Carbon Returns and Risk Premia in a Macro-Finance Model for the Climate Transition

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Abstract

This paper proposes a macro-finance model that allows us to characterize asset prices, risk premia, and macroeconomic quantities over the climate transition. The calibrated model shows that it is excessively difficult to quantify carbon risk premia based on stock returns realized since the start of the climate transition. In contrast, one can very well pin down when the market started pricing the climate transition and how much valuations were affected through the combined cash flow and risk premium effects. Applying the model insights to the oil sector, we find that relative oil firm valuations have declined by more than one third since around the year 2000 as a result of the climate transition.

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1 Introduction

Scientists, business leaders, and policy-makers worldwide predict almost unanimously that the world will be transitioning towards a low-carbon economy in the next 50 years to avoid the worst possible climate change scenarios. This situation presents a unprecedented challenge for the economy, and there is strong agreement that the transition is a new main driver of capital allocation decisions, firms' cash flows, and stock market valuations. Moreover, climate policy risk becomes a key systematic risk factor in this new era, and one of the most widely debated questions in financial economics today is whether brown or green firms have higher stock returns as a consequence. Despite a large body of empirical work, there is no consensus on this question. Different papers find that the time-series average of brown-minus-green returns is significantly positive, significantly negative, or statistically indistinguishable from zero, for both the United States and internationally, as Table 1 summarizes.

In this paper, we ask and address the question what outcomes regarding firm valuations, brown-minus-green returns, and risk premia would be expected from a quantitative theoretical perspective. How do climate policy risk premia look like in a tightly calibrated macro asset pricing model for the climate transition? Would an econometrician be able to identify those risk premia based on 15 years of realized returns? What is the range of possible return realizations in different sample economies? Overall, we show that it is very difficult to reliably identify brown-minus-green risk premia (also known as carbon premia) based on observed returns realized since the start of the climate transition. In virtually all cases, the inference of carbon premia from realized returns gives rise to false negatives (no carbon premium detected even though there is one), false positives (significant carbon premium detected even though there is none), or upward-biased estimates. As a silver lining, we show that one *can* reliably identify when markets started pricing the climate transition and pin down how much valuations are affected through the combined cash flow and risk premium effects.

Our quantitative framework is a structural macro asset pricing model for the climate transition. The proposed model is based on a production economy with a "brown" and a "green" sector and features a *climate change externality*. Environmental quality, which enters the utility function of

Table 1: Empirical papers analyzing brown-minus-green returns. This table summarizes recent papers which compute the difference in realized equity returns between brown and green firms and statistically determine whether these are positive, negative, or not significantly different from zero. We include only papers that classify firms as brown or green based on their carbon emissions, while we do not list papers that use other criteria such as ESG scores.

Paper	Period	Scope	Brown–Green Returns
In, Park, and Monk (2018)	2005–2015	US	negative
Görgen et al. (2020)	2010–2017	international	insignificant
Bolton and Kacperczyk (2021)	2005–2017	US	positive
Pastor, Stambaugh, and Taylor (2022)	2013–2020	US	negative
Bolton and Kacperczyk (2023)	2005–2018	international	positive
Aswani, Raghunandan, and Rajgopal (2024)	2005–2019	US	insignificant
Zhang (2024)	2009–2021	international	negative (US), insignificant (global)

households, is negatively affected by permanent changes in temperature, and the global temperature level is influenced by the greenhouse gas emissions of the economy. Brown (fossil-fuel consuming) firms have a higher emissions intensity than green firms, and they do not internalize the negative effect of their emissions on the households' utility, such that a climate change externality arises. To bring the economy closer to the social optimum, the regulator introduces a carbon tax.[1] As in the real world, the tax set by the regulator may be far away from the theoretically optimal level — especially in the beginning of the climate transition period — which it approaches over time. The carbon tax is also subject to regulatory shocks, standing for hardly predictable results of political processes, which are the source of *climate policy risk* in the model.

Asset exposures to these regulatory shocks are compensated by climate policy risk premia. Since brown and green firms naturally respond to climate policy shocks in an opposite way (for example, brown firms are negatively affected and green firms positively affected by a tax-increasing shock), climate policy risk premia give rise to a return spread between brown sector equity and green sector equity. We first ask whether this return spread (the carbon premium) is positive or negative in our model and find that, in principle, both outcomes are possible. The impact of climate policy shocks on the stochastic discount factor depends on the impact on current consumption

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[1] We interpret the carbon tax as a dollar-equivalent of all implemented measures to disincentivize emissions-intensive goods production.

and expected future utility. As the prevailing carbon tax is typically lower than socially optimal during the climate transition, a positive climate policy shock speeds up the convergence towards the optimal tax level and has a positive effect on future utility. At the same time, the effect on current consumption is negative, such that the aggregate response of the stochastic discount factor depends on the relative magnitude of both effects. The compensation for climate policy risk and the resulting brown-minus-green premia can therefore in principle be negative or positive. In our model calibration, the negative effect on current consumption is quantitatively larger, leading to an increase of the stochastic discount factor and to positive brown-minus-green premia overall.

We use our framework to simulate the climate transition. As a starting point, we initialize the model by considering a special case which represents the 'pre-transition' economy. In the pre-transition economy, agents believe that there is no causal relation between the economy's greenhouse gas emissions and global temperature levels, such that the climate change externality is neglected and the optimal carbon tax is zero. We use this economy to calibrate the model to empirical moments computed for the time before 1995. Besides serving as a starting point for our simulation of the climate transition, the pre-transition economy also provides a benchmark on brown-minus-green premia when climate risks are not priced or present. We find that even in the absence of climate policy risk premia, substantial brown-minus-green premia can arise, which result from a different riskiness of capital investments in the two sectors due to differential adjustment costs, for example. As a consequence, brown-minus-green returns observed in a simulated pre-transition sample of 15 years length can indicate that there is a significantly positive carbon premium, even though no climate risks are priced.

We simulate the transition from the pre-transition state towards the full model equilibrium where agents are fully aware of the effect of carbon emissions on temperature and environmental quality and in which carbon taxes slowly drift towards the social optimum. Our model produces very realistic dynamics, with temperatures topping out right below the 2-degree mark, and carbon emissions reaching their peak around the year 2050. Aggregate output, consumption, and investment fall relative to the balanced growth path as a result of the increased regulation, while environmental quality recovers as temperature stops to rise further. The start of the climate transition has a substantial negative impact on the market valuations (Tobin's Qs) of brown firms as a result of the combined cash flow and risk premium effects, which subsequently leads to a reallocation of capital to the green sector as intended by the regulator.

When analyzing realized returns of the brown-minus-green equity portfolio, we find that a wide range of different outcomes is obtained over different sample periods and across different sample economies even if the carbon premium is the same. For a climate policy risk premium of 1.31%, which we can directly observe in the model, the outcomes for realized returns range from -4.54% to 4.57% in different simulated 15-year samples. One source of variation is the start of the sample, since starting early in the transition includes the substantial devaluation of the brown sector, resulting in large negative realized returns which are, however, unrelated to risk premia. If the initial steep drop is not included, the average brown-minus-green return in the median economy is 1.54% and thus reasonably close to the actual carbon premium. However, the econometrician would deem this premium to be statistically indistinguishable from zero due to the large standard error resulting from the volatility of the brown-minus-green portfolio. Statistical significance would, in contrast, be established for the 4.57% carbon return observed in the 95% quantile economy. In other words, the simulated samples show that if the econometrician observes a significantly positive carbon premium based on realized returns, then the point estimate is likely upward-biased. Finally, the range of possible realized return outcomes is very similar if the actual carbon premium is close to zero instead of 1.31%, implying that there is also a high chance for false positives.

These results provide a very pessimistic view on inferring carbon premia from realized brown-minus-green returns observed over the last one or two decades. We discuss that there is no obvious remedy for this issue; for example, it may be possible to control for short-run cash flow shocks, but much harder to reliably capture and quantitatively control for long-run shifts in cash flow expectations.[2] On the positive side, our model results suggest that one can very well pin down when markets started pricing the climate transition and quantify the magnitude of the brown sector's devaluation, which results from the combined cash flow and discount rate effects. More precisely, the start of the climate transition is reflected by a disconnect between current cash flows and firm valuations.

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[2] The problem can be circumvented if risk premia are directly observed by means of forward-looking returns computed using options data. So far, Eskildsen et al. (2024) is the only paper in the literature considering forward-looking brown-minus-green returns.

We bring our model insights to application by focusing on the oil sector. Analyzing oil firms in particular has the advantage that one avoids classification issues regarding the brown- and greenness of different firms, as the oil sector is clearly brown and negatively impacted by increasing climate regulations. In addition, the effects of the climate transition on stock returns and valuations of oil firms have received relatively little attention in the literature so far. We first show that the return spread between oil firms and other firms over 15-year sample periods can be significantly negative or positive, both before and during the climate transition. This finding confirms our model prediction that a variety of different outcomes can be obtained for realized returns in different samples, and one should be very careful to interpret these as risk premia. As suggested by our model, we therefore focus on the question when the market started pricing the climate transition, as can be pinned down by a notable disconnect of current cash flows and firm valuations. For oil firms, current cash flows can be proxied by the current oil price, and we clearly observe such disconnect in the data during the 2000s, since when oil firm valuations have lost around one third in their relative valuations. We round off the analysis by providing additional evidence that the oil firms' devaluation indeed coincides with the increase in climate change risk awareness, and that it is less pronounced for firms with fewer stranded assets.

Literature Our paper relates to a fast-growing literature on the effects of climate change on the macroeconomy and on asset prices. Several recent studies consider the exposure of equities to climate change risks and analyze related risk premia. Balvers, Du, and Zhao (2017) and Bansal, Kiku, and Ochoa (2017) investigate the effect of temperature shocks on the stock market and find evidence for positive temperature risk premia. On the other hand, Oestreich and Tsiakas (2015), Görgen et al. (2020), and In, Park, and Monk (2018) categorize firms by their carbon emission intensity and consider related portfolios over time, all focusing on sample periods of 10 years or less. While Oestreich and Tsiakas (2015) find higher returns for dirty firms in Europe between 2004 and 2009, which can be explained by a positive cash flow effect due to the free allocation of carbon permits based on past emissions, Görgen et al. (2020) find that brown ("dirty") firms have lower returns for the sample considered. This result could be due to a negative carbon risk premium, or due to the economy being in a transition phase to an economy in which these risks are priced with a positive premium. In, Park, and Monk (2018) also find lower returns for carbon inefficient firms compared to carbon efficient firms. Relatedly, Ilhan, Sautner, and Vilkov (2021) show that dirty firms exhibit increased downside risk as measured from out-of-the-money put options. Baker, Hollifield, and Osambela (2019) develop a portfolio allocation model with externalities, clean and dirty stocks, and households that are differently exposed to climate change.

Coming from a different angle, Engle et al. (2018) construct climate change hedging portfolios using a dynamic approach based on climate change news. Several other papers ask the question whether climate change risk is priced in stock markets or other asset classes. Hong, Li, and Xu (2019) focus on food stocks and show that a publicly available index on drought time trends forecasts profits and stock returns for the food industry in the affected countries, consistent with a market-underreaction to these risks. Baldauf, Garlappi, and Yannelis (2020) show that real estate prices are affected only in regions where people believe in climate change. Bernstein, Gustafson, and Lewis (2019) and Murfin and Spiegel (2020) analyze the effect of sea level rises on the prices of coastal homes. Delis, de Greiff, and Ongena (2018) study the pricing of climate policy risks in bank loans given to fossil fuel firms.

The analysis of climate change on asset prices, empirically and within general equilibrium models, is motivated by the related macroeconomics literature. Important papers showing a significantly impact of higher temperatures on economic activity and growth rates include Nordhaus (2006) and Dell, Jones, and Olken (2012). Colacito, Hoffmann, and Phan (2019) and Donadelli et al. (2017) focus particularly on the United States and find a significantly negative effect of temperature shocks on economic growth. Deryugina and Hsiang (2017) and Lemoine (2018) discuss the relationship between climate and weather risks. General equilibrium models, such as the well-known integrated assessment models developed by Nordhaus (2008), are calibrated to match this empirical evidence in order to quantify the social cost of carbon as well as resulting optimal policies. Acemoglu et al. (2012) develop a non-stochastic model featuring directed technical change and show that the optimal environmental policy involves both a carbon tax and research subsidies. Golosov et al. (2014), Cai, Judd, and Lontzek (2019), and Hambel, Kraft, and Schwartz (2018) build DSGE models that allow to compute the social cost of carbon under different types of modeling assumptions.

2 A Macro Asset Pricing Model for the Climate Transition

We propose a quantitative model for the climate transition that allows us to simulate and analyze the dynamics of macroeconomic variables and asset prices. In our model, brown (fossil-fuel-consuming) firms emit greenhouse gases into the atmosphere, which lead to higher global temperatures in the long run, with a negative effect on the environmental quality that depresses household utility. This effect gives rise to a negative climate externality for the overall economy, which these brown firms do not fully internalize in a competitive setting. It is therefore optimal for the regulator to introduce a carbon tax, which we assume to fluctuate between zero and the socially optimal level. The speed at which the carbon tax converges to its optimal level drives the climate transition, and unexpected regulation shocks give rise to climate policy risk in the model.

2.1 Setup

Households The households in our model consume a constant elasticity of substitution (CES) bundle of the consumption-leisure aggregate $\widetilde{C}_t$ and environmental quality X_t,

$$v(\widetilde{C}_t, X_t) = \left[(1-\theta)\widetilde{C}_t^{1-\frac{1}{\rho}} + \theta(A_t X_t)^{1-\frac{1}{\rho}}\right]^{\frac{1}{1-\frac{1}{\rho}}}. \tag{1}$$

Here, θ is the weight on environmental quality in the bundle and ρ determines the elasticity of substitution between consumption of final goods and environmental quality. Consumption and leisure are, as usual, also aggregated by a CES function,

$$\widetilde{C}_t = \left[(1-\alpha_c)C_t^{1-\frac{1}{\eta_c}} + \alpha_c(A_t l_t)^{1-\frac{1}{\eta_c}}\right]^{\frac{1}{1-\frac{1}{\eta_c}}}, \tag{2}$$

with labor weight α_c and substitution elasticity η_c. The households maximize Epstein and Zin (1991) utility

$$V_t = \left[(1-\beta)v(\widetilde{C}_t, X_t)^{1-\frac{1}{\psi}} + \beta\left(\mathbb{E}_t[V_{t+1}^{1-\gamma}]\right)^{\frac{1-\frac{1}{\psi}}{1-\gamma}}\right]^{\frac{1}{1-\frac{1}{\psi}}} \tag{3}$$

with risk aversion γ and elasticity of intertemporal substitution ψ over the overall bundle of environmental quality, goods consumption, and leisure.

Production The final consumption good is produced by composing goods from a brown and a green intermediate goods sector (labeled by b and g, respectively),

$$Y_t = \left(Y_{b,t}^{1-\frac{1}{\varepsilon}} + Y_{g,t}^{1-\frac{1}{\varepsilon}} \right)^{\frac{1}{1-\frac{1}{\varepsilon}}}, \tag{4}$$

as a constant elasticity of substitution aggregate with parameter ε. The main difference between the brown and the green sector is that the brown sector uses fossil fuel (oil) as part of its production input, while the green sector does not. In particular, with capital $K_{i,t}$ and labor $L_{i,t}$ allocated to the brown and green sector ($i \in \{b, g\}$), the respective production functions are

$$Y_{b,t} = (A_t L_{b,t})^{1-\alpha} Z_t^{\alpha} \qquad \text{and} \qquad Y_{g,t} = (A_t L_{g,t})^{1-\alpha} K_{g,t}^{\alpha}, \tag{5}$$

where Z_t is a constant-elasticity-of-substitution (CES) aggregate of physical capital $K_{b,t}$ and oil O_t with the elasticity of substitution given by the parameter o and the weight of oil in the bundle given by the parameter ι,

$$Z_t = \left((1-\iota) K_{b,t}^{1-\frac{1}{o}} + \iota O_t^{1-\frac{1}{o}} \right)^{\frac{1}{1-\frac{1}{o}}}. \tag{6}$$

The quantity of oil O_t is produced by the oil sector, which will be described in detail below.

Emissions, temperature, and the environment By burning fossil fuels, firms in the brown sector emit ξ_b tons of greenhouse gas for each unit of produced output. Therefore, the production of the brown firms increases the level of greenhouse gas emissions in the atmosphere, which evolves as

$$\mathcal{E}_{t+1} = (1-\eta)\mathcal{E}_t + \frac{\xi_b}{A_t} \cdot Y_{b,t}, \tag{7}$$

where η specifies the rate at which the atmosphere recovers from greenhouse gases and ξ_b/A_t is the carbon intensity of the brown firms' production process. We assume for simplicity that green firms do not produce any greenhouse gas emissions. The brown firm's carbon intensity declines with productivity A_t to account for the fact that technological progress nowadays usually leads to a less carbon-intensive production. Greenhouse gas emissions affect the global temperature level, which follows the dynamics

$$T_{t+1} = \nu T_t + (1-\nu)\chi \mathcal{E}_{t+1} + \sigma_T \varepsilon^T_{t+1}. \tag{8}$$

Here, χ is the climate sensitivity to emissions and ν is the cooling rate similar to Bansal, Kiku, and Ochoa (2017), and we also incorporate weather shocks ε^T_{t+1} in our framework. Note that T_t is interpreted as the global temperature anomaly in our model, describing how much the temperature is above the pre-industrial level.

Rising temperature levels due to climate change have a negative effect on the quality of the environment. In particular, we assume that environmental quality X_t is affected by a Nordhaus (1992) damage function

$$X_t = \frac{\bar{X}}{1 + \kappa_{x,1} T_t^{\kappa_{x,2}}}, \tag{9}$$

where $\bar{X}$ is the level of environmental quality at pre-industrial temperatures and $\kappa_{x,1}$ and $\kappa_{x,2}$ are temperature sensitivity parameters.

In the competitive equilibrium, brown firms do not take into account the effect of their emissions on environmental quality and therefore on the households' utility, which gives rise to a climate change externality.

Carbon tax To address this climate change externality, the regulator introduces a tax on greenhouse gas emissions (or equivalently, on brown-sector output), which evolves as

$$\tau_t = \theta_t \tau^*_t, \tag{10}$$

$$\theta_{t+1} = (1-\rho_\theta)(1-\mu_\theta) + \rho_\theta \theta_t + \sigma_\theta \varepsilon^\theta_{t+1}, \tag{11}$$

where τ^*_t is the theoretically socially optimal tax level, and the process θ_t governs the extent of environmental regulation. The carbon tax narrows the wedge between the competitive equilibrium and the social planner's solution, which we formally derive in Appendix C.2, and thus reduces the climate change externality. While the social optimum is attained with an optimal carbon tax of τ_t^* under perfect competition, we assume that the *implemented* tax τ_t deviates from the optimal tax, and is particularly affected by climate policy shocks $\varepsilon_{t+1}^{\theta}$. These shocks give rise to climate policy risk premia in the model, resulting in a return spread between brown and green equities. The parameter $\mu_\theta \geq 0$ sets the steady-state tax level relative to the optimal tax, and ρ_θ determines the speed of convergence to that level.

Oil sector We explicitly model the oil sector, which is populated by a perfectly competitive representative firm that extracts oil from its wells at a constant rate and builds new oil wells using physical capital and labor as inputs. The oil wells accumulate according to

$$U_{t+1} = (1-\kappa_o)U_t + N_t, \tag{12}$$

where N_t are new oil wells produced according to the technology

$$N_t = (A_t L_{o,t})^{1-\tau} K_{o,t}^{\tau}. \tag{13}$$

Oil is extracted at a constant rate κ_o, and we abstract from inventory holdings in our model. Therefore, the quantity O_t of oil consumed by the brown firms is equal to the quantity of oil E_t extracted by the oil firm:

$$O_t = E_t = \kappa_o U_t. \tag{14}$$

Capital, wages, and productivity Finally, we specify the dynamics of capital, wages, and productivity in our model. The capital stock in each of the three sectors, $i \in \{b, g, o\}$, follows a law of motion of the form

$$K_{i,t+1} = (1-\delta)K_{i,t} + I_{i,t} - G_{i,t}K_{i,t}, \tag{15}$$

where δ_i is the sector's capital depreciation rate and $G_{i,t}$ is a Jermann (1998) adjustment cost function of the form $G_{i,t}(I_{i,t}/K_{i,t}) = I_{i,t}/K_{i,t} - \left(a_{0,i} + \frac{a_{1,i}}{1-\frac{1}{\zeta_i}} \left(I_{i,t}/K_{i,t}\right)^{1-\frac{1}{\zeta_i}}\right)$.

Following Favilukis and Lin (2016), we introduce wage ridigities into the model to generate realistic asset price dynamics. In particular, the average wage paid in sector i is given by

$$w_t L_{i,t} = \widetilde{w}_t (L_{i,t} - \bar{L}_i) + \bar{L}_i \sum_{k=1}^{5} \frac{1}{5} \widetilde{w}_{t-k}, \tag{16}$$

where $\widetilde{w}_t$ is the competitive wage and $\bar{L}_i$ is the amount of labor that does not pay the competitive wage. Instead, it pays the moving average of the competitive wages in the previous five months such that overall, wages are adjusted over a cycle of six months.

The labor productivity A_t of the economy and its long-run trend x_t follow the processes

$$\ln(A_{t+1}) = \ln(A_t) + \mu_A + x_t + \sigma_A \varepsilon^A_{t+1} \tag{17}$$

$$x_{t+1} = \rho_x x_t + \sigma_x \varepsilon^x_{t+1} \tag{18}$$

with productivity shocks ε^A_{t+1} and long-run growth shocks ε^x_{t+1}.

Firm optimization problems and market clearing All firms in the model are perfectly competitive and maximize their cash flows. In particular, final goods producers maximize

$$\mathbb{E}_t \left[\sum_{t=0}^{\infty} \mathbb{M}_t (Y_t - p_{b,t} Y_{b,t} - p_{g,t} Y_{g,t}) \right], \tag{19}$$

taking the prices $p_{b,t}$ and $p_{g,t}$ of the brown and green intermediate goods as given. We choose the final good to be the numeraire in our economy, such that it always trades at a price of 1. The stochastic discount factor is denoted by $\mathbb{M}_t$. The intermediate goods firms maximize

$$\mathbb{E}_t \left[\sum_{t=0}^{\infty} \mathbb{M}_t \left(p_{g,t} Y_{g,t} - R^K_{g,t} K_{g,t} - w_t L_{g,t} \right) \right], \tag{20}$$

$$\mathbb{E}_t \left[\sum_{t=0}^{\infty} \mathbb{M}_t \left(p_{b,t} Y_{b,t} - R^K_{b,t} K_{b,t} - w_t L_{b,t} - p_{o,t} O_t - \tau_t Y_{b,t} \right) \right], \tag{21}$$

taking intermediate goods prices $p_{i,t}$, capital rental rates $R^K_{i,t}$, labor wages w_t, the oil price $p_{o,t}$, and the carbon tax τ_t as given. Finally, the oil firm maximizes

$$\mathbb{E}_t \left[\sum_{t=0}^{\infty} \mathbb{M}_t \left(p_{o,t} O_t - R^K_{o,t} K_{o,t} - w_t L_{o,t} \right) \right] \tag{22}$$

and takes the amount of physical capital rented out ($K_{o,t}$) and labor ($L_{o,t}$), the oil price ($p_{o,t}$), the rental rate of capital ($R^K_{o,t}$), and the labor wages (ω_t) as given.

In equilibrium, the labor and final goods markets clear, and we have the conditions

$$1 - l_t = L_{b,t} + L_{g,t} + L_{o,t}, \tag{23}$$

$$Y_t = C_t + I_{b,t} + I_{g,t} + I_{o,t} + \bar{G}, \tag{24}$$

where in the latter equation, we account for government consumption $\bar{G}$ in order to match the investment and consumption shares in GDP (see Sims and Wu 2021).

2.2 Equilibrium

We derive the household's and the firms' first order conditions in order to solve for the model equilibrium. Defining the pricing kernel as

$$\mathbb{M}_{t+1} = \beta \left(\frac{C_{t+1}}{C_t}\right)^{-\frac{1}{\eta_c}} \left(\frac{\widetilde{C}_{t+1}}{\widetilde{C}_t}\right)^{\frac{1}{\eta_c}-\frac{1}{\rho}} \left(\frac{\vartheta(A_{t+1}X_{t+1}/\widetilde{C}_{t+1})}{\vartheta(A_tX_t/\widetilde{C}_t)}\right)^{\frac{1}{\rho}-\frac{1}{\psi}} \left(\frac{V_{t+1}}{\mathbb{E}_t\left[V_{t+1}^{1-\gamma}\right]^{\frac{1}{1-\gamma}}}\right)^{\frac{1}{\psi}-\gamma} \tag{25}$$

with

$$\vartheta\left(\frac{A_tX_t}{\widetilde{C}_t}\right) = \left(1 - \theta + \theta\left(\frac{A_tX_t}{\widetilde{C}_t}\right)^{1-\frac{1}{\rho}}\right)^{\frac{1}{1-\frac{1}{\rho}}},$$

the household's condition yields that the Euler equation

$$\mathbb{E}_t\left[\mathbb{M}_{t+1}R_{t+1}\right] = 1 \tag{26}$$

holds for the returns R_{t+1} of all assets traded in the economy. We also obtain the first order condition equalizing the marginal utility of final goods consumption and leisure,

$$(1-\alpha_c)C^{\frac{1}{\eta_c}} = \alpha_c \widetilde{\omega}_t l_t^{\frac{1}{\eta_c}}. \tag{27}$$

From the firms' side, we obtain that (26) holds for the investment returns in the three sectors

$(i \in \{b, g, o\})$,

$$R_{i,t+1} = \frac{R^K_{i,t+1} + ((1-\delta) + G'_{i,t+1}\frac{I_{i,t+1}}{K_{i,t+1}} - G_{i,t+1})Q_{i,t+1}}{Q_{i,t}}, \tag{28}$$

with marginal products of capital $R^K_{i,t}$ as well as $Q_{i,t}$ given by

$$R^K_{g,t} = \alpha p_{g,t}\frac{Y_{g,t}}{K_{g,t}}, \quad R^K_{b,t} = \alpha(1-\iota)(p_{b,t} - \tau_t)\frac{Y_{b,t}}{Z_t^{1-\frac{1}{o}} K_{b,t}^{\frac{1}{o}}}, \quad R^K_{o,t} = \tau\lambda_{o,t}\frac{N_t}{K_{o,t}}, \quad Q_{i,t} = \frac{1}{1-G'_{i,t}}, \tag{29}$$

where $\lambda_{o,t}$ is the Lagrange multiplier in the oil firm's problem attached to the production function for new oil wells (see Appendix C.1 for details). Additionally, the oil price $p_{o,t}$ satisfies the following condition, as implied by the brown firm's optimization problem:

$$p_{o,t} = \lambda_{b,t}\alpha\iota\frac{Y_{b,t}}{Z_t^{1-\frac{1}{o}} O_t^{\frac{1}{o}}}. \tag{30}$$

We furthermore obtain the condition

$$Y_{i,t} = p_{i,t}^{-\varepsilon} Y_t. \tag{31}$$

Finally, we show in Appendix C.3 that the socially optimal carbon tax is

$$\tau_t^* = \epsilon_t^S \xi_b, \tag{32}$$

where ϵ_t^S is a Lagrange multiplier describing the shadow cost of an additional unit of emissions in the social planner equilibrium of the model as defined in Appendix C.2.

With these conditions as well as the laws of motion at hand, we can solve for the model equilibrium. In particular, we use a numerical second-order approximation computed by perturbation methods, as provided by the `dynare` package. We apply the pruning scheme proposed by Andreasen, Fernández-Villaverde, and Rubio-Ramírez (2018), which allows us to compute unconditional moments and impulse response functions in closed form.

We furthermore compute the risk-free rate, the market return, and the equity premium based on the model solution, as defined by the equations

$$R_t^f = \frac{1}{\mathbb{E}_t[\mathbb{M}_{t+1}]}, \tag{33}$$

$$R_{t+1}^M = \frac{K_{b,t}Q_{b,t}R_{b,t+1}^K + K_{g,t}Q_{g,t}R_{g,t+1}^K + K_{o,t}Q_{o,t}R_{o,t+1}^K}{K_{b,t}Q_{b,t} + K_{g,t}Q_{g,t} + K_{o,t}Q_{o,t}}, \tag{34}$$

$$R_{ex,t}^{LEV} = (1 + \overline{DE})(R_t^M - R_{t-1}^f). \tag{35}$$

In line with Croce (2014), we assume an average debt-to-equity ratio $\overline{DE}$ of 1, and a non-fundamental volatility of 6.5% per year that adds to the fundamental equity volatilities generated by the model.

3 Model Results and Implications

Based on our model, we simulate the climate-related transition to a low-carbon economy and analyze its effect on macroeconomic quantities and asset prices. Besides understanding the general dynamics, we particularly use the calibrated model as a benchmark for evaluating to what extent carbon premia can be inferred based on realized returns observed over a 15-year sample period. Section 3.1 details the calibration of the model, and Section 3.2 discusses the general determinants and features of climate policy risk premia, both in general and specifically for the given calibration. In Section 3.3, we simulate the transition from the pre-transition state towards the full model equilibrium in which agents understand the effect of emissions on temperatures and where the carbon tax converges to a level where it fully accounts for the climate externality. We analyze the detailed dynamics of macroeconomic quantities and asset prices during the transition in Section 3.4, with a particular focus on brown-minus-green returns and risk premia. Section 3.5 summarizes the main implications of our results and provides guidance for empirical research.

3.1 Calibration

We choose the preference parameters of our model in line with the asset pricing literature (e.g., Bansal and Yaron 2004; Croce 2014), with a relative risk aversion γ of 10 and an elasticity of intertemporal substitution ψ of 2, yielding a preference for the early resolution of uncertainty. The time discount factor β is set to 0.98, consistent with the literature and matching the level of the risk-free rate in our model. Environmental quality accounts for an important part of household utility as specified by a share θ of 0.25 in the household's consumption bundle. We further set the elasticity of substitution ρ between environmental quality and goods consumption to 0.4, making them complements rather than substitutes. While there is no clear guidance in the literature for these two parameters, we show in Sections 3.4 and 4.2 that the chosen values allow us to reproduce realistic asset price dynamics in the climate transition within our model.

For the production sector, we set the depreciation rate of capital δ to 0.06, in line with Croce (2014), for all three sectors. Similarly, we assume the capital share of production α to be identical for the brown, the green, and the oil sector, and set it to 0.21 to match the investments-to-output ratio in the model. Capital adjustment costs ζ_i in the different sectors are chosen to match differences in equity premia, and we assume a high elasticity of substitution between green and brown sector output in line with Acemoglu et al. (2012), setting ε to 3. In the labor market, the labor share α_c is calibrated to match the average work hours of a full-time worker in the US (equal to 21.58%), and the elasticity of substitution between consumption and labor η_c is set to 0.7, following Croce, Nguyen, and Raymond (2021). Finally, the average growth rate of productivity and its volatility, μ and σ_A, are calibrated to match the mean and standard deviation of the output growth rate in the pre-transition period, as described in detail in Section 3.3. The mean-reversion of the long-run growth rate is set to 0.8 following Croce (2014), and its volatility is 0.035 that of the short-term volatility σ_A in order to match the market equity premium. All of these parameters are summarized in Table 2.

The brown and the green sector differ along three dimensions. First, the brown sector uses oil as an input in addition to capital and labor, with an elasticity of substitution between physical capital and oil of $o = 0.4$ as in Gao et al. (2022) and a share ι of oil of 6% to match the size of the oil sector. Oil is produced by the oil sector with an extraction rate κ_o of 8% per year, also as in Gao et al. (2022), and a capital share τ in oil wells production of 40%. Second, the brown sector generates greenhouse gas emissions as part of the production process, and a value of $\xi_b = 3.309$ matches the US emissions intensity in 1995. The green sector's emissions intensity is

Table 2: Preference and production parameters. This table reports parameters describing the household's preferences, the labor market, and the production sectors in the model. All parameter values are annualized.

Parameter		Value
Preferences		
Subjective discount factor	β	0.98
Relative risk aversion	γ	10
Intertemporal elasticity of substitution	ψ	2
Environmental quality share in utility bundle	θ	0.25
Elasticity of substitution between env. quality and consumption	ρ	0.4
Labor market		
Leisure share	α_c	0.133
Elasticity of substitution between consumption and leisure	η_c	0.7
Final goods production		
Depreciation rate of capital	δ	0.06
Capital adjustment costs	$(\zeta_b, \zeta_g, \zeta_o)$	(3.75, 1.25, 3.75)
Capital share of intermediate goods production	α	0.21
Elasticity of substitution between brown and green sector output	ε	3
Average productivity growth rate	μ	0.02
Volatility of productivity growth	σ_A	0.05
Mean-reversion of long-run growth rate	ρ_x	0.8
Volatility oflong-run growth rate	σ_x	$0.035\sigma_A$
Oil production and input		
Oil share in brown sector's production function	ι	0.06
Elasticity of substitution between capital and oil	o	0.4
Capital share of oil wells production	τ	0.4
Oil extraction rate	κ_o	0.08

set to 0. Third, we assume that environmental quality is affected by temperature levels beyond pre-industrial levels with parameters $\kappa_{x,1} = 0.075$ and $\kappa_{x,2} = 2$. These two parameter choices are motivated by the results in Nordhaus (1992). Moreover, the level of environmental quality at pre-industrial temperatures is assumed to be $\bar{X} = 0.1$.

Parameters driving the overall emissions in the atmosphere as well as the global temperature dynamics are chosen in line with climate models. Specifically, the cooling rate is $\nu = 0.962$ (see Bansal, Kiku, and Ochoa 2017; Cai, Judd, and Lontzek 2019), the atmosphere recovery rate is $\eta = 0.0021$ (Reilly and Richards, 1993), and the climate sensitivity to emissions is $\chi = 0.004$. We set the volatility of temperature shocks σ_T to 0.138 to match the observed volatility of the annual

Table 3: Emissions, temperature, and carbon tax parameters. This table reports parameters describing the emissions and temperature dynamics and the carbon tax set by the regulator. All parameter values are annualized.

Parameter		Value
Emissions and Temperature		
Emissions intensity of brown sector	ξ_b	3.309
Environmental quality level at pre-industrial temperature level	$\bar{X}$	0.1
Temperature-sensitivity of environmental quality	$\kappa_{x,1}$	0.075
Temperature-sensitivity of environmental quality	$\kappa_{x,2}$	2
Cooling rate	ν	0.962
Atmosphere recovery rate	η	0.0021
Climate sensitivity to emissions	χ	0.004
Volatility of temperature shocks	σ_T	0.138
Carbon Tax		
Average distance of carbon tax to optimal tax	μ_θ	0
Persistence of carbon tax	ρ_θ	0.95
Volatility of policy shocks	σ_θ	0.16

global temperature anomaly. Finally, we assume that policy-makers set the carbon tax to the theoretically optimal level in the steady state of the model, $\mu_\theta = 0$; recall that our analysis focuses on the transition of the model towards this steady state, with a persistence of $\rho_\theta = 0.95$ and policy volatility of $\sigma_\theta = 0.16$ in line with the real-world volatilities of carbon prices. The parameters related to the sectors' emissions, the temperature dynamics, and the carbon tax are summarized in Table 3.

3.2 Climate Policy Risk Premia in Theory

The model produces climate policy risk premia as a compensation for assets' exposure to policy shocks ε^θ_{t+1}. Climate policy risk premia can in principle be positive or negative, depending on the shock's impact on the considered asset and the investors' pricing kernel. We first discuss the climate policy risk premia of brown and green stocks as well as the resulting brown-minus-green policy risk premium in general based on our model.

When climate policy is tightened due to an unexpected carbon tax shock, the brown firms' revenues are negatively affected according to (21), leading to a negative return on the brown sector's equity, see equation (29). The tax burden on the brown sector also induces a greater demand for green sector capital, yielding a positive return on the green sector's equity on impact. Thus, the returns of green firms increase and the returns of brown firms decline in response to positive climate policy shocks, in line with intuition. The effect of climate policy shocks on the pricing kernel is more ambiguous and can be well understood based on formula (25). On the one hand, the additional tax makes the final good more expensive, such that current household consumption declines. On the other hand, the increased tax partly closes the negative climate externality, leading to an increase in future environmental quality and utility. In principle, either effect can dominate and therefore lead to an increase or decrease in the pricing kernel depending on the model calibration, such that the sign of brown-minus-green climate policy premia is not determined without calibrating the model.

We therefore demonstrate and analyze the precise effects of carbon tax shocks in the calibrated model by means of impulse response functions (see Figure 1). Importantly, we consider the impulse response functions at states where the tax is at 25%, 50%, or 75% of its optimal level, which is representative of the climate transition period.[3] The figures confirm the carbon tax shock's negative effect on consumption and positive effect on environmental quality and show that the former effect overweighs in the calibrated model, resulting in a positive effect on the pricing kernel. Interestingly, it is not a contradiction that on the one hand, the shock brings the carbon tax closer to the optimal level and is thus welfare-improving and on the other hand, today's marginal utility still goes up, due to the limited transferability of consumption over time. Taking this together with the response of brown and green equity returns, we obtain positive climate policy risk premia for the brown sector and negative premia for the green sector, overall leading to positive brown-minus-green climate policy risk premia. This prediction is in line with Pastor, Stambaugh, and Taylor (2021) who do, however, not consider climate policy shocks in a general equlibrium sense. Moreover, our result alleviates the theoretical result by Baker et al. (2019) and Roth Tran (2019) that brown firms should paradoxically have negative risk premia as they perform well in states that yield negative climate outcomes.

In our simulation of the climate transition, we also introduce an exogenously negative correlation

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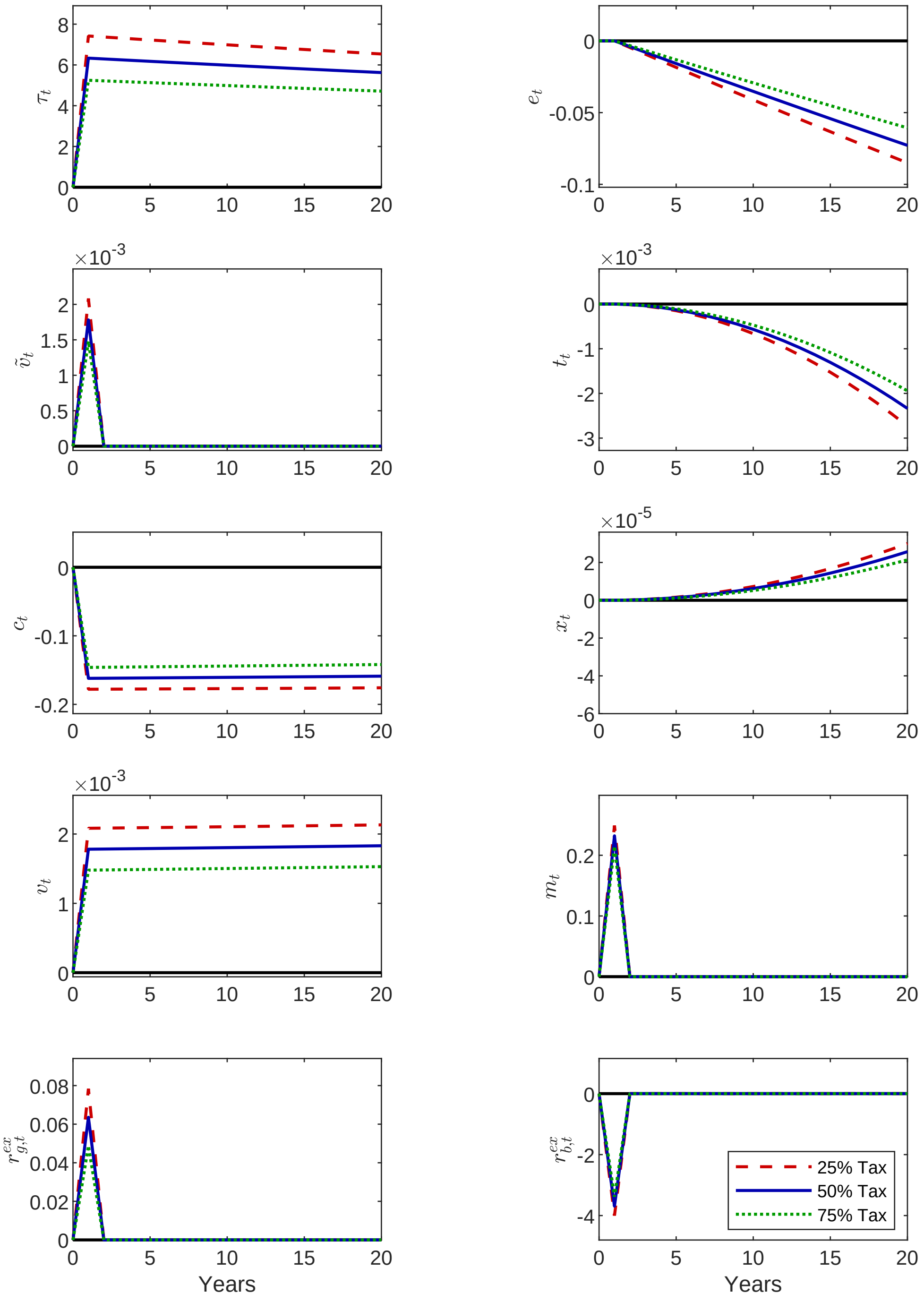
[3] While it is usual to compute impulse response functions around the model's steady state, which would correspond to a 100% tax in our case, it is important in our context to account for the fact that the tax attains values way below 100% for a long time during the climate transition. The methodology by Andreasen, Fernández-Villaverde, and Rubio-Ramírez (2018) allows us to compute conditional impulse functions around such states of the economy.

Figure 1: Impact of carbon tax shocks on brown and green sectors for three values of the carbon tax level: 25%, 50%, and 75% of the optimal carbon tax. The figure shows conditional impulse response functions of quantities and prices to a positive one-standard-deviation policy shock materializing at $t = 1$. Lowercase letters refer to log variables.



between the carbon tax shocks $\varepsilon_{t+1}^{\theta}$ and long-run economic growth shocks ε_{t+1}^{x}. Intuitively, climate policy shocks may suppress long-run growth due to the additional regulations and frictions that are imposed on the economy. As a result, the pricing kernel increases more strongly in response to policy shocks, leading to quantitatively larger positive brown-minus-green climate policy risk premia. We will show in the following that even if climate policy risk premia are large, they can often not well be captured by realized brown-minus-green equity returns over relatively short simulated sample periods.

3.3 State of the Pre-Transition Economy

To explicitly simulate the climate transition, we initialize the model at the pre-transition state. Empirically, we identify the time before 1995 as the pre-transition period, when agents paid arguably little attention to the relation between greenhouse gas emissions, temperatures, and economic risks. We technically implement this pre-transition state in the model by assuming that the agents' *perceived* χ is zero, which makes them disregard the effect of emissions on the temperature level. Under this assumption, the optimal carbon tax also results to zero as the shadow costs of emissions become zero in the social planner economy (see Appendix C). Furthermore, the global temperature anomaly as specified by the dynamics (8) is not endogenous to the model anymore, but perceived as an exogenous process by the agents.

We first evaluate whether the pre-transition state in the calibrated model matches well U.S. macroeconomic and asset price data from 1927 to 1995. Table 4 reports the simulated moments based on the model and its empirical counterparts based on U.S. data. The model matches well the size of the different sectors in the economy in terms of output and the investment-output ratio. Moreover, it is is calibrated to match the average output growth rate and also does a reasonable job explaining the volatilities of output, consumption, and investment growth. When it comes to asset prices, the model produces both a low risk-free rate and high equity premia. As in the data, the equity premia differ across the different sectors, which is achieved by calibrating the sectoral adjustment costs accordingly. Remarkably, the model produces high equity volatilities, which is achieved through a combination of adjustment costs, wage rigidities, and a non-fundamental volatility component.

Table 4: Model moments. This table reports simulated macroeconomic and asset price moments for the pre-transition economy. The moments are computed using 1,000 simulations for 68 years, as in the data. The model is simulated at a monthly frequency. The data column is based on U.S. macroeconomic and asset price data for the period 1927–1995. Details on the construction of the sectoral output data are given in Appendix B.

Moment		Data	Model
	Size of different sectors		
Investment-output ratio	$\mathbb{E}[I/Y]$	15.06	13.90
Brown sector output share	$\mathbb{E}[p_b Y_b/Y]$	20.99	24.25
Green sector output share	$\mathbb{E}[p_g Y_g/Y]$	76.86	71.54
Oil sector output share	$\mathbb{E}[p_o O/Y]$	2.16	4.21
	Economic growth and volatilities		
Output growth rate	$\mathbb{E}[\Delta y]$	2.29	1.94
Output growth volatility	$\sigma(\Delta y)$	5.81	5.03
Consumption growth volatility	$\sigma(\Delta c)$	3.74	4.68
Investment growth volatility	$\sigma(\Delta i)$	5.86	6.65
	Risk-free rate and equity premia		
Risk-free rate	$\mathbb{E}[r_f]$	0.51	0.43
Market equity premium	$\mathbb{E}[r_m - r_f]$	8.49	8.56
Brown sector equity premium	$\mathbb{E}[r_b - r_f]$	10.19	10.48
Green sector equity premium	$\mathbb{E}[r_g - r_f]$	9.63	9.68
Oil sector equity premium	$\mathbb{E}[r_o - r_f]$	6.71	3.58
	Equity volatilities		
Market equity volatility	$\sigma(r_m - r_f)$	21.10	15.79
Brown sector equity volatility	$\sigma(r_b - r_f)$	23.38	17.64
Green sector equity volatility	$\sigma(r_g - r_f)$	26.28	16.96
Oil sector equity volatility	$\sigma(r_o - r_f)$	29.07	10.99

Second, we evaluate realized returns of brown-minus-green equity portfolios in the pre-transition economy. As empirical research typically analyzes brown-minus-green returns during the transition period and associates positive or negative returns with climate policy risk premia, we ask whether it is — according to the theoretical benchmark provided by our model — correct to assume that these returns are zero prior to the transition. To tackle this question, we simulate 15 years of data for 1,000 pre-transition sample economies and report statistics on brown-minus-green equity returns and risk premia in Table 5. Panel A considers the benchmark calibration. While there are no climate policy risk premia in the pre-transition model by definition, the brown-minus-green risk premium is slightly positive, highlighting that other factors besides climate policy risk can be

Table 5: Simulated brown-minus-green returns and risk premia before the climate transition. This table reports statistics of realized returns and risk premia for the brown-minus-green equity portolio in the simulated pre-transition economy. We simulate 1,000 economies for 15 years at a monthly frequency. The table shows the time-series average of the monthly ex-post realized returns and risk premia (i.e., ex-ante expected returns) for the median economy and the 5% and 95% quantile economies. In brackets, we report *p*-values of the returns and risk premia for the respective economy.

Panel A: Benchmark Calibration

	5%	Median	95%
Brown-minus-green returns	0.20%	0.39%	0.61%
	[0.07]	[0.00]	[0.00]
Brown-minus-green risk premia	0.40%	0.40%	0.40%
	[0.00]	[0.00]	[0.00]

Panel B: Modified Adjustment Costs ($\xi_b = 1.25$)

	5%	Median	95%
Brown-minus-green returns	1.20%	2.01%	2.85%
	[0.02]	[0.00]	[0.00]
Brown-minus-green risk premia	2.00%	2.00%	2.00%
	[0.00]	[0.00]	[0.00]

responsible for a return spread between brown and green equity.

To strengthen this point, we consider a slight variation of our calibration in Panel B, where the brown sector has higher adjustment costs and thus carries larger risk premia. As a result, brown-minus-green risk premia are substantial in this case. When an econometrician observes 15 years of monthly brown-minus-green returns in this scenario, she will in virtually all simulated economies come to the conclusion that the time-series average of brown-minus-green returns is positive and significantly different from zero. The main takeaway is that risk premia on brown sector equity may be significantly different from risk premia on green sector equity due to factors unrelated to climate policy risk. Besides attempting to control for those factors, our results suggest that conducting a placebo test of brown-minus-green returns in the pre-transition period is commendable for empirical research.

3.4 Simulating the Climate Transition

We now use the calibrated model to simulate the climate transition period. The starting point of the climate transition is the unconditional mean of the pre-transition model.[4] We then simulate the transition paths towards the equilibrium of the full model — in which agents understand the relation of emissions and global temperatures as defined through the parameter χ — for 1,000 economies.

We first discuss the dynamics of temperature, emissions, carbon tax, and macroeconomic variables during the transition period, which we depict in Figure 2. The figures show the average path of the considered variables as well as confidence bands around it. In our simulation of the climate transition, the temperature anomaly reaches a value of about 1.9 degrees Celsius, approximately in the year 2040, before it slowly declines. Staying below the 2-degrees mark is achieved through a carbon tax which starts at a low value and gradually converges towards the socially optimal tax.[5] As a result, emissions also reach their peak at around 2050 and decline quickly after that. Environmental quality declines first and then stabilizes once temperatures do not rise anymore. The figures also show that aggregate consumption, investment, and output all decline — relative to the balanced growth path — during the climate transition. This behavior reflects the fact that increasing the carbon tax, which is welfare-improving and necessary to prevent catastrophic temperature increases, naturally comes at the cost of a reduction in economic growth.

Figure 3 depicts the average transition paths and confidence bands of key asset price variables in the economy, showing the behavior of firm valuations (Tobin's Qs) in the first row. Our analysis reveals that the valuations of the brown and the oil sector substantially decline in the beginning of the climate transition. The Tobin's Q of the green sector swiftly increases, on the other hand, consistent with the intuition that low-carbon industries become more profitable relative to fossil-fuel-consuming industries as the carbon tax increases. Importantly, all industry valuations revert

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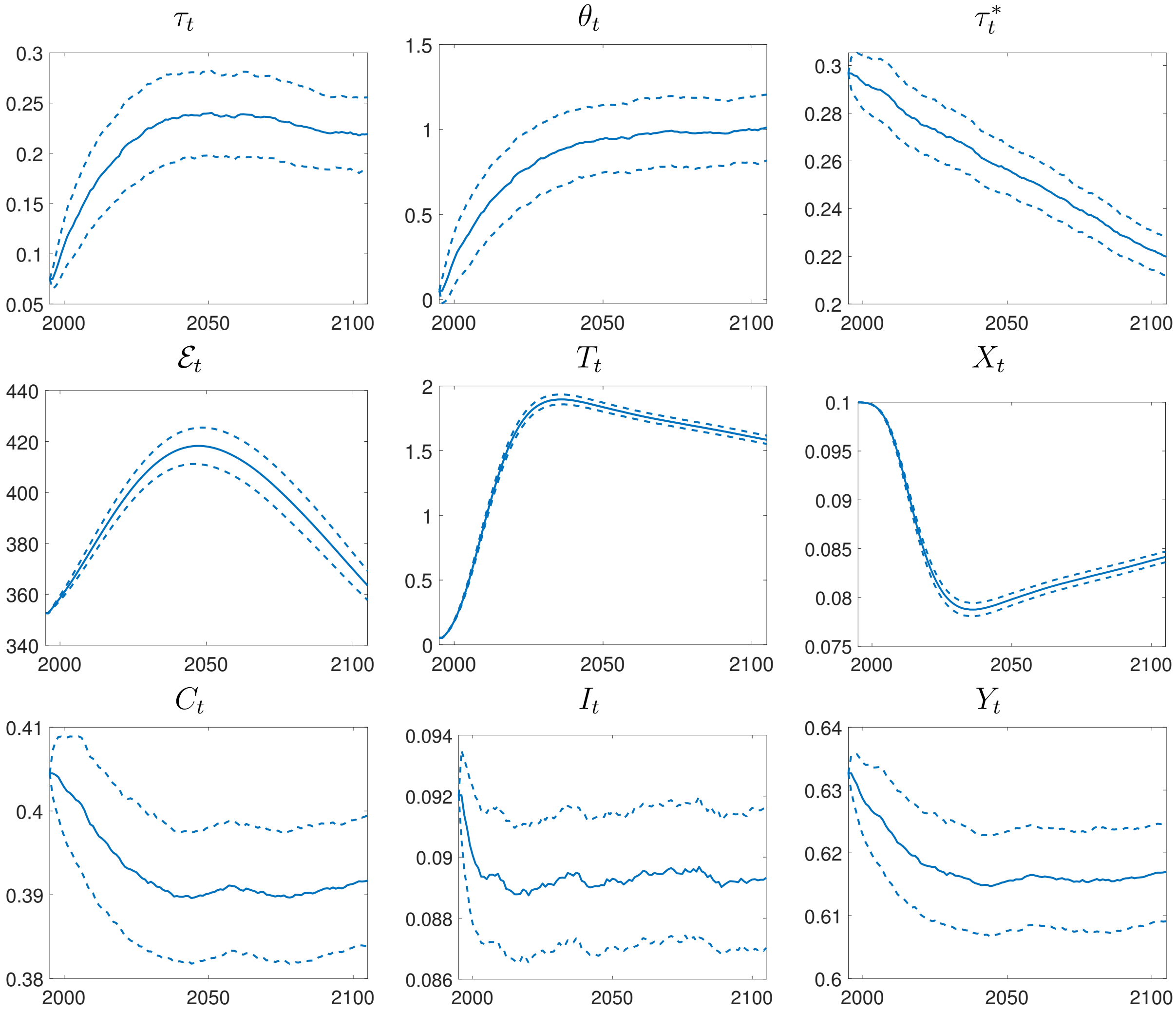
[4] We can compute the unconditional mean in closed form under the pruning scheme proposed by Andreasen, Fernández-Villaverde, and Rubio-Ramírez (2018), and do not rely on a simulation of the pre-transition model for obtaining this starting point.

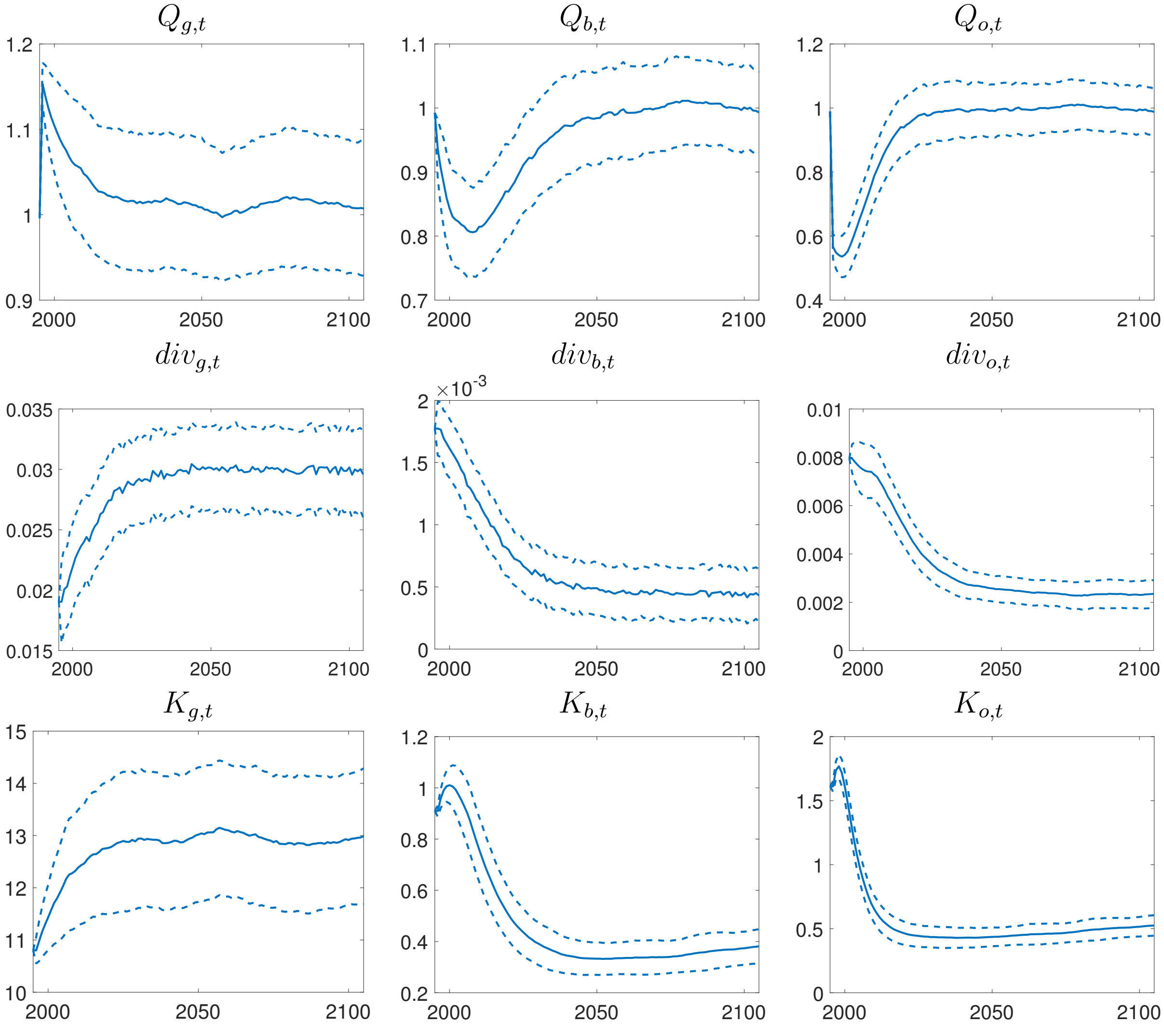
[5] Our results also confirm the finding by Daniel, Litterman, and Wagner (2019) that under Epstein and Zin (1991) preferences, the optimal tax starts at a very high level and slowly declines. In our case, the actually implemented tax starts at zero and drifts slowly towards the optimal tax, therefore following a hump shape.

Figure 2: Transition dynamics of macroeconomic quantities. The transition dynamics are computed for 110 years (from 1995 to 2105) and 1,000 sample economies. The initial point of the simulation is the mean state of the pre-transition economy. The mean path across the 1,000 economies is depicted for key macroeconomic variables, alongside confidence bands computed as mean path plus/minus one half times the standard deviation of observations across paths at any given point in time.



back to a Tobin's Q of 1 in the longer run as capital is being reallocated in line with q theory. In particular, the lower valuations of the brown and oil sector lead to a divestment of capital (see third row of Figure 3), and some capital is flowing to the green sector. As a result of this reallocation, the relative market valuations of brown and oil firms start increasing again later in the climate transition, and the green sector's valuation declines. While the climate transition's effect on valuations is immediate, the decline of dividends in the brown sector and the oil sector

Figure 3: Transition dynamics of asset prices. The transition dynamics are computed for 110 years (from 1995 to 2105) and 1,000 sample economies. The initial point of the simulation is the mean state of the pre-transition economy. The mean path across the 1,000 economies is depicted for key asset pricing variables, alongside confidence bands computed as mean path plus/minus one half times the standard deviation of observations across paths at any given point in time.



(see the second row of the figure) is slow, and dividends reach their new steady state only around the year 2050. As valuations directly incorporate this decline in future dividends, there is a strong disconnect between firm valuations and contemporaneous dividends in the beginning of the climate transition. While valuations fall strongly, dividends first stay at a high level and decline only slowly.

We now analyze returns and risk premia during the transition period. We start with the case in which climate policy shocks are strongly negatively correlated with long-run growth shocks, which produces quantitatively meaