (TRACE) Enhanced and follow the procedures of Dick-Nielsen (2009) and Dick-Nielsen (2014) to clean prices. More details about dataset construction are provided in Appendix D, which also includes descriptive statistics for the bond sample in Table D1.

Figure D1 in Appendix D presents average carbon betas by bond issuer industry. The pattern in industry variation in bond carbon betas is close to that of industry variation in equity carbon betas in Figure 2A. Large positive carbon betas occur mainly in the Energies and Materials sectors, while there are negative carbon betas in the Financial sector. Unique to the sample of corporate bonds is that we can exploit variation in credit ratings and bond maturities. We expect lower credit ratings to cause higher transition risk exposure, as capital-constrained firms are less able to meet the investment needed for a low-carbon transition. We also expect bonds of longer maturity to be more exposed, as the effects of transition are expected to be more severe further into the future. Figure D2 in Appendix D shows that our expectations hold.

5 CONCLUSION

We propose a new and complementary measure of climate risk determined by the extent to which an asset's return correlates with a carbon risk factor. This carbon risk factor seeks to capture unexpected changes in consumers' and investors' concerns about the climate. We propose the pollutive-minus-clean (PMC) portfolio as the carbon risk factor. The PMC portfolio is a self-financing portfolio formed by a long position in the 30% of stocks with the highest carbon emissions, offset by a short position in the 30% of stocks with the lowest emissions. Regressing individual stock returns on the PMC portfolio's returns and the Fama and French (1993) and Carhart (1997) factors, we regard the loadings on the PMC portfolio as the firm-level exposure to climate transition risk.

Our approach is complementary to conventional approaches that measure climate risk exposure; comparisons of carbon beta estimates with alternative measures of climate risk at the firm level also reveal robust positive associations. Carbon beta, however, has a number of characteristics that capture its economic contribution. First, due to the market-based nature of our measure, potentially any aspect deemed relevant to (future) climate risk exposure might be reflected. For

example, the availability of clean technologies, a company's innovative ability, leadership quality, industry competition, and financial condition. Regression of carbon beta on firm characteristics indeed shows that variation in carbon beta aligns with our expectations. Larger, innovative, and profitable firms have lower climate risk exposure, while capital-intensive and carbon-intensive firms have higher climate risk exposure. In addition, our results indicate a negative and statistically significant association between carbon beta and green innovation. Second, our concept enables an intuitive distinction between assets that are most *at risk* from a low-carbon transition and assets that are well-posed to benefit from such a shift. We show in related analyses that returns between low- and high-carbon beta firms differ markedly in months in which climate shocks materialise. Our results indicate that during months in which uncertainty surrounding future climate policy spikes, assets with low carbon betas outperform assets with high carbon beta. We observe similar return patterns for months with abnormally high temperatures, and for months that are exceptionally dry in precipitation. Third and finally, the approach allows us to calculate carbon betas for any asset for which returns are observed. Thus, our procedure allows the estimation of carbon betas for asset classes that have no other carbon-related measures available, for which it is inherently difficult to construct such measures (e.g. commodities), or which are by their nature opaque (e.g. hedge funds for which the holdings data are not publicly available). We illustrate this point with an application to corporate bonds.

A shortcoming of our approach lies in the use of emissions as the basis for the PMC portfolio. As corporations only started reporting emissions in the early 2000s, our proxy for the carbon risk factor covers a relatively limited history. In addition, alternative proxies for a carbon risk factor could be informative as well. For example, the price of emission allowances can be used, now that emissions trading schemes are becoming more prevalent. Weather-related securities, or certain commodities, might also be suitable candidates. Even non-tradable climate risk factors could be evaluated, perhaps based on textual information akin to the Climate Policy Uncertainty index which we utilised.

Investors can use our framework to create climate-aware investment strategies. Most investors can utilise our approach as it is transparent, accessible, and easily replicated. Carbon betas could thus be used by investors for whom it is too costly to use commercial alternatives, e.g. small retail investors or low-cost ETF providers. Carbon beta can also be employed as an indicator of 'climate hedge' potential and used for the construction of hedge portfolios with high returns in periods of climate stress. Our methodology might be valuable to academics in assessing the asset pricing implications of climate risk, as our approach yields a cross-sectionally 'rich' dataset. Lastly, regulators and policymakers could use carbon beta to identify highly exposed firms to carbon risk. Our empirical results indicate that carbon betas capture green innovation, in particular in the emission-intensive Energies sector.

As such, regulators and policymakers could employ our framework as a tool to disentangle ‘green innovators’ from otherwise pollutive firms.

REFERENCES

- Addoum, J. M., Ng, D. T., and Ortiz-Bobea, A. (2018). Temperature shocks and earnings news. *Working Paper*. (Not cited.)
- Alekseev, G., Giglio, S., Maingi, Q., Selgrad, J., and Stroebel, J. (2022). A quantity-based approach to constructing climate risk hedge portfolios. *NBER Working Paper 30703*. (Not cited.)
- Bai, J., Bali, T. G., and Wen, Q. (2019). Common risk factors in the cross-section of corporate bond returns. *Journal of Financial Economics*, 131(3):619–642. (Not cited.)
- Baker, S. R., Bloom, N., and Davis, S. J. (2016). Measuring economic policy uncertainty. *The Quarterly Journal of Economics*, 131(4):1593–1636. (Not cited.)
- Bansal, R., Kiku, D., and Ochoa, M. (2016). Price of long-run temperature shifts in capital markets. *NBER Working Paper 22529*. (Not cited.)
- Bansal, R., Kiku, D., and Ochoa, M. (2019). Climate change risk. *Working Paper*. (Not cited.)
- Banz, R. W. and Breen, W. J. (1986). Sample-dependent results using accounting and market data: Some evidence. *The Journal of Finance*, 41(4):779–793. (Not cited.)
- Berg, F., Koelbel, J., and Rigobon, R. (2022). Aggregate confusion: The divergence of ESG ratings. *Review of Finance*, 26(6):1315–1344. (Not cited.)
- Bolton, P. and Kacperczyk, M. (2021a). Do investors care about carbon risk? *Journal of Financial Economics*, 142:517–549. (Not cited.)
- Bolton, P. and Kacperczyk, M. (2021b). Global pricing of carbon-transition risk. *NBER Working Paper 28510*. (Not cited.)
- Bortolan, L., Dey, A., and Taschini, L. (2022). Nailing down volatile temperatures: Examining their effects on asset prices. *Working Paper*. (Not cited.)
- Busch, T., Johnson, M., Pioch, T., and Kopp, M. (2018). Consistency of corporate carbon emissions data. *Working Paper*. (Not cited.)
- Campbell, J. Y., Giglio, S., and Polk, C. (2013). Hard times. *The Review of Asset Pricing Studies*, 3(1):95–132. (Not cited.)
- Campbell, J. Y. and Vuolteenaho, T. (2004). Bad beta, good beta. *American Economic Review*, 94(5):1249–1275. (Not cited.)

- Carhart, M. (1997). On persistence in mutual fund returns. *The Journal of Finance*, 52(1):57 – 82. (Not cited.)
- Chatterji, A., Durand, R., Levine, D., and Touboul, S. (2016). Do rating firms converge? Implications for managers, investors, and strategy researchers. *Strategic Management Journal*, 37:1597–1614. (Not cited.)
- Choi, D., Gao, Z., and Jiang, W. (2020). Attention to global warming. *The Review of Financial Studies*, 33(3):1112–1145. (Not cited.)
- Cohen, L., Gurun, U. G., and Nguyen, Q. H. (2020). The ESG-innovation disconnect: Evidence from green patenting. *NBER Working Paper 27990*. (Not cited.)
- Daniel, K. and Titman, S. (1997). Evidence on the characteristics of cross sectional variation in stock returns. *The Journal of Finance*, 52(1):1–33. (Not cited.)
- Dick-Nielsen, J. (2009). Liquidity biases in TRACE. *The Journal of Fixed Income*, 19(2):43–55. (Not cited.)
- Dick-Nielsen, J. (2014). How to clean enhanced TRACE data. *Working Paper*. (Not cited.)
- Dick-Nielsen, J., Feldhütter, P., and Lando, D. (2012). Corporate bond liquidity before and after the onset of the subprime crisis. *Journal of Financial Economics*, 103(3):471–492. (Not cited.)
- Engle, R., Giglio, S., Lee, H., Kelly, B., and Stroebel, J. (2020). Hedging climate change news. *The Review of Financial Studies*, 33(3):1184–1216. (Not cited.)
- Fama, E. and French, K. (1993). Common risk factors in the returns on stocks and bonds. *Journal of Financial Economics*, 33:3–56. (Not cited.)
- Fama, E. and French, K. (2015). A five-factor asset pricing model. *Journal of Financial Economics*, 116:1–2. (Not cited.)
- Giglio, S., Kelly, B., and Stroebel, J. (2020). Climate finance. *Working Paper*. (Not cited.)
- Goldsmith-Pinkham, P., Gustafson, M., Lewis, R., and Schwert, M. (2022). Sea level rise exposure and municipal bond yields. *NBER Working Paper 30660*. (Not cited.)
- Goldstein, I., Kopytov, A., Shen, L., and Xiang, H. (2022). On ESG investing: Heterogeneous preferences, information, and asset prices. *NBER Working Paper 29839*. (Not cited.)
- Görge, M., Jacob, A., Nerlinger, M., Riordan, R., Rohleder, M., and Wilkens, M. (2020). Carbon risk. *Working Paper*. (Not cited.)

- Haščič, I. and Migotto, M. (2015). Measuring environmental innovation using patent data. Technical report, OECD. (Not cited.)
- Hong, H., Li, F. W., and Xul, J. (2019). Climate risks and market efficiency. *Journal of Econometrics*, 208(1):265–281. (Not cited.)
- Hsu, P.-H., Li, K., and Tsou, C.-Y. (2023). The pollution premium. *Forthcoming Journal of Finance*. (Not cited.)
- Huynh, T. and Xia, Y. (2021). Climate change news risk and corporate bond returns. *Journal of Financial and Quantitative Analysis*, 65(6):1985–2009. (Not cited.)
- Huynh, T. D., Li, F. W., and Xia, Y. (2021). Something in the air: Does air pollution affect fund managers' carbon divestment? *Working Paper*. (Not cited.)
- Ilhan, E., Sautner, Z., and Vilkov, G. (2021). Carbon tail risk. *The Review of Financial Studies*, 34(3):1540–1571. (Not cited.)
- Jegadeesh, N. (1990). Evidence of predictable behavior of security returns. *The Journal of Finance*, 45(3):881–898. (Not cited.)
- Jegadeesh, N., Noh, J., Pukthuanthong, K., Roll, R., and Wang, J. (2019). Empirical tests of asset pricing models with individual assets: Resolving the errors-in-variables bias in risk premium estimation. *Journal of Financial Economics*, 133(2):273–298. (Not cited.)
- Kalesnik, V., Wilkens, M., and Zink, J. (2022). Green data or greenwashing? Do corporate carbon emissions data enable investors to mitigate climate change? *The Journal of Portfolio Management Novel Risks*, 48(10):119–147. (Not cited.)
- Karl, T. R. (1986). The sensitivity of the Palmer Drought Severity Index and Palmer's Z-Index to their calibration coefficients including potential evapotranspiration. *Journal of Climate and Applied Meteorology*, pages 77–86. (Not cited.)
- Kölbel, J., Leipold, M., Rillaerts, J., and Wang, Q. (2020). Does the CDS market reflect regulatory climate risk disclosures. *Working Paper*. (Not cited.)
- Kotsantonis, S. and Serafeim, G. (2019). Four things no one will tell you about ESG data. *Journal of Applied Corporate Finance*, 39:50–58. (Not cited.)
- Krueger, P., Sautner, Z., and Starks, L. (2020). The importance of climate risks for institutional investors. *The Review of Financial Studies*, 33(3):1067–1111. (Not cited.)

- Li, Q., Hongyu, S., Tang, T., and Yao, V. (2020). Corporate climate risk: Measurements and responses. *Working Paper*. (Not cited.)
- Lin, H., Wang, J., and Wu, C. (2011). Liquidity risk and expected corporate bond returns. *Journal of Financial Economics*, 99(3):628–650. (Not cited.)
- Maio, P. (2013). Intertemporal CAPM with conditioning variables. *Management Science*, 59(1):122–141. (Not cited.)
- Matsumura, E. M., Prakash, R., and Vera-Munoz, S. C. (2014). Firm-value effects of carbon emissions and carbon disclosures. *The Accounting Review*, 89(2):695–724. (Not cited.)
- Monasterolo, I. and De Angelis, L. (2020). Blind to carbon risk? An analysis of stock market reaction to the Paris Agreement. *Ecological Economics*, 170:106571. (Not cited.)
- Painter, M. (2020). An inconvenient cost: The effects of climate change on municipal bonds. *Journal of Financial Economics*, 135(2):468–482. (Not cited.)
- Palmer, W. C. (1965). *Meteorological drought*. US Department of Commerce, Weather Bureau. (Not cited.)
- Pankratz, N., Bauer, R., and Derwall, J. (2019). Climate change, firm performance, and investor surprises. *Working Paper*. (Not cited.)
- Pástor, L., Stambaugh, R. F., and Taylor, L. A. (2020). Sustainable investing in equilibrium. *Journal of Financial Economics*. (Not cited.)
- Pástor, L., Stambaugh, R. F., and Taylor, L. A. (2022). Dissecting green returns. *Journal of Financial Economics*, 146(2):403–424. (Not cited.)
- Pástor, L. and Veronesi, P. (2013). Political uncertainty and risk premia. *Journal of Financial Economics*, 110(3):520–545. (Not cited.)
- Sautner, Z., Van Lent, L., Vilkov, G., and Zhang, R. (2022). Firm-level climate change exposure. *Forthcoming Journal of Finance*. (Not cited.)
- United Nations (2015). Adoption of the Paris Agreement, 21st Conference of the Parties, Paris. (Not cited.)
- Welch, I. and Goyal, A. (2008). A comprehensive look at the empirical performance of equity premium prediction. *The Review of Financial Studies*, 21(4):1455–1508. (Not cited.)

6 TABLES AND FIGURES

Figure 1: Performance of the PMC Portfolio

The figure in (a) plots the cumulative log return on the pollutive-minus-clean portfolio. The PMC portfolio is constructed by taking a long position in the 30% of firms with the highest carbon emissions, offset by a short position in the 30% of firms with the lowest emissions. Similar to Fama and French (1993), we enforce size neutrality by defining the PMC portfolio separately for samples of small and large firms. Details of the construction procedure are described in Section 3.1. The figure in (b) plots the performance of the PMC portfolio conditional on two proxies for materialising climate risks: Terciles of month-to-month changes in the Climate Policy Uncertainty index introduced in Section 2.3 and the 10% of months with the highest temperature deviations from long-term averages (see Section 2.4).

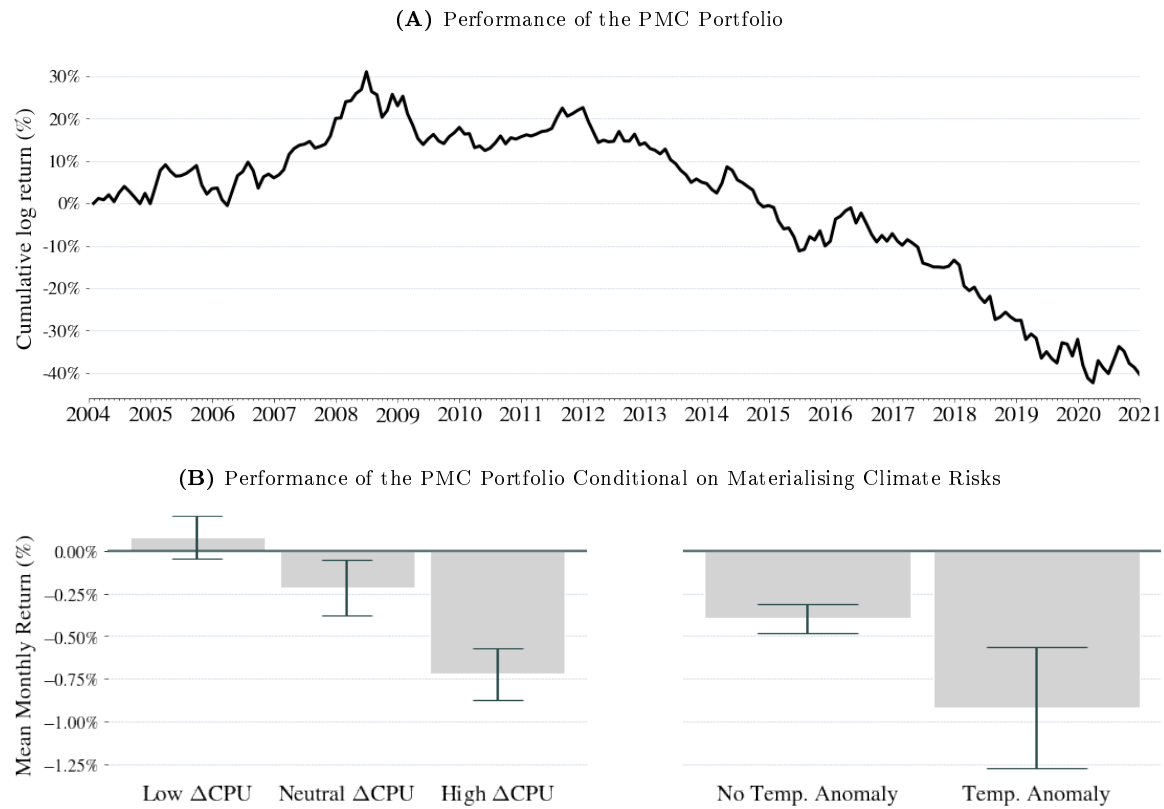


Figure 2: Industry Sector and Geographic Variation in Carbon Beta

The figure displays the coefficients estimated by regressing Carbon Beta on two-digit GICS Industry Sector fixed effects (Panel A) and headquarter state fixed effects (Panel B). The sample period is January 2007 to December 2020. The coefficients in Panel A are estimated with the specification in Equation (9), while Panel B follows a similar specification. The 95% confidence intervals displayed in Panel A are based on robust standard errors adjusted for clustering at the firm level.

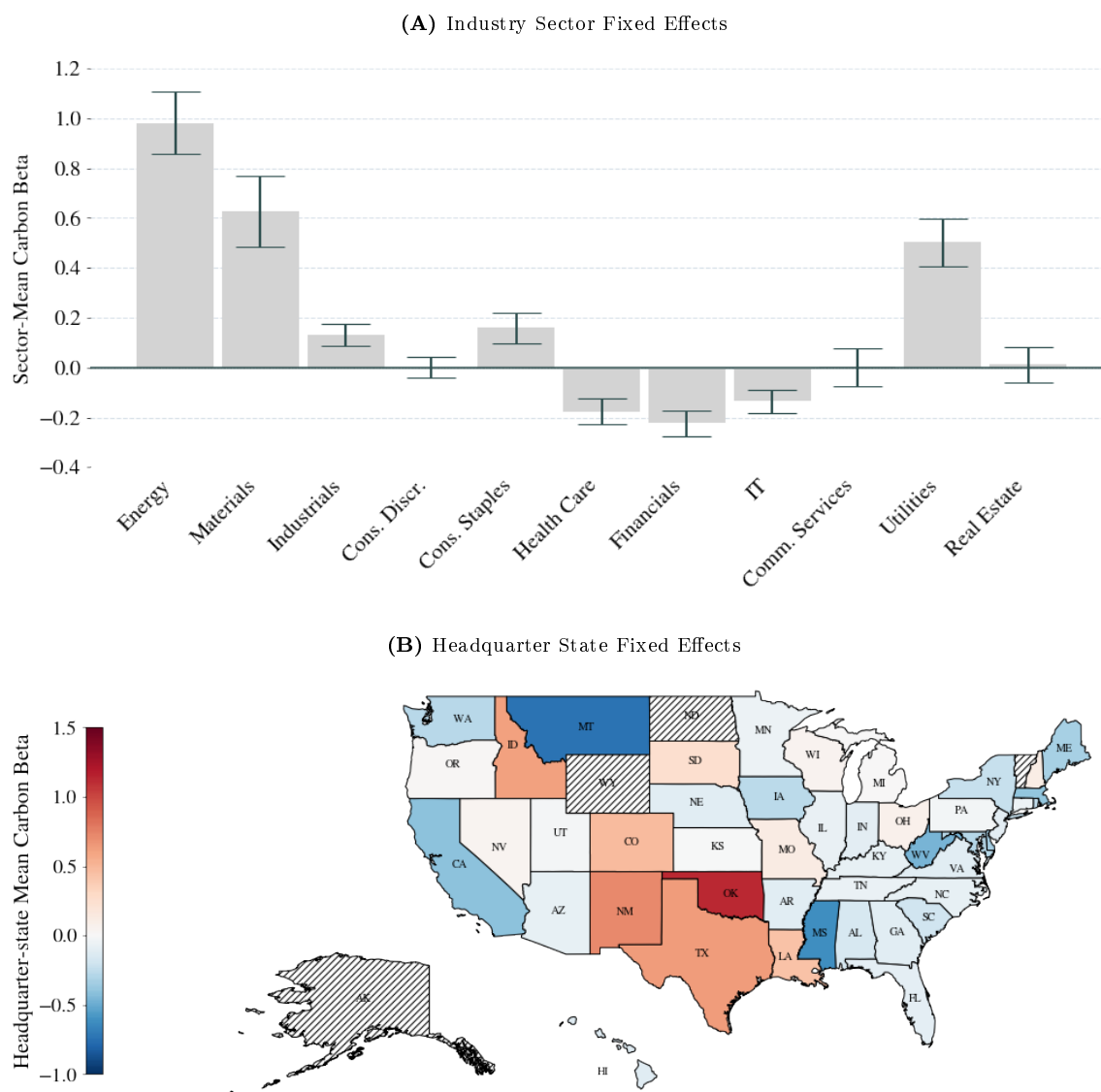


Figure 3: International Variation in Carbon Beta

The figure displays the coefficients estimated by regressing international Carbon Beta on country-fixed effects. Returns are based on each country's respective MSCI country index. The sample period is January 2015 to December 2020. Data comes from Refinitiv (formerly Thomson Reuters) Eikon.

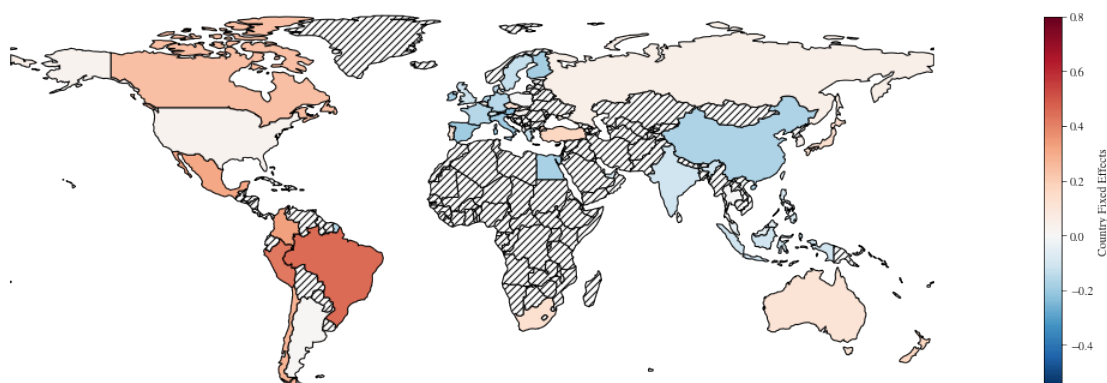


Figure 4: Climate Policy Uncertainty Index

The figure plots the Wall Street Journal-based Climate Policy Uncertainty (CPU) index over time alongside various events related to climate policy. The CPU index is defined as the textual similarity between daily articles published in the Wall Street Journal and a corpus of documents on climate change.

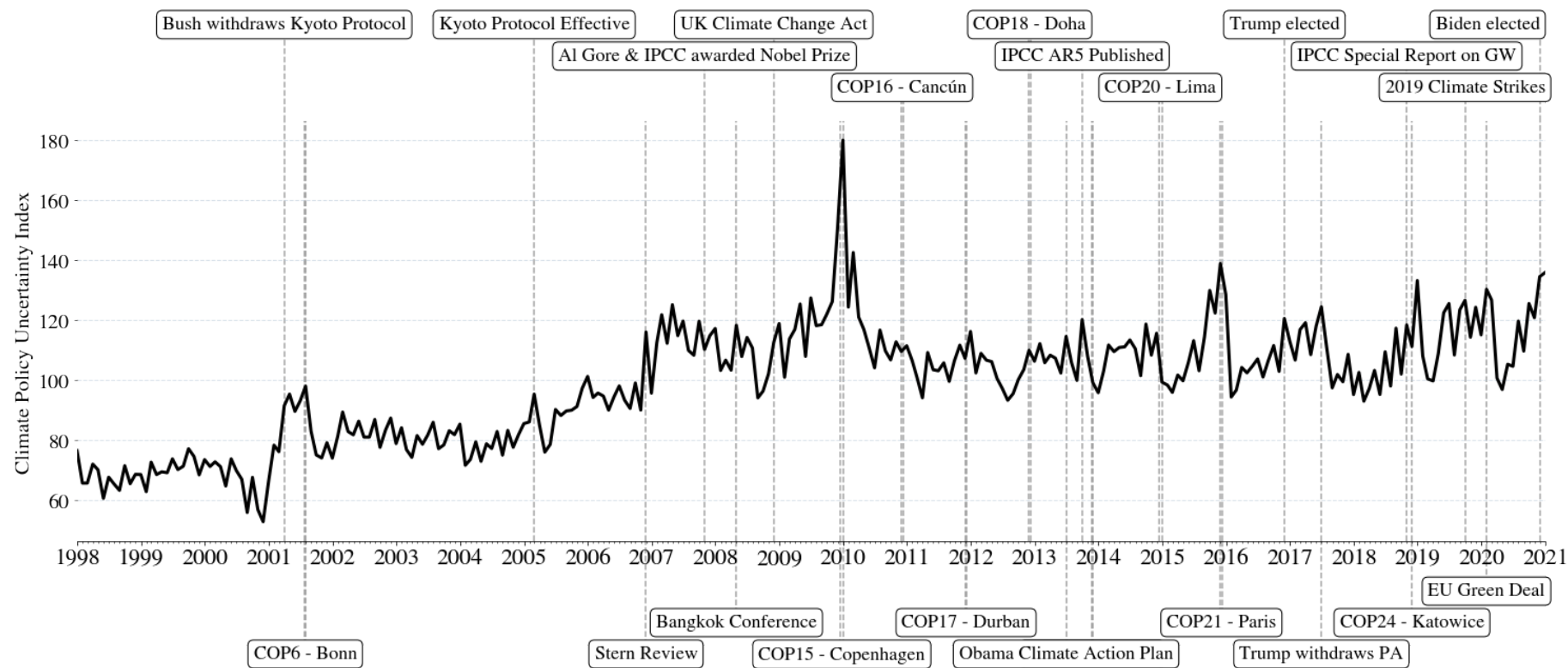


Table 1: Factor Return Descriptive Statistics

This table reports the mean monthly returns, the monthly return volatilities, and pairwise return correlations of the market (RMRF), value (HML), size (SMB), momentum (UMD), and carbon (PMC) factors. Returns on the RMRF, HML, SMB, and UMD factors are obtained from Kenneth French's website. The sample period is January 2004 to December 2020. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

	Mean Return (%)	Std. Dev. (%)	Correlations				
			RMRF	HML	SMB	UMD	PMC
RMRF	0.62	4.35	1.00	-	-	-	-
HML	-0.12	2.71	0.24***	1.00	-	-	-
SMB	0.14	2.40	0.34***	0.19***	1.00	-	-
UMD	0.17	4.62	-0.43***	-0.33***	-0.10	1.00	-
PMC	-0.28	1.97	-0.13**	0.18***	-0.09	0.13*	1.00

Table 2: Descriptive Statistics CRSP - Compustat - Trucost Merged

The table reports descriptive statistics on the variables used in our analysis. *Panel A* reports company and market variables. *Panel B* reports emissions variables. *Panel C* reports descriptive statistics for firms with high emissions \times market capitalisation: firms in the top 30% of emissions with market capitalisations below the median NYSE firms (Small / Polluting) and firms in the top 30% of emissions with market capitalisations above the median NYSE firm (Big / Polluting). These firms constitute the long leg of the Pollutive-Minus-Clean portfolio. *Panel D* reports descriptive statistics for firms with low emissions \times market capitalisation: firms in the bottom 30% of emissions with market capitalisations below the median NYSE firms (Small / Clean) and firms in the bottom 30% of emissions with market capitalisations above the median NYSE firm (Big / Clean). These firms constitute the short leg of the Pollutive-Minus-Clean portfolio. See Section 3.1 for more details.

	N.o. Obs.	Mean	SD	Percentiles						
				1%	5%	25%	Median	75%	95%	99%
<i>Panel A: Firm-level and market variables</i>										
Excess Return (%)	786,481	0.676	14.712	-39.801	-21.837	-6.243	0.359	6.764	23.540	51.866
Market Cap. (millions)	701,774	5,358	24,972	7	19	132	592	2,545	21,098	88,765
Book/Market*	701,774	0.663	0.678	-0.617	0.034	0.268	0.509	0.856	1.852	4.152
Return on Equity*	788,412	-0.015	0.711	-3.970	-0.934	-0.040	0.073	0.148	0.445	3.209
Debt/Assets*	785,576	0.190	0.208	0.000	0.000	0.006	0.124	0.312	0.603	0.901
Investment/Assets*	783,907	0.041	0.057	0.000	0.000	0.005	0.021	0.052	0.156	0.324
Property, Plant, & Equipment/Assets*	701,774	0.418	0.436	0.000	0.000	0.066	0.268	0.674	1.242	1.936
Research & Development/Assets*	701,774	0.049	0.119	0.000	0.000	0.000	0.000	0.037	0.261	0.672
Carbon Beta	682,022	0.052	0.557	-1.197	-0.777	-0.266	0.013	0.312	1.034	1.830
Idiosyncratic Volatility (%)	765,204	40.823	21.938	11.855	15.195	23.903	35.437	52.546	85.790	110.428
CAPM Beta	765,204	0.976	0.510	-0.127	0.125	0.631	0.976	1.304	1.850	2.303
Momentum	737,261	0.065	0.469	-0.831	-0.621	-0.216	0.031	0.265	0.879	2.033
<i>Panel B: Emission variables</i>										
Scope 1 Emissions (millions tons CO ₂)	238,902	1.558	8.921	0.000	0.000	0.003	0.020	0.128	4.692	40.364
Scope 2 Emissions (millions tons CO ₂)	238,902	0.276	0.987	0.000	0.000	0.006	0.032	0.136	1.227	4.600
Scope 1 & 2 Emissions (millions tons CO ₂)	238,902	1.834	9.298	0.000	0.000	0.011	0.065	0.339	6.091	42.451
Scope 1 Emission Intensity (tons CO ₂ /\$ mil- lion)	238,902	161.869	596.842	0.234	0.540	3.716	13.580	30.009	764.240	4303.386
Scope 2 Emission Intensity (tons CO ₂ /\$ mil- lion)	238,902	33.099	45.600	0.929	1.127	7.822	17.611	41.608	117.576	285.483
Scope 1 & 2 Emission Intensity (tons CO ₂ /\$ million)	238,902	198.877	623.588	1.731	2.133	13.942	38.246	77.493	893.624	4447.235

*Winsorised at the 2% level.

Table 3: Carbon Beta and Firm Characteristics

This table reports the regression coefficients obtained from regressing monthly, firm-level estimates of Carbon Beta on firm characteristics. The regression equation is given by Equation (10). Firm-specific characteristics are derived from Compustat data. Corporate greenhouse gas emissions are obtained from Trucost. Standard errors are clustered at the firm level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

Dependent variable:	<i>Carbon Beta</i> [†]			
	(1)	(2)	(3)	(4)
ln(Market Cap.)	-0.023*** (0.005)	-0.197*** (0.012)	-0.052*** (0.004)	-0.127*** (0.011)
Book/Market	0.124*** (0.014)	0.100*** (0.033)	0.078*** (0.013)	0.051* (0.027)
Return on Equity	-0.013 (0.009)	-0.024* (0.013)	-0.012* (0.007)	-0.012 (0.011)
Debt/Assets	0.368*** (0.044)	0.310*** (0.067)	0.164*** (0.035)	0.166*** (0.053)
Investment/Assets	2.944*** (0.237)	3.138*** (0.493)	1.136*** (0.169)	1.100*** (0.289)
Property, Plant, & Equipment/Assets	0.740*** (0.032)	0.524*** (0.058)	0.183*** (0.025)	0.151*** (0.040)
Research & Development/Assets	-0.886*** (0.076)	-1.244*** (0.144)	-0.526*** (0.077)	-1.171*** (0.147)
ln(Emissions) [†]	- (0.076)	0.510*** (0.025)	- (0.077)	0.266*** (0.025)
Year - Month FE	Yes	Yes	Yes	Yes
Industry FE	No	No	Yes	Yes
N.o. Obs.	595,293	200,917	595,202	200,917
R ² -Adj.	0.243	0.472	0.421	0.608

[†] Indicates a cross-sectionally standardised variable.

Table 4: Correlations Between Carbon Beta and Alternative Measures of Climate Risk

This table reports pairwise correlation coefficients between carbon beta and alternative firm-level measures of climate risk. The sample period is January 2007 to December 2020. SvLVZ CCE is the Sautner et al. 2022 Climate Change Exposure measure. MSCI CVaR is the MSCI Climate-Value-at-Risk measure. Emissions and emission intensity data are from Trucost. Other data collection procedures are described in Section 2.4. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

	Carbon Beta	ln(Emissions)	Emission Intensity	SvLVZ CCE	MSCI CVaR
Carbon Beta	1.00	-	-	-	-
ln(S1&2 Emissions)	0.49***	1.00	-	-	-
S1&2 Emission Intensity	0.34***	0.48***	1.00	-	-
CC Exposure	0.19***	0.24***	0.50***	1.00	-
CVaR	0.36***	0.44***	0.41***	-0.03	1.00

Table 5: Carbon Beta and the Sautner et al. (2022) Climate Change Exposures

This table reports the full set of coefficients obtained from estimating a similar model as in Equation (10). The sample period is from January 2007 to December 2020. CCE is the Sautner et al. (2022) Climate Change Exposure defined as the extent to which a company's earnings analyst calls are devoted to discussing regulatory risks, opportunities, and physical risks related to climate change. This table reports the coefficients obtained from estimating a similar regression as in Equation (10). All variables are standardised. Standard errors are clustered at the firm level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

Dependent variable:	<i>Carbon Beta</i> [†]				
	(1)	(2)	(3)	(4)	(5)
CCE [†]	0.205*** (0.012)	-	-	-	-
CCE _{Regulatory} [†]	-	0.158*** (0.009)	-	-	0.112*** (0.009)
CCE _{Opportunities} [†]	-	-	0.159*** (0.012)	-	0.114*** (0.011)
CCE _{Physical} [†]	-	-	-	0.044*** (0.006)	0.027*** (0.005)
N.o. Obs.	350,339	350,339	350,339	350,339	350,339
R ² -Adj.	0.043	0.026	0.026	0.002	0.038

[†]Indicates a cross-sectionally standardised variable.

Table 6: Carbon Beta, Climate Policy Uncertainty, and Stock Returns

This table reports the full set of coefficients obtained from estimating Equation (4). The sample period is from January 2007 to December 2020. ΔCPU is the monthly percentage change in the Climate Policy Uncertainty index, as defined in Section 2.3. All regressions include sector and year-month fixed effects. Standard errors are clustered at the firm level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

Dependent variable:	<i>Monthly excess return ($\times 100$)</i>				
	(1)	(2)	(3)	(4)	(5)
Carbon Beta [†] \times ΔCPU [†]	-0.150*** (0.019)	-0.072*** (0.025)	- (0.018)	- (0.018)	-0.058* (0.029)
Carbon Beta [†]	0.037 (0.028)	0.045 (0.047)	- (0.047)	- (0.047)	0.014 (0.047)
Emissions Intensity [†] \times ΔCPU [†]	- (0.012)	- (0.012)	-0.026 (0.018)	- (0.018)	0.012 (0.022)
Emissions Intensity [†]	- (0.038)	- (0.038)	-0.052* (0.031)	- (0.031)	-0.112*** (0.038)
ln(Emissions) [†] \times ΔCPU [†]	- (0.037)	- (0.037)	- (0.037)	-0.064** (0.028)	-0.040 (0.037)
ln(Emissions) [†]	- (0.092)	- (0.092)	- (0.092)	0.181** (0.081)	0.245*** (0.092)
ΔCPU [†]	0.873** (0.398)	1.293* (0.743)	1.275* (0.742)	1.274* (0.743)	1.293* (0.741)
ln(Market Cap.)	-0.014 (0.013)	0.062*** (0.023)	0.064*** (0.023)	-0.003 (0.035)	-0.019 (0.038)
Book/Market	0.130*** (0.046)	-0.175 (0.120)	-0.161 (0.119)	-0.239* (0.126)	-0.253** (0.127)
Return on Equity	0.143*** (0.042)	0.109 (0.076)	0.109 (0.076)	0.100 (0.076)	0.096 (0.076)
Debt/Assets	0.149 (0.111)	0.291 (0.202)	0.314 (0.203)	0.219 (0.201)	0.193 (0.201)
Investment/Assets	-1.645*** (0.596)	-1.139 (1.217)	-1.145 (1.206)	-0.888 (1.211)	-0.942 (1.202)
Property, Plant, & Equipment/Assets	0.075 (0.073)	-0.145 (0.133)	-0.108 (0.135)	-0.242* (0.138)	-0.237* (0.138)
CAPM Beta	0.153*** (0.044)	-0.481*** (0.111)	-0.491*** (0.109)	-0.494*** (0.109)	-0.495*** (0.112)
Idio. Volatility	-1.520*** (0.189)	3.918*** (0.540)	3.930*** (0.538)	3.905*** (0.539)	3.951*** (0.537)
Momentum	0.296*** (0.054)	-0.086 (0.112)	-0.088 (0.112)	-0.091 (0.112)	-0.093 (0.112)
Year - Month FE	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes
N.o. Obs.	593,367	200,309	200,309	200,309	200,309
R ² -Adj.	0.175	0.253	0.253	0.253	0.253

[†] Indicates a standardised variable. Firm-level variables are cross-sectionally standardised.

Table 7: Carbon Beta, Extreme Temperature, and Stock Returns

This table reports the full set of coefficients obtained from estimating regression Equation (5). The sample period is from January 2007 to December 2020. *Temp. Anomaly* is a dummy variable equal to 1 if the associated month's temperature anomaly is above the 90th percentile and 0 otherwise. All regressions include sector and year-month fixed effects. Returns are multiplied by 100. Standard errors are clustered at the firm level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

Dependent variable:	<i>Monthly excess return ($\times 100$)</i>				
	(1)	(2)	(3)	(4)	(5)
Carbon Beta [†] \times Temp. Anomaly	-0.330*** (0.070)	-0.315*** (0.098)	- -	- -	-0.352*** (0.114)
Carbon Beta [†]	0.069** (0.028)	0.083* (0.048)	- -	- -	0.057 (0.049)
Emissions Intensity [†] \times Temp. Anomaly	- -	- -	-0.052 (0.067)	- -	0.062 (0.073)
Emissions Intensity [†]	- -	- -	-0.045 (0.029)	- -	-0.119*** (0.037)
ln(Emissions) [†] \times Temp. Anomaly	- -	- -	- -	-0.105 (0.085)	0.046 (0.106)
ln(Emissions) [†]	- -	- -	- -	0.192** (0.081)	0.236** (0.093)
Temp. Anomaly	-1.552* (0.888)	-2.447 (1.660)	-2.460 (1.651)	-2.405 (1.655)	-2.456 (1.655)
ln(Market Cap.)	-0.013 (0.013)	0.064*** (0.023)	0.065*** (0.023)	-0.001 (0.035)	-0.017 (0.038)
Book/Market	0.132*** (0.046)	-0.169 (0.120)	-0.161 (0.119)	-0.238* (0.126)	-0.245* (0.127)
Return on Equity	0.143*** (0.042)	0.109 (0.076)	0.109 (0.076)	0.100 (0.076)	0.097 (0.076)
Debt/Assets	0.154 (0.111)	0.296 (0.202)	0.314 (0.203)	0.222 (0.201)	0.198 (0.201)
Investment/Assets	-1.682*** (0.596)	-1.152 (1.217)	-1.140 (1.208)	-0.877 (1.213)	-0.967 (1.203)
Property, Plant, & Equipment/Assets	0.082 (0.073)	-0.139 (0.133)	-0.109 (0.135)	-0.242* (0.138)	-0.229* (0.137)
CAPM Beta	0.152*** (0.044)	-0.485*** (0.111)	-0.492*** (0.109)	-0.493*** (0.109)	-0.501*** (0.111)
Idio. Volatility	-1.514*** (0.189)	3.942*** (0.539)	3.933*** (0.538)	3.912*** (0.539)	3.978*** (0.535)
Momentum	0.298*** (0.054)	-0.088 (0.112)	-0.088 (0.112)	-0.091 (0.112)	-0.094 (0.112)
Year - Month FE	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes
N.o. Obs.	593,367	200,309	200,309	200,309	200,309
R ² -Adj.	0.175	0.253	0.253	0.253	0.253

[†]Indicates a standardised variable. Firm-level variables are cross-sectionally standardised.

Table 8: Carbon Beta, Extreme Drought, and Stock Returns

This table reports the full set of coefficients obtained from estimating regression Equation (5). The sample period is from January 2007 to December 2020. *Drought* is a dummy variable equal to 1 if the associated month's Palmer Z-Index is below the 10th percentile and 0 otherwise. All regressions include sector and year-month fixed effects. Returns are multiplied by 100. Standard errors are clustered at the firm level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

Dependent variable:	<i>Monthly excess return</i> ($\times 100$)				
	(1)	(2)	(3)	(4)	(5)
Carbon Beta [†] \times Drought	-0.393*** (0.069)	-0.310*** (0.112)	- (0.093)	- (0.107)	-0.445*** (0.132)
Carbon Beta [†]	0.066** (0.028)	0.064 (0.047)	- (0.031)	- (0.083)	0.042 (0.047)
Emissions Intensity [†] \times Drought	- (0.093)	- (0.093)	-0.077 (0.093)	- (0.107)	-0.068 (0.102)
Emissions Intensity [†]	- (0.038)	- (0.038)	-0.047 (0.031)	- (0.083)	-0.108*** (0.038)
ln(Emissions) [†] \times Drought	- (0.142)	- (0.142)	- (0.142)	0.063 (0.107)	0.337** (0.142)
ln(Emissions) [†]	- (0.094)	- (0.094)	- (0.083)	0.177** (0.083)	0.220** (0.094)
Drought	-1.965** (0.872)	-2.437 (1.644)	-2.432 (1.634)	-2.364 (1.637)	-2.431 (1.637)
ln(Market Cap.)	-0.014 (0.013)	0.062*** (0.023)	0.064*** (0.023)	-0.003 (0.035)	-0.019 (0.038)
Book/Market	0.128*** (0.046)	-0.181 (0.120)	-0.161 (0.119)	-0.240* (0.126)	-0.258** (0.127)
Return on Equity	0.142*** (0.042)	0.106 (0.076)	0.109 (0.076)	0.100 (0.076)	0.095 (0.076)
Debt/Assets	0.149 (0.111)	0.290 (0.202)	0.314 (0.203)	0.218 (0.201)	0.192 (0.201)
Investment/Assets	-1.678*** (0.596)	-1.169 (1.216)	-1.147 (1.206)	-0.885 (1.211)	-0.987 (1.201)
Property, Plant, & Equipment/Assets	0.076 (0.073)	-0.142 (0.133)	-0.108 (0.135)	-0.243* (0.138)	-0.232* (0.138)
CAPM Beta	0.151*** (0.044)	-0.484*** (0.111)	-0.493*** (0.109)	-0.493*** (0.109)	-0.491*** (0.112)
Idio. Volatility	-1.523*** (0.189)	3.908*** (0.540)	3.931*** (0.538)	3.906*** (0.539)	3.932*** (0.536)
Momentum	0.294*** (0.054)	-0.091 (0.112)	-0.087 (0.112)	-0.091 (0.112)	-0.098 (0.112)
Industry FE	Yes	Yes	Yes	Yes	Yes
Year - Month FE	Yes	Yes	Yes	Yes	Yes
N.o. Obs.	593,367	200,309	200,309	200,309	200,309
R ² -Adj.	0.175	0.253	0.253	0.253	0.254

[†]Indicates a standardised variable. Firm-level variables are cross-sectionally standardised.

Table 9: Carbon Beta and Green Innovation

This table reports the coefficients obtained from estimating regression Equation (6). Green Share (%) is the measure of green patent innovation from Cohen et al. (2020). We collect data on U.S. patents issuance from the U.S. Patent and Trademark Office's Bulk Data Storage System. The data are from December 2010 to December 2020. Standard errors are clustered at the firm level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

Dependent variable:	Carbon Beta [†]	Carbon Beta [†]	Emissions Intensity [†]	ln(Emissions) [†]
Green Share (%)	-0.071* (0.041)	-0.344** (0.148)	-0.161 (0.274)	0.297 (0.264)
ln(Market Cap.)	-0.044*** (0.006)	0.006 (0.028)	0.086** (0.039)	0.413*** (0.028)
Book/Market	0.109*** (0.027)	0.065 (0.082)	0.158 (0.122)	0.200*** (0.076)
Return on Equity	-0.003 (0.010)	0.009 (0.050)	-0.032 (0.050)	0.002 (0.037)
Debt/Assets	0.187*** (0.054)	0.708** (0.302)	0.600 (0.475)	0.688** (0.276)
Investment/Assets	0.078 (0.330)	1.263 (0.849)	-1.639* (0.869)	-1.161** (0.497)
Property, Plant, & Equipment/Assets	0.380*** (0.045)	0.636*** (0.141)	0.509*** (0.147)	0.246*** (0.092)
Research & Development/Assets	-0.686*** (0.104)	-1.712* (1.043)	-4.136 (6.582)	-6.527 (6.580)
Year-Month	Yes	Yes	Yes	Yes
Industry FE	Yes	No	No	No
Sectors	All	Energy	Energy	Energy
N.o. Obs.	223,659	12,660	6,859	6,859
R ² -Adj.	0.432	0.342	0.136	0.726

[†]Indicates a cross-sectionally standardised variable.

Table 10: Carbon Beta and Unobserved Climate Risk Factors

This table reports the coefficients obtained from estimating regression Equation (7). MSCI CVaR is MSCI's Climate-Value-at-Risk. Standard errors are clustered at the firm level. Specification (1) does not control for industry-fixed effects, while Specification (2) does. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

Dependent variable:	<i>MSCI CVaR</i> [†]	
	(1)	(2)
Carbon Beta [†]	0.209*** (0.030)	0.077*** (0.028)
MSCI S1&2 Emissions [†]	0.353*** (0.032)	0.281*** (0.038)
MSCI Green Patent Share [†]	-0.191*** (0.073)	-0.191*** (0.070)
Year - Month FE	Yes	Yes
Industry FE	No	Yes
N.o. Obs	167,055	167,055
<i>R</i> ²	0.261	0.317

[†]Indicates a sectionally standardised variable.

Table 11: Pricing of Carbon Risk with Errors-in-Variables Correction

This table reports the regression coefficients obtained from regressing monthly excess returns on estimates of carbon beta. The sample period is from January 2007 to December 2020. The regression optionally includes the natural logarithm of market capitalisation, book-to-market ratio, return on equity, book leverage, investments-to-assets, PP&E-to-assets, CAPM beta, idiosyncratic volatility, and 12-month momentum as control variables. Regressions contain year-month fixed effects and optionally include sector-fixed effects. We use Jegadeesh et al. (2019)'s IV-estimation methodology to account for errors-in-variables (see Appendix C for details). Standard errors are clustered at the firm level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

Dependent variable:	<i>Monthly excess return ($\times 100$)</i>			
	(1)	(2)	(3)	(4)
Carbon Beta [†]	-0.137*** (0.019)	-0.043** (0.021)	-0.010 (0.026)	0.096*** (0.027)
ln(Market Cap.)	-	-0.014 (0.012)	-	-0.017 (0.012)
Book/Market	-	-0.342*** (0.050)	-	-0.167*** (0.054)
Return on Equity	-	0.095** (0.047)	-	0.120** (0.047)
Debt/Assets	-	-0.007 (0.098)	-	0.126 (0.105)
Investment/Assets	-	-1.851*** (0.536)	-	-1.137** (0.560)
Property, Plant, & Equipment/Assets	-	0.005 (0.061)	-	-0.046 (0.069)
CAPM Beta	-	0.277*** (0.045)	-	0.301*** (0.048)
Idio. Volatility	-	-0.807*** (0.230)	-	-1.148*** (0.246)
Momentum	-	0.287*** (0.059)	-	0.244*** (0.059)
Industry FE	Yes	Yes	Yes	Yes
Year - Month FE	Yes	Yes	Yes	Yes
N.o. Obs.	427,876	427,955	427,876	427,876
R^2 -Adj.	0.229	0.230	0.230	0.230

[†]Indicates a standardised variable. Firm-level variables are cross-sectionally standardised.

APPENDIX A: ADDITIONAL TABLES AND FIGURES

Table A1: Descriptive Statistics on Top and Bottom Subindustries by Carbon Beta

This table reports the mean and median carbon beta of the top and bottom 15 GICS-subindustries by median carbon beta. The table also reports the number of firms by subindustry and the number of return and carbon beta observations by subindustry. The sample period is from January 2007 to December 2020.

Sub-Industry	Mean	Median	N. Firms	N. Obs.
<i>Panel A: Top 15 sub-industries by mean carbon beta</i>				
Silver	1.51	1.46	7	983
Gold	1.28	1.21	67	5507
Oil & Gas Drilling	1.18	1.27	32	2931
Oil & Gas Exploration & Production	1.14	1.13	266	23578
Precious Metals & Minerals	1.08	1.16	10	774
Copper	1.02	1.04	5	624
Coal & Consumable Fuels	0.93	0.89	36	3486
Oil & Gas Equipment & Services	0.90	0.87	119	10272
Steel	0.80	0.77	58	5624
Integrated Oil & Gas	0.79	0.71	24	3191
Aluminum	0.77	0.72	12	866
Diversified Metals & Mining	0.73	0.74	38	2935
Oil & Gas Refining & Marketing	0.69	0.68	49	4574
Oil & Gas Storage & Transportation	0.60	0.58	158	13309
Independent Power Producers & Energy Traders	0.58	0.55	22	1540
<i>Panel B: Bottom 15 sub-industries by mean carbon beta</i>				
Financial Exchanges & Data	-0.42	-0.41	16	2563
Investment Banking & Brokerage	-0.40	-0.42	67	6084
Other Diversified Financial Services	-0.38	-0.28	6	490
Internet Services & Infrastructure	-0.35	-0.39	27	2293
Biotechnology	-0.34	-0.29	561	34386
Systems Software	-0.34	-0.33	105	7676
Regional Banks	-0.33	-0.29	618	58638
Life & Health Insurance	-0.29	-0.26	41	4516
Consumer Finance	-0.28	-0.30	68	5762
Highways & Railroads	-0.26	-0.24	2	66
Interactive Media & Services	-0.24	-0.25	60	5012
Insurance Brokers	-0.23	-0.23	21	1651
Semiconductors	-0.21	-0.23	182	17002
Application Software	-0.20	-0.21	325	23816
Life Sciences Tools & Services	-0.19	-0.20	91	7269

Table A2: Carbon Beta and MSCI Green Patent Share

This table reports the coefficients obtained from estimating regression Equation (6). Here, Green Share MSCI (%) is a measure of green patent innovation constructed and provided by MSCI. The data are from January 2010 to end of December 2020. Standard errors are clustered at the firm level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

Dependent variable	Carbon Beta [†]	Carbon Beta [†]	S1&2 Intensity [†]	ln(S1&2 Emissions) [†]
MSCI Green Patent Share [†]	0.020 (0.021)	-0.231*** (0.089)	0.362 (0.269)	0.130*** (0.046)
ln(Market Cap.)	-0.026*** (0.008)	-0.007 (0.035)	-0.190 (0.124)	0.418*** (0.053)
Book/Market	0.126*** (0.039)	0.207 (0.128)	-0.155 (0.280)	0.395*** (0.107)
Return on Equity	-0.004 (0.013)	-0.090* (0.055)	0.666 (0.481)	0.189 (0.140)
Debt/Assets	0.141** (0.066)	0.245 (0.410)	1.345 (0.841)	0.676 (0.429)
Investment/Assets	-0.283 (0.403)	1.081 (1.384)	-5.444** (2.473)	-2.492*** (0.761)
Property, Plant, & Equipment/Assets	0.392*** (0.051)	0.481** (0.199)	1.009** (0.499)	0.202 (0.167)
Research & Development/Assets	-0.984*** (0.141)	0.583 (1.622)	-20.170 (17.600)	-16.644 (12.999)
Year-Month FE	Yes	Yes	Yes	Yes
Industry FE	Yes	No	No	No
Sectors	All	Energy	Energy	Energy
N.o. Obs.	150,576	6,539	4,423	4,423
R ² -Adj.	0.487	0.340	0.227	0.665

[†]Indicates a cross-sectionally standardised variable.

Figure A1: Alternative PMC Portfolio Construction

The figure displays PMC portfolios that were constructed in different ways. The baseline PMC as used in the paper is compared to alternative constructions based on estimated emissions (PMC Estimated), reported emissions (PMC Reported), emission intensities (PMC Intensity), and emissions provided by MSCI (PMC MSCI) instead of by Trucost.

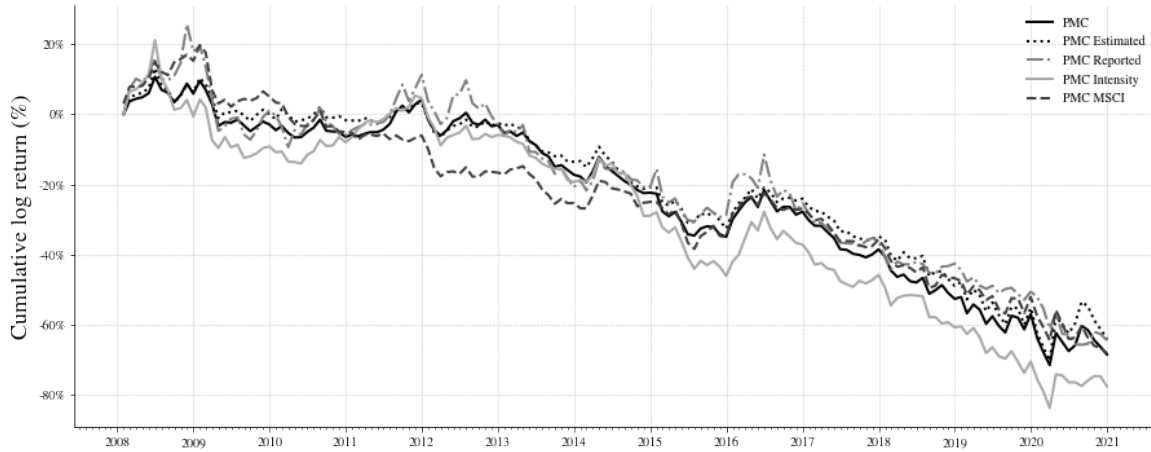


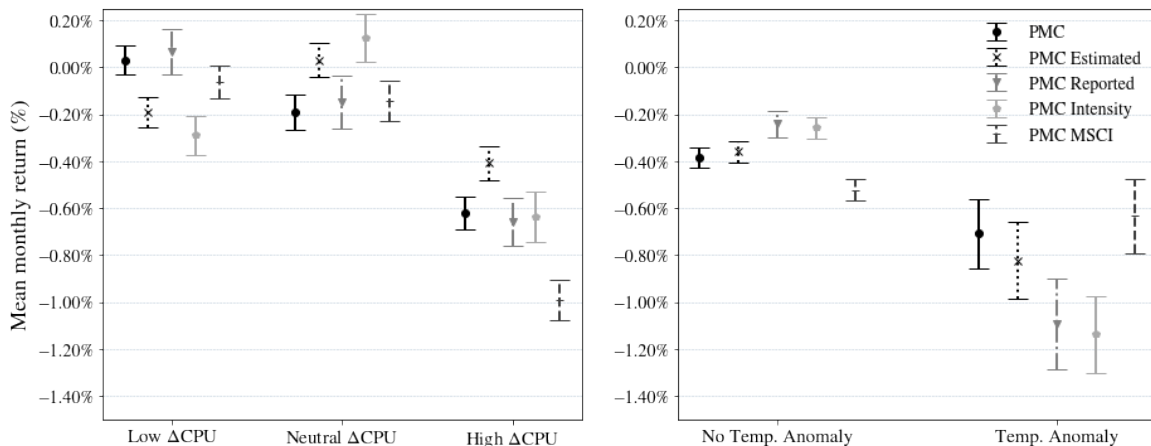
Table A3: Correlations Between Alternative PMC Portfolios

The table reports pairwise correlation coefficients between alternatively constructed PMC portfolios. PMC is the pollutive-minus-clean portfolios as employed in the paper.

	PMC	PMC _{Estimated}	PMC _{Reported}	PMC _{Intensity}	PMC _{MSCI}
PMC	1.00	-	-	-	-
PMC _{Estimated}	0.95	1.00	-	-	-
PMC _{Reported}	0.73	0.59	1.00	-	-
PMC _{Intensity}	0.79	0.79	0.68	1.00	-
PMC _{MSCI}	0.85	0.83	0.63	0.72	1.00

Figure A2: Returns to Alternative PMC Portfolios Conditional on CPU and Temperature Anomalies

The figure reports the mean monthly returns of various PMC portfolio definitions during various regimes of Climate Policy Uncertainty (low change in CPU, neutral change in CPU, high change in CPU) and Temperature Anomalies. The baseline PMC as used in the paper is compared to alternative constructions based on estimated emissions (PMC Estimated), reported emissions (PMC Reported), emission intensities (PMC Intensity), and emissions provided by MSCI (PMC MSCI) instead of by Trucost.



APPENDIX B: VALIDATION OF CARBON BETAS

In our validation test, we first compare estimates of carbon beta across sectors, headquartered states, and countries. We then run panel regressions to uncover how firm characteristics are correlated with corporate climate risk. Next, we perform a firm-level comparison of carbon betas with alternative measures of climate risk, amongst which the Sautner et al. (2022)'s measure constructed from analyst earnings calls and MSCT's Climate-Value-at-Risk measure.

B1 SECTOR, HEADQUARTERED STATE, AND COUNTRY VARIATION IN CARBON BETAS

In this section, we first seek to analyse how carbon beta is associated with variation in industry sector membership. To do so, we estimate:

$$CB_{it} = \sum_{k=1}^{11} \mathbb{I}[k_i = k] + \epsilon_{it}, \quad (9)$$

where CB_{it} is firm i 's carbon beta at the end of time t , k denotes any of 11 GICS industry sectors, and $\mathbb{I}[k_i = k]$ indicates whether or not stock i 's industry classification belongs to industry k . The coefficients obtained from this regression can be interpreted as sector-average carbon betas.

Figure 2A reports the estimated coefficients from regressing individual stock's carbon betas on their respective industry dummies. The figure shows that the Energies, Utilities, and Materials sectors exhibit the highest carbon betas. In contrast, for the Financials, IT, and Health Care sectors, we observe negative mean carbon betas. These findings are in line with commonly held beliefs about sectors' relative carbon risk exposure. While the figure shows differences in the carbon risk exposure across sectors, the variation of carbon betas within specific sectors is also informative. For example, the Energies sector houses several firms with very high carbon betas, however, also includes some firms that hold much lower exposure to climate risks (not reported). Note that in later regression specifications, we include industry fixed effects, so that we only exploit variation in carbon betas *within* industries, rather than the variation *across* industries reported in Figure 2A. We believe this is a conservative approach, as we control for any unobserved industry effect and can circumvent the effect of potential industry biases in the definition of the carbon risk factor.

We now modify Equation (9) to regress on headquarter state dummies. The regression coefficients can be interpreted as average carbon betas by headquarter state. Figure 2B presents our results. Particularly in Texas, Oklahoma, and New Mexico, average carbon betas are high. This is likely the

result of the large concentration of oil and gas firms operating in this region. In California, on the contrary, carbon betas are on average negative. This might stem from the state's dominant Technology sector. Overall, geographic variation in carbon betas seems to align with prior expectations, yet is strongly driven by industry effects. As mentioned earlier, we include industry dummies in most regressions to make sure that such effects do not confound our results.

Lastly, we investigate how carbon betas vary over countries. We exploit international variation in a sample of carbon betas estimated from the returns of different MSCI Country indices. The estimation of carbon betas is based on a sample of 48 different MSCI country indices. We estimate carbon betas with the same estimation window and control factors as described in Section 3, yet now utilise Ken French's Developed Market factors rather than their U.S. factor equivalents. We again estimate a modified version of Equation (9) that includes country-fixed effects. Figure 3 shows the coefficients from regressing international carbon betas on their respective country dummies, a similar specification as in Equation (9). As can be seen, carbon betas in South America, South Africa, and Australia are relatively high. On the one hand, this might be related to the vast amounts of natural resources present in these regions and the carbon intensity of the industries involved in extracting them. On the other hand, these regions are well-known to have weak climate policies in place. Countries in Europe, generally, have low to negative carbon betas. This might be a reflection of the European Union being at the forefront of regulating climate change. The difference between the U.S. and Canada is also striking. While both nations have a large oil and gas industry, the U.S. at the same time houses many technology companies. Besides, Canada's petroleum industry is especially pollutive as a large part of its fossil resources are found in oil sands.

B2 CARBON BETA AND FIRM CHARACTERISTICS

In this section, we investigate how firm characteristics correlate with corporate climate risk exposure. Firm characteristics are known to be related to climate risk exposure, see, for example, Bolton and Kacperczyk (2021a), Hsu et al. (2023), Sautner et al. (2022), and Li et al. (2020). We make several predictions based on economic theory and related research. First, we expect larger firms to be better equipped at dealing with transition risks as they are more diversified across operating activities. Larger firms can also exert greater lobbying power, leaving them less exposed to potentially adverse effects of climate regulation. On the contrary, we expect that firms holding more physical assets are vulnerable to rising costs of climate regulation via the greenhouse gas emissions and energy requirements of their assets (see Sautner et al. 2022 and Li et al. 2020 for empirical evidence). Many studies report lower firm valuations as a result of higher climate risk exposure (for example, Bolton and Kacperczyk 2021a, Matsumura et al. 2014, and Li et al. 2020). Moreover, it is more difficult

for capital-constrained firms to make investments in low-carbon technologies. A reduced ability to adapt leaves these firms at greater transition risk. The opposite holds for firms that actively invest in research & development. Such firms will either have better low-carbon technologies available or are better able to capitalise on such technologies as they become available in the future. Indeed, Sautner et al. (2022) find firm-level climate risks to be negatively correlated with R&D expenses relative to assets.

To test our expectations, we estimate via panel regression:

$$CB_{i,t} = \lambda X_{i,t-1} + c_i + \mu_t + \epsilon_{i,t}, \quad (10)$$

where $CB_{i,t}$ is a firm i 's carbon beta at month t , $X_{i,t}$ is a vector of lagged firm characteristics that includes the natural logarithm of the firm's market capitalisation, its book-to-market ratio, return on equity, book leverage, investments-to-assets, PP&E-to-assets, and R&D-to-assets, c_i is an optional sector (two-digit GICS) fixed effect, and μ_t is a year-month fixed effect. We cluster standard errors by firms, as residuals within firms are correlated over time. We optionally include industry-fixed effects to control for variation that can be attributed to sector differences. Our model includes time-fixed effects to exploit the cross-sectional variation in carbon beta estimates and to help mitigate omitted variable bias by controlling for unobserved effects that vary over time but not over firms.

Table 3 reports our estimates. When the regression specification includes sector-fixed effects, as in columns (3) and (4), identification only comes from the cross-section of firms active in the same sector. Negative correlates of climate risk exposure are company size (market capitalisation), profitability (return-on-equity), and innovation (R&D-to-assets). For company size, we find a positive coefficient in column (1), yet this specification omits corporate emissions as a control variable and thereby fails to control for the indirect effect of corporate emissions on transition exposure via company size. The positive association also turns negative after we account for industry-specific differences in company size and carbon beta, indicating that within industry sectors, larger firms have lower carbon betas. We find capital intensity (proxied for by investments-to-assets and PP&E-to-assets) and corporate greenhouse gas emissions to be positively associated with carbon beta. The association between emissions and carbon beta is economically sizeable, as a standard deviation increase in the log-transformed emissions variable tends to be associated with a 0.22 to 0.50 standard deviation increase in carbon beta, depending on whether or not sector effects are considered. Our results for book-to-market and book leverage are mixed. Columns (1) and (3) report a positive relationship between the book-to-market ratio and our measure, suggesting that firms exposed to climate risk trade at lower valuations. Yet this does not survive the addition of corporate emissions as a control

variable in (2), and therefore merely reflects a tendency of emission-heavy firms to trade at lower valuations. However, in specification (4), which controls for industry differences, book-to-market remains to hold explanatory value beyond the effect of corporate emissions. We find a negative association between book leverage and carbon beta in columns (1) and (2), yet it disappears after the inclusion of sector-fixed effects in columns (3) and (4), suggesting it can only be attributed to general differences in leverage and carbon betas across sectors.

B3 COVARIATION WITH ALTERNATIVE MEASURES OF CLIMATE RISK

We now compare carbon betas with alternative firm-level measures of climate risk. Here we consider the natural logarithm of firm emissions, emission intensity, the Sautner et al. (2022) measure of corporate Climate Change Exposure (CCE), and MSCI's Climate-Value-at-Risk (CVaR). We standardise all measures of corporate climate risks to enable comparison. Table 4 reveals robust correlations between carbon beta and each of the four alternative measures. The correlation coefficients are highly significant and their signs are in line with expectations. It is interesting to note that while the log of emissions and emission intensities show 'only' a 51% correlation, the correlation coefficients of carbon beta with the log of emissions and carbon beta with emission intensities are close, at 51% respectively 40%. This suggests that while there is different information contained in emissions and intensities, there is still a large overlap between the information in emissions and emissions intensities deemed relevant to carbon beta. Moreover, the robust associations between carbon beta and the scores on the forward-oriented CVaR and Sautner et al. (2022) measures are reassuring, as they suggest that carbon beta partly picks up the information that these measures have been designed to capture, such as green innovative ability and analyst's perceptions of firm-level climate risk. We explore the relationship between our measure and CVaR in more detail in Section 4.3.2.

We now conduct a more detailed comparison between estimates of carbon beta and the Sautner et al. (2022)'s Climate Change Exposures, where we exploit that Sautner et al. (2022)'s measure is decomposed into three components: exposure to regulatory risks, climate opportunities, and physical risks. This allows us to analyse which aspects of climate risk are captured by carbon beta. We estimate a similar model as in Equation (10), yet we alternatively include the main CCE, each of its three components, and all three of the components. In our regressions, we standardise the CCEs for reasons of comparability and interpretability. We again cluster standard errors at the firm level to account for serial correlation in our variables. Table 5 reveals that carbon betas are positively related to CCE and all of its three components. A standard deviation increase in CCE tends to be associated with about 23% of a standard deviation increase in carbon beta. We observe effects of similar magnitudes for the subcomponents measuring exposures related to regulatory risks and

climate opportunities. Interesting to note is the positive sign on the latter subcomponent's coefficient: this indicates that the firms whose carbon beta is *higher* are also the firms with which analysts more frequently discuss climate change opportunities. This finding might seem counterintuitive but suggests that today's major emitters have an important role to play in enabling low-carbon technologies. Sautner et al. (2022) observe the same pattern when comparing $CCE_{Opportunities}$ with *ISS Carbon Risk Ratings*. Our results for the component of CCE measuring physical climate risks are somewhat of an exception. Although the coefficient reported in column (4) is statistically significant at the 1% level, its magnitude is much smaller than the overall CCE coefficients and other components. The adjusted R-squared reported in column (4) also reveals that physical climate change exposure is of little help in explaining variation in carbon beta. This finding does not come as a surprise to us. Physical climate risks are more idiosyncratic and largely unrelated to corporate carbon emissions, rather much more driven by geographic vulnerabilities. Hence, our approach is unlikely to pick up differences in physical climate risk exposure, and our analysis confirms that carbon betas are more related to regulatory and opportunity risks that are more systematic in nature.

APPENDIX C: ERRORS-IN-VARIABLES ADJUSTMENT

Carbon betas – like all regression coefficients – are subject to estimation error. The use of carbon beta as an explanatory variable leads to an errors-in-variables (EIV) problem: when explanatory variables are subject to measurement error, regression coefficients are biased towards zero. This ‘attenuation bias’ thus overestimates the ‘true’ coefficient when it is negative and underestimates it when it is positive. We employ the instrumental variable (IV) approach of Jegadeesh et al. (2019) to resolve these EIV-induced problems. Jegadeesh et al. (2019) propose a framework in which the betas are estimated on two disjoint sets. Similar to Jegadeesh et al. (2019), we implement this by estimating carbon betas in even months separately from carbon betas in odd months. In even (odd) months, we only use the daily returns in previous even (odd) months in the estimation window.²⁴ The estimator of Jegadeesh et al. (2019) is defined as:

$$\hat{\lambda}_{IV} = (X_{IV}X'_{EV})^{-1}(X_{IV}R') \quad (11)$$

where X_{IV} is the matrix of instrumental variables with odd-month (even-month) estimated carbon betas in even (odd) months, X_{EV} is the matrix of explanatory variables with even-month (odd-month) estimated carbon betas in even (odd) months, and R is a vector of stock returns in excess of the risk-free rate. Note that the matrices X_{IV} and X_{EV} contain estimated (carbon) betas, firm characteristics, and market variables, so that $\hat{\lambda}_{IV}$ is a vector of both estimated risk premia and characteristics premia.

The estimator can be decomposed into two parts by expressing it as a two-stage least squares regression. In the first stage, the explanatory variables are regressed on the instrumental variables:

$$\hat{\delta} = (X_{IV}X'_{IV})^{-1}(X_{IV}X'_{EV}) \quad (12)$$

Whereas in the second stage, the OLS estimator is pre-multiplied by the inverse of scaling matrix $\hat{\delta}$:

$$\hat{\lambda}_{IV} = \hat{\delta}^{-1}((X_{IV}X'_{IV})^{-1}(X_{IV}R')), \quad (13)$$

By estimating betas on disjoint samples, the measurement error is uncorrelated. This property allows the IV estimation methodology to yield unbiased estimates of the true risk premia. Jegadeesh et al. (2019) point out that the diagonal elements in $\hat{\delta}$ are smaller than 1 and equal to the ratio of the

²⁴This effectively halves the estimation window, from around 750 daily observations to around 375. While this increases estimation errors, Jegadeesh et al. (2019) show in simulation exercises that this does not lead to large deviations from the true coefficients.

variance in the beta divided by the sum of the variance in beta and in measurement error. Hence, the inverse of $\hat{\delta}$ effectively scales up the OLS coefficients and thereby alleviates the attenuation bias. As the standard errors are scaled by the same constants, there is no effect on the t -statistics.

Table C1: Pricing of Carbon Risk without Errors-in-Variables Correction

This table reports the regression coefficients obtained from regressing monthly excess returns on estimates of carbon beta. The sample period is from January 2007 to December 2020. The regression optionally includes the natural logarithm of market capitalisation, book-to-market ratio, return on equity, book leverage, investments-to-assets, PP&E-to-assets, CAPM beta, idiosyncratic volatility, and 12-month momentum as control variables. Regressions contain year-month fixed effects and optionally include sector-fixed effects. Standard errors are clustered at the firm level. *, **, and *** denote statistical significance at the 10%, 5%, and 1% level, respectively.

Dependent variable:	<i>Monthly excess return ($\times 100$)</i>			
	(1)	(2)	(3)	(4)
Carbon Beta [†]	-0.084*** (0.018)	-0.017 (0.021)	0.007 (0.026)	0.056** (0.026)
ln(Market Cap.)	-	-0.014 (0.011)	-	-0.019 (0.012)
Book/Market	-	-0.348*** (0.050)	-	-0.156*** (0.053)
Return on Equity	-	0.088* (0.047)	-	0.115** (0.047)
Debt/Assets	-	-0.043 (0.097)	-	0.117 (0.104)
Investment/Assets	-	-1.866*** (0.530)	-	-1.068* (0.552)
Property, Plant, & Equipment/Assets	-	0.010 (0.060)	-	-0.033 (0.068)
CAPM Beta	-	0.263*** (0.044)	-	0.271*** (0.047)
Idio. Volatility	-	-0.805*** (0.226)	-	-1.136*** (0.243)
Momentum	-	0.302*** (0.059)	-	0.257*** (0.059)
Industry FE	No	No	Yes	Yes
Year - Month FE	Yes	Yes	Yes	Yes
N.o. Obs.	437,847	437,847	437,847	437,847
R^2 -Adj.	0.227	0.227	0.227	0.228

[†]Indicates a standardised variable. Firm-level variables are cross-sectionally standardised.

APPENDIX D: APPLICATION TO CORPORATE BONDS

In this section, we apply the concept of carbon beta to a sample of corporate bonds. Our data collection and estimation procedure follows Huynh and Xia (2021), who estimate bond returns sensitivities to the Engle et al. (2020) Climate Change News Index. We download data on corporate bond prices for the period January 2012 to December 2021 from the FINRA's Trade Reporting and Compliance Engine (TRACE) Enhanced database. We follow the procedure of Dick-Nielsen (2009, 2014) to clean prices in TRACE. Observations in TRACE are merged with Mergent's Fixed Income Securities Database (FISD) to obtain the characteristics of the bonds and issuers in our sample. We also map S&P's credit ratings²⁵ from Compustat's Capital IQ to our data. Following Bai et al. (2019), we eliminate trades reported in: (1) bonds other than corporate bonds, (2) convertible bonds, (3) bonds with reported prices below \$5 or above \$1000, (4) bonds with floating coupon rates, (5) and bonds with maturities shorter than 1 year. We exclude the least liquid bonds from our sample by requiring bonds to be traded on at least 50% of trading days. Finally, we merge corporate emissions data from Trucost on 6-digit CUSIP numbers. We calculate the monthly corporate bond return as of month t as in Lin et al. (2011):

$$R_{i,t} = \frac{(P_{i,t} + AI_{i,t}) + C_{i,t} - (P_{i,t-1} + AI_{i,t-1})}{(P_{i,t-1} + AI_{i,t-1})}, \quad (14)$$

where $P_{i,t}$ is the volume-weighted average of intraday transaction prices of bond i on the last trading day of month t , $AI_{i,t}$ is accrued interest, and $C_{i,t}$ is the coupon payment.

We construct the pollutive-minus-clean (PMC) portfolio similarly as in our main analysis; by going long the bonds that are in the top 30% of emissions, offset by a short position in the 30% of emissions.

To estimate carbon betas for corporate bonds, we adjust the factor model of Huynh and Xia (2021):

$$R_{i,t}^e = \alpha_i + \beta_i^{PMC} PMC_t + \beta_i^{MKT} MKT_t + \beta_i^{TRM} TRM_t + \beta_i^{DEF} DEF_t + \beta_i^{TED} TED_t + \beta_i^{ILLIQ} ILLIQ_t + \epsilon_{i,t}, \quad (15)$$

where $R_{i,t}^e$ is the return on bond i as of month t calculated in (14), in excess of the 1-month T-Bill rate, α_i is the bond's risk-adjusted outperformance, β 's denote sensitivities to the factors, MKT_t is the aggregate bond market return, TRM_t is the term spread of Welch and Goyal (2008),²⁶ DEF_t is the default spread of Welch and Goyal (2008),²⁶ TED_t is the TED spread,²⁷ $ILLIQ_t$ is the Dick-

²⁵Converted to numerical scale as follows: AAA \rightarrow 1, AA+ \rightarrow 2, ..., C \rightarrow 19, D \rightarrow 20.

²⁶Available at Amit Goyal's website: <https://sites.google.com/view/agoyal145>

²⁷Obtained from Federal Reserve Bank of Saint Louis: <https://fred.stlouisfed.org/series/TEDRATE>

Nielsen et al. (2012) bond market illiquidity series,²⁸ and $\epsilon_{i,t}$ is the residual term. Our interest lies in β_i^{PMC} , which denotes the bond i 's carbon beta.

Table D1 provides descriptive statistics of our sample of corporate bonds as well as the betas estimated. The mean corporate bond return equals 53 bps a month, very similar to the mean bond return in the sample of Huynh and Xia (2021). In contrast to our equities sample, the mean corporate bond carbon beta is negative. Figure D1 presents mean bond carbon betas by issuer GICS industry. We obtain a pattern that is similar to the sectoral distribution of carbon betas in equity securities: the highest exposures are found in the Energy and Materials sectors, while the lowest are found in the Financials sector. Figure D2 provides empirical evidence on the relationship between climate risk exposures with credit ratings and bond maturities. We expect that bonds of lower-rated issuers have higher transition risk exposure, as such firms have greater difficulty in meeting the investments required for a low-carbon transition. This is also consistent with our findings on the firm-level drivers of carbon beta in Section B2. Bonds rated investment grade - that is, bonds with a credit rating of BBB or above - indeed have lower climate risk exposures than bonds with lower ratings. Regarding bond climate betas and maturities, we expect that longer-dated bonds hold larger climate risk exposures, as the impact of low-carbon transition shifts likely has larger effects in the distant future than in the near future. In line with this hypothesis, we find a strong positive association between bond maturities and bond carbon betas.

²⁸ Available at Peter Feldhütter's website: <https://feldhutter.com/>

Table D1: Descriptive Statistics TRACE - FISD - Trucost - S&P Ratings Merged

The table reports descriptive statistics on the variables used in our analysis. Our corporate bond sample is the result of merging trade reports by TRACE, bond and issuer characteristics by FISD, corporate emissions by Trucost, and bond credit ratings by S&P CapitalIQ Compustat. Bond market betas are obtained by estimating Equation (15). The sample period is January 2010 to December 2021.

	N.o. Obs.	Mean	SD	Percentiles				
				5%	25%	Median	75%	95%
Excess Return (%)	526,880	0.530	2.576	-2.963	-0.270	0.357	1.314	4.381
YTM (%)	456,108	4.630	1.707	1.985	3.256	4.478	5.907	7.723
Maturity (Years)	557,138	8.728	8.350	1.522	3.381	5.875	9.411	27.853
Offering Amount (\$ thousands)	557,138	921,933	745,615	250,000	500,000	750,000	1,100,000	2,250,000
Security Rating	222,552	8.926	3.250	4.000	7.000	9.000	10.000	16.000
Equity Market Cap. (\$ millions)	213,623	89,012	143,906	1,751	11,778	38,196	119,925	285,479
Scope 1&2 Emissions (millions tons CO_2)	263,721	6.417	19.588	0.037	0.221	0.924	3.600	29.662
Scope 1&2 Emission Intensity (tons CO_2 /\$ million)	263,721	290.176	998.287	2.673	12.343	35.395	139.658	1344.835
Bond Carbon Beta	183,280	0.022	1.215	-2.207	-0.555	-0.121	0.479	2.805
Bond Market Beta	183,280	0.920	0.551	0.166	0.501	0.814	1.220	2.103
Default Spread Beta	183,280	-0.307	20.737	-46.306	-10.107	2.076	11.497	35.672
Term Spread Beta	183,280	-0.102	0.269	-0.759	-0.206	-0.033	0.068	0.257
Ted Spread Beta	183,280	0.512	3.467	-6.280	-1.019	0.393	1.842	8.020
Illiquidity Beta	183,280	0.001	0.016	-0.030	-0.007	0.000	0.008	0.035

Figure D1: Corporate Bond Carbon Beta by Issuer Industry

The figure displays the coefficients estimated by regressing corporate bond carbon betas on issuer two-digit GICS Industry Sectors. The sample period is January 2012 to December 2021. The 95% confidence intervals are based on robust standard errors adjusted for clustering at the bond level.

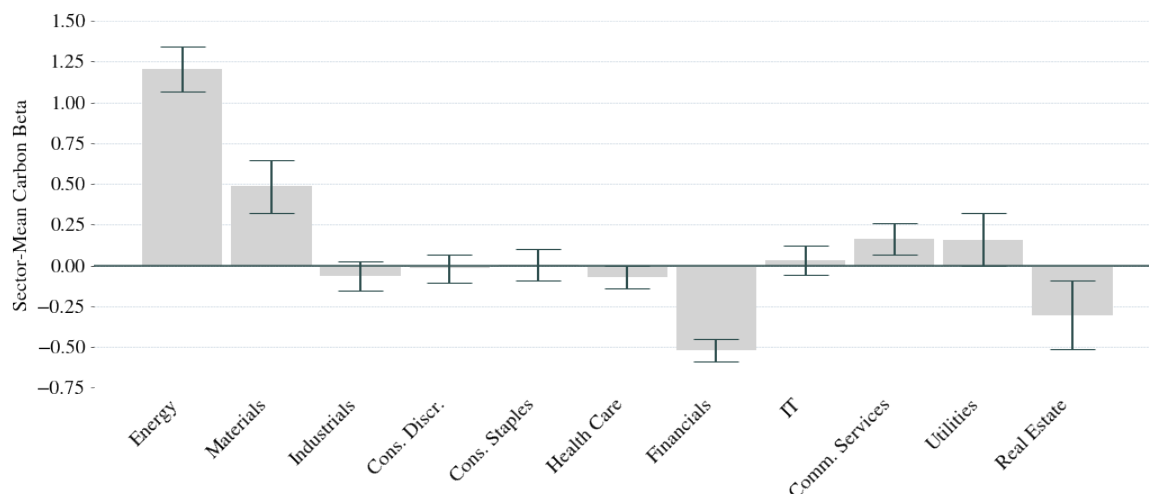


Figure D2: Corporate Bond Carbon Beta by Rating Group and Maturity Group

The figures display the coefficients estimated from regressing corporate bond carbon betas on groups formed on bond credit rating and bond maturities. The sample period is January 2012 to December 2021. The 95% confidence intervals are based on robust standard errors adjusted for clustering at the bond level.

