Carbon Beta:
A Market-Based Measure of Climate Risk

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- The agreement explicitly calls on the finance industry to *"finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development."*
- Investors are increasingly becoming aware of the potentially enormous consequences of unabated climate change

Sustainable Investments are on the Rise

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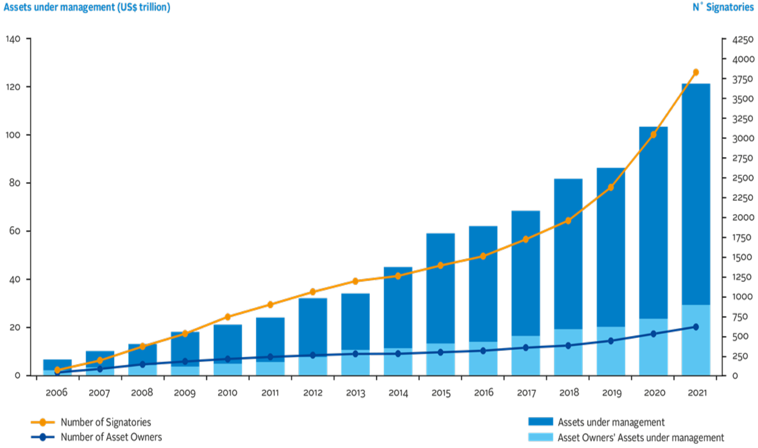

Source: *https://www.unpri.org/pri/about-the-pri*

Yet it remains challenging to address climate risks

- Krüger, Sautner & Starks (2020) survey 439 investment professionals: *"... integrating climate risks into the investment process can prove to be challenging, with investment tools and best practices not yet well established."* (p. 1068)

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- Giglio, Kelly & Stroebel (2020) propose a research agenda for Climate Finance:
  "On the empirical side, there is substantial scope for improvements of the measures of climate risk exposure in different asset classes, and in particular for equity assets." (p. 24).

Our paper: Carbon Beta

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- Intuition: An asset with high (low) Carbon Beta has a tendency to depreciate (appreciate) in value in times when climate risks increase
- Our measure provides high coverage *across* and *within* asset classes, allows for a natural distinction between "winners" and "losers" from climate change

Findings

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- When uncertainty around climate policies increases, assets with higher Carbon Betas have lower returns
- Similar effect in months with abnormally high temperatures and in months that are extremely dry
- Unlike conventional measures, our measure captures firm-level differences in green innovation

Data

1. Stock market and accounting variables from merging CRSP and S&P Capital IQ Compustat
    - Over 570k firm-month observations on over 6,900 unique firms.
2. Corporate emissions from S&P Trucost
    - We merge over 199k firm-month observations on over 2,700 unique firms.
3. Climate Policy Uncertainty
    - Daily Wall Street Journal archives, IPCC Assessment Reports, and all articles in Wikipedia Climate Change category
4. Temperature and Drought data from NOAA
    - Temperature anomalies and Palmer Z-Index (Palmer, 1965)
5. Green Innovation
    - Patent issues from the U.S. Patent Office Bulk Data Storage System
    - Green Patent classification from the OECD (Haščič and Migotto; 2015) and the WIPO Green Inventory
    - Patent-Company mapping by WRDS U.S. Patents (Bèta) product.

Descriptive Statistics

Pollutive-Minus-Clean Portfolio

Double-sorts on previous year's emissions (30^{th} and 70^{th} percentiles) and size (median NYSE market cap.)

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	$MCap_{t-1} < P_{50,NYSE}$	$MCap_{t-1} \geq P_{50,NYSE}$
$Emiss_{t-12} > P_{70}$	SP	BP
$P_{30} \leq Emiss_{t-12} \leq P_{70}$	SN	BN
$Emiss_{t-12} < P_{30}$	SC	BC

PMC portfolio's return given by:

$$PMC_t = \frac{1}{2}(SP_t + BP_t) - \frac{1}{2}(SC_t + BC_t)$$

Estimating Carbon Betas

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- Based on 36-month, rolling-window, regressions

$$R_{it} = \alpha_i + \beta_{i,PMC} PMC_t + \theta_i F_t + \epsilon_{it}, \tag{1}$$

$$\theta_i' = \begin{pmatrix} \beta_{i,RMRF} \\ \beta_{i,SMB} \\ \beta_{i,HML} \\ \beta_{i,WML} \end{pmatrix} \quad and \quad F_t = \begin{pmatrix} RMRF_t \\ SMB_t \\ HML_t \\ WML_t \end{pmatrix}$$

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PMC Portfolio Returns

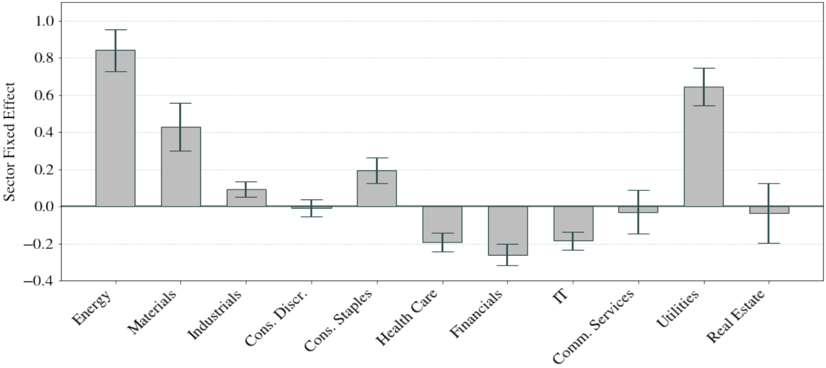
Figure 1: Performance of PMC Portfolio and Alternative PMC Constructions

Factor Descriptive Statistics | Correlations between Alternative PMC Portfolios

Validation

Validation: Industry-Sector Variation

Figure 2: Sector Variation in Climate Risk
Coefficients from regressing carbon betas on industry sector (two-digit GICS) dummy variables



Headquarter State Variation
International Variation

Validation: Correlation with Other Climate Risk Measures

	Carbon Beta	ln(Emissions)	Emission Intensity	SvLVZ CCE	MSCI CVaR
Carbon Beta	1.00	-	-	-	-
ln(Emissions)	0.51^{***}	1.00	-	-	-
Emission Intensity	0.40^{***}	0.51^{***}	1.00	-	-
SvLVZ CCE	0.22^{***}	0.27^{***}	0.52^{***}	1.00	-
MSCI CVaR	0.32^{***}	0.43^{***}	0.40^{***}	-0.04	1.00

Validation: Firm-level Drivers of Climate Risk Exposure

We estimate:

$$CB_{i,t} = \lambda X_{i,t-1} + c_i + \mu_t + \epsilon_{i,t}, \tag{2}$$

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Where:

- $CB_{i,t}$ is firm i's Carbon Beta at the end of time t,
- $X_{i,t-1}$ is a vector of lagged firm characteristics including size, B/M, ROE, leverage, Investment to Assets, PP&E to Assets, and R&D to Assets
- c_i is the industry effect
- μ_t is the time effect

Validation: Firm-level Drivers of Climate Risk Exposure (cont'd)

	Dependent variable: Carbon Beta†			
	(1)	(2)	(3)	(4)
ln(Market Cap.)	0.014**	-0.143***	-0.015***	-0.074***
	(0.006)	(0.014)	(0.005)	(0.013)
Book/Market	0.076***	0.031	0.053***	0.058**
	(0.011)	(0.028)	(0.010)	(0.022)
Return on Equity	-0.162***	-0.144***	-0.068***	-0.035
	(0.019)	(0.035)	(0.017)	(0.030)
Debt/Assets	-0.309***	-0.412***	-0.016	0.012
	(0.059)	(0.088)	(0.050)	(0.068)
Investment/Assets	0.211**	-0.136	0.449***	0.538***
	(0.090)	(0.156)	(0.075)	(0.120)
Property, Plant, & Equipment/Assets	0.801***	0.652***	0.221***	0.193***
	(0.035)	(0.061)	(0.026)	(0.041)
Research & Development/Assets	-1.887***	-2.064***	-0.953***	-1.529***
	(0.108)	(0.206)	(0.105)	(0.185)
ln(Emissions)†	-	0.504***	-	0.221***
	-	(0.031)	-	(0.030)
Year - Month FE	Yes	Yes	Yes	Yes
Industry FE	No	No	Yes	Yes
N.o. Obs.	368,319	144,077	368,319	144,077
R^2-Adj.	0.183	0.426	0.360	0.591

†Indicates a cross-sectionally standardised variable.

External Validation: Market Responses

Climate Policy Uncertainty

- Similarly constructed as Engle, Giglio, Lee, Kelly, & Stroebel (2020) Climate Change News Index

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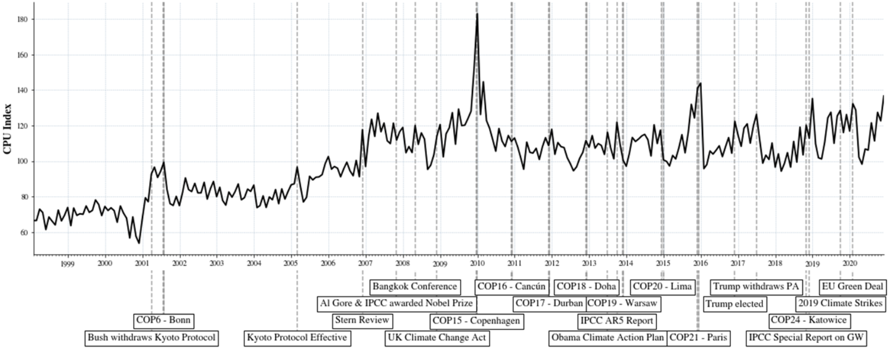
- Textual similarity between a corpus of climate change texts and daily Wall Street Journal archive
- Corpus of climate texts: 5 Assessment Reports by the UN IPCC and all articles in Wikipedia Climate Change category

Details

Climate Policy Uncertainty (cont'd)

Figure 3: Climate Policy Uncertainty over time
CPU is the textual similarity between daily news articles in the Wall Street Journal and a corpus of climate change texts.



Market Responses to Shocks to CPU

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

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Where:

- $R_{i,t}$ is the excess return on 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 change in Climate Policy Uncertainty index during month t
- $X_{i,t-1}$ is a vector of lagged control variables including size, B/M, ROE, leverage, capital intensity, market beta, volatility, and momentum
- c_i is the industry effect
- μ_t is the time effect

Market Responses to Shocks to CPU (cont'd)

	Dependent variable: Monthly excess return (×100)				
		$\Delta CPU \geq 0$	$\Delta CPU < 0$		
	(1)	(2)	(3)	(4)	(5)
Carbon Beta† × ΔCPU†	-0.103***	-0.420***	-0.176**	-	-
	(0.025)	(0.069)	(0.068)	-	-
Carbon Beta†	0.098***	0.425***	-0.042	-	-
	(0.037)	(0.075)	(0.076)	-	-
Emission Intensity† × ΔCPU†	-	-	-	-0.015	-
	-	-	-	(0.017)	-
Emission Intensity†	-	-	-	-0.089***	-
	-	-	-	(0.025)	-
ln(Emissions)† × ΔCPU†	-	-	-	-	-0.038
	-	-	-	-	(0.030)
ln(Emissions)†	-	-	-	-	-0.081
	-	-	-	-	(0.061)
Controls	Yes	Yes	Yes	Yes	Yes
Year - Month FE	Yes	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes	Yes
N.o. Obs.	207,727	105,506	102,221	141,331	141,331
R^2-Adj.	0.261	0.279	0.240	0.276	0.276

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

Market Responses to Extreme Weather Events

	Dependent variable: Monthly return (×100)		
	(1)	(2)	(3)
Panel A: Returns during high temperature anomalies			
Carbon Beta† × Temp. Anomaly	-0.314***	-	-
	(0.101)	-	-
Carbon Beta†	0.171***	-	-
	(0.046)	-	-
Emission Intensity† × Temp. Anomaly	-	-0.108*	-
	-	(0.059)	-
Emission Intensity†	-	-0.061**	-
	-	(0.025)	-
ln(Emissions)† × Temp. Anomaly	-	-	-0.330***
	-	-	(0.106)
ln(Emissions)†	-	-	0.058
	-	-	(0.054)
Controls	Yes	Yes	Yes
Year - Month FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
N.o. Obs.	136,136	136,136	136,136
R^2-Adj.	0.285	0.285	0.285

†Indicates a cross-sectionally standardised variable.

Market Responses to Droughts

Economic Implications

Pricing of Climate Risk

$$R_{i,t} = \alpha + \theta CB_{i,t-1} + \lambda X_{i,t-1} + c_i + \mu_t + \epsilon_{i,t} \tag{4}$$

Where:

- $R_{i,t}$ is the excess return on 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 a 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 12-month-minus-1-month momentum
- c_i is the industry effect
- μ_t is the time effect

We correct for EIV-induced bias using Jegadeesh et al. (2019)'s IV approach Details

Pricing of Climate Risk (cont'd)

	Dependent variable: Monthly excess return ($\times$100)			
	(1)	(2)	(3)	(4)
Carbon Beta†	-0.238***	-0.068	0.143*	0.260***
	(0.053)	(0.062)	(0.080)	(0.083)
ln(Market Cap.)	-	0.094***	-	0.108***
	-	(0.018)	-	(0.020)
Book/Market	-	0.272***	-	0.282***
	-	(0.082)	-	(0.083)
Return on Equity	-	0.025	-	0.045
	-	(0.139)	-	(0.142)
Debt/Assets	-	0.772***	-	0.774***
	-	(0.163)	-	(0.166)
Investment/Assets	-	-0.313	-	-0.459*
	-	(0.210)	-	(0.246)
Property, Plant, & Equipment/Assets	-	-0.212***	-	-0.094
	-	(0.073)	-	(0.080)
CAPM Beta	-	0.091	-	0.182**
	-	(0.073)	-	(0.083)
Idio. Volatility	-	2.674***	-	2.801***
	-	(0.328)	-	(0.350)
Momentum	-	-0.173**	-	-0.184**
	-	(0.076)	-	(0.076)
Year - Month FE	Yes	Yes	Yes	Yes
Industry FE	No	No	Yes	Yes
N.o. Obs.	206,797	206,797	206,797	206,797
R^2-Adj.	0.231	0.232	0.231	0.232

†Indicates a cross-sectionally standardised variable.

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- As emissions and Carbon Betas are correlated, this provides a good setting to study their differences
- Measure of Green Innovation (similar to Cohen, Gurun & Nguyen; 2020):

$$GreenShare_{i,t} = \frac{N.o.\ \ Green\ Patents_{i,t}}{N.o.\ \ Total\ Patents_{i,t}} \tag{5}$$

Green Patents Data

Green Innovation and Carbon Beta

	Dependent variable			
	Carbon Beta†	Carbon Beta†	Emission Intensity†	ln(Emissions)†
Green Share (%)	-0.098**	-0.458*	-0.201	0.223
	(0.043)	(0.257)	(0.419)	(0.279)
ln(Market Cap.)	-0.024***	0.069*	0.081	0.384***
	(0.007)	(0.036)	(0.064)	(0.034)
Book/Market	0.073***	0.086	-0.238*	0.204***
	(0.020)	(0.076)	(0.138)	(0.079)
Return on Equity	-0.051**	-0.219**	0.223	-0.016
	(0.024)	(0.095)	(0.222)	(0.103)
Debt/Assets	-0.014	-0.207	0.773	1.134
	(0.068)	(0.418)	(0.709)	(0.700)
Investment/Assets	0.528***	-0.302	-2.530	-0.741
	(0.113)	(0.697)	(2.068)	(1.344)
Property, Plant, & Equipment/Assets	0.302***	0.337*	0.720	0.271
	(0.043)	(0.173)	(0.448)	(0.194)
Research & Development/Assets	-1.040***	-2.435	1.573	-10.912*
	(0.143)	(2.456)	(8.758)	(6.355)
Year-Month	Yes	Yes	Yes	Yes
Industry FE	Yes	No	No	No
Sectors	All	Energy	Energy	Energy
N.o. Obs.	183,707	7,899	4,205	4,205
R^2-Adj.	0.351	0.284	0.261	0.704

†Indicates a cross-sectionally standardised variable.

Robustness: Green Innovation by MSCI

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- Carbon Betas can be estimated for a wide variety of assets, have high cross-sectional coverage, help in identifying both climate "winners" and "losers", and capture forward-looking information such as green innovation
- We intend to publicly distribute our data and methodology for usage by investors, academics and regulators

Appendix

Appendix: Sample Construction - CRSP Compustat Merged

We follow Fama and French (1993) by:

- Linking companies in CRSP with Compustat with link types *LU*, *LC*, *LS*, *LX*, *LD*, *LN*, or *LO* and primary links *P* or C;
- Including common equities (share codes 10 and 11) traded on the NYSE, AMEX, or Nasdaq (exchange codes 1, 2, and 3);
- Only including firms after they appeared on Compustat for two consecutive years;
- In each June, calculating Book Value of Equity by: Book Value of Stockholders' Equity (SEQ) + Deferred Taxes and Investment Tax Credits (TXDITC) - Book Value of Preferred Stock (PSTK);
- Deleting observations with negative market capitalisation or negative book value;

Back

Appendix: Correlations between Alternative PMC Portfolios

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

Back

Appendix: Details on CPU Index Construction

- Text preprocessing: removing punctuation, splitting sentences into words (tokenising), removing stop words, reducing words to their word roots (lemmatising), converting into bigrams
- *Climate Change Corpus*, denoted by $\mathbb{C}_{CC}$: consists of all bigrams in the 5 UN IPCC Assessment Reports and all articles in the Wikipedia 'Climate Change' category.
- Each daily collection of news articles in the Wall Street Journal, starting from 1997, denoted by $\mathbb{C}_{WSJ,t}$
- Convert text articles into numerical vector form by applying a Term Frequency - Inverse Document Frequency (TF-IDF) transformation to $\mathbb{C}_{CC}$ and each of $\mathbb{C}_{WSJ,t}$, resulting in respectively $v_{WSJ,t}$ and v_{CC}.
- For each day, calculate cosine similarity between v_{CC} and $v_{WSJ,t}$, resulting in a series of daily cosine similarities
- Intuition: when news articles use climate change terms in similar proportions as texts related to climate change, the index indicates a high level of climate change news risk

Back

Appendix: Market Responses to Extreme Droughts

	Dependent variable: Monthly return (×100)		
	(1)	(2)	(3)
Panel B: Returns during drought spells			
Carbon Beta x Drought	-0.234**	-	-
	(0.104)	-	-
Carbon Beta†	0.159***	-	-
	(0.046)	-	-
Emission Intensity† × Drought	-	-0.052	-
	-	(0.064)	-
Emission Intensity†	-	-0.070***	-
	-	(0.026)	-
ln(Emissions)† × Drought	-	-	0.228**
	-	-	(0.114)
ln(Emissions)†	-	-	0.010
	-	-	(0.054)
Controls	Yes	Yes	Yes
Year - Month FE	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes
N.o. Obs.	136,136	136,136	136,136
R^2-Adj.	0.286	0.286	0.286

†Indicates a cross-sectionally standardised variable.

Back

Appendix: Additional information on S&P Trucost and "Scope" of CO_2 Emissions

S&P Trucost collects reported GHG emissions and provides estimations for GHG emissions on more than 18,000 international companies from 2002 to 2019.

Emissions are classified into "scopes", in accordance with the Greenhouse Gas Protocol:

- Scope 1: Direct emissions occurring in a company's production process
- Scope 2: Indirect emissions associated with the purchase of energy
- Scope 3: All other emissions taking place in a company's value chain

Back

Descriptive Statistics

	N.o. Obs.	Mean	SD	Percentiles 1%	5%	25%	Median	75%	95%	99%
Panel A: Firm-level and market variables										
Excess Return (%)	541,953	0.831	17.588	-39.710	-22.010	-6.384	0.282	6.788	23.811	52.560
Market Cap. (millions)	541,973	5,475	28,069	6	17	107	495	2,270	20,371	100,358
Book/Market*	522,559	0.769	0.913	0.044	0.088	0.286	0.542	0.912	2.244	4.139
Return on Equity*	541,835	-0.085	0.529	-2.608	-1.099	-0.065	0.065	0.130	0.321	0.526
Debt/Assets*	431,785	0.246	0.164	0.028	0.061	0.128	0.206	0.317	0.599	0.779
Investment/Assets*	536,154	0.084	0.116	0.000	0.000	0.000	0.023	0.131	0.350	0.466
Property, Plant, & Equipment/Assets*	460,619	0.444	0.394	0.002	0.019	0.128	0.313	0.682	1.236	1.560
Research & Development/Assets*	541,973	0.052	0.110	0.000	0.000	0.000	0.000	0.050	0.303	0.513
Carbon Beta	476,984	-0.010	0.553	-1.330	-0.854	-0.310	-0.026	0.249	0.921	1.671
Idiosyncratic Volatility (%)	528,178	45.526	29.409	12.368	15.478	24.925	37.296	56.952	105.749	147.768
CAPM Beta	534,781	0.998	0.373	0.204	0.389	0.760	1.003	1.228	1.605	1.934
Momentum	508,265	0.078	0.640	-0.833	-0.627	-0.218	0.029	0.266	0.877	2.020
Panel B: Emission variables										
Scope 1 Emissions (millions tons CO_2)	189,843	0.955	3.853	0.000	0.000	0.003	0.022	0.140	4.972	23.800
Scope 2 Emissions (millions tons CO_2)	189,843	0.195	0.481	0.000	0.000	0.005	0.028	0.122	1.126	2.877
Scope 1 & 2 Emissions (millions tons CO_2)	189,843	1.150	4.035	0.000	0.000	0.011	0.064	0.338	6.017	24.461
Scope 1 Emission Intensity (tons CO_2/$ million)	189,843	169.996	623.976	0.308	0.557	3.591	14.144	32.006	903.338	4293.119
Scope 2 Emission Intensity (tons CO_2/$ million)	189,843	28.191	35.950	0.657	1.127	7.485	15.955	35.718	105.842	180.798
Scope 1 & 2 Emission Intensity (tons CO_2/$ million)	189,843	198.187	631.160	1.984	2.133	12.882	37.565	78.794	961.195	4293.551

*Winsorized at the 2% level.

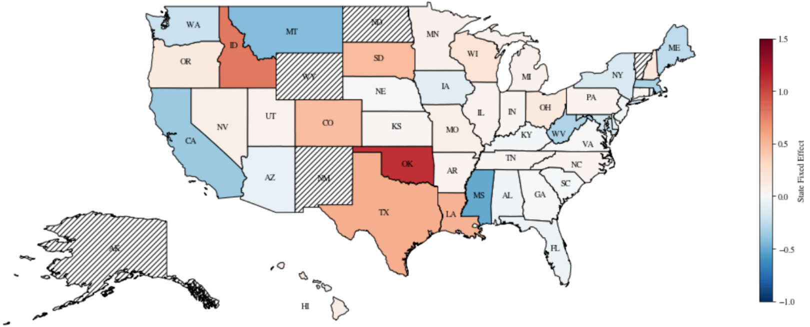
Back

Appendix: Factor descriptive statistics

	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

Back

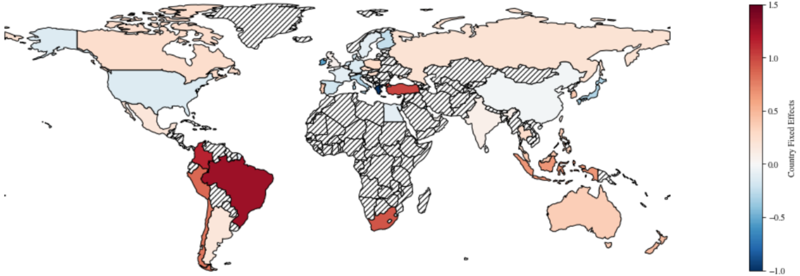
Figure 4: State Variation in Climate Risk
Coefficients from regressing carbon betas on headquarter state dummy variables



Back

Validation: International Variation

Figure 5: Country Variation in Climate Risk
Coefficients from regressing carbon betas on MSCI country indices



Back

Appendix: Jegadeesh et al. (2019) IV Approach to Resolve EIV-Induced Bias

- *Estimation error* in carbon betas leads to *measurement error* when betas are included as explanatory variables
- Presence of measurement error causes estimated coefficients to be biased towards zero: *"attenuation bias"*
- Jegadeesh et al. (2019) propose estimation of betas on disjoint sample, which causes estimation errors to be uncorrelated. A two-step least square regression approach with the 'other' betas as instrumental variables uncovers the 'true' coefficients
- 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, and we use the odd-month (even-month) estimate carbon betas as instumental variables

Back

Appendix: Green Patents Data

- We download all patents issued in the U.S. from 2010 to 2020 from the USPTO Bulk Data Storage System
- We combine patents' classification codes with guidelines by the OECD and by the World Intellectual Property Organization to classify patents as “green” and “non-green”
- We use the WRDS Patent Compustat Link to match patent assignees to companies in the Compustat database
- For patents not included in the WRDS Patent Link we utilise an algorithm that matches by company name
- In 2020, roughly 8% of the patents are classified as green

Back

Appendix: Green Innovation by MSCI and Carbon Beta

	Dependent variable			
	Carbon Beta†	Carbon Beta†	S1&2 Intensity†	ln(S1&2 Emissions)†
Green Share MSCI (%)	-0.045	-0.878*	0.238	0.534
	(0.094)	(0.453)	(1.219)	(0.486)
ln(Market Cap.)	-0.014	0.002	-0.122	0.349***
	(0.010)	(0.040)	(0.113)	(0.054)
Book/Market	0.088***	0.006	-0.415	0.192
	(0.033)	(0.107)	(0.263)	(0.138)
Return on Equity	-0.042	-0.139	0.581	0.312
	(0.034)	(0.112)	(0.401)	(0.238)
Debt/Assets	0.012	-0.341	2.002	2.562***
	(0.083)	(0.478)	(1.285)	(0.904)
Investment/Assets	0.668***	-0.862	-6.803*	-0.682
	(0.152)	(1.034)	(3.884)	(2.223)
Property, Plant, & Equipment/Assets	0.335***	0.254	0.530	0.224
	(0.051)	(0.160)	(0.681)	(0.275)
Research & Development/Assets	-1.408***	-1.298	23.407	-9.414
	(0.198)	(2.138)	(20.706)	(15.228)
Year-Month FE	Yes	Yes	Yes	Yes
Industry FE	Yes	Yes	Yes	Yes
Sectors	All	Energy	Energy	Energy
N.o. Obs.	112,997	3,831	2,957	2,957
R^2-Adj.	0.436	0.328	0.207	0.647

†Indicates a cross-sectionally standardised variable.

Back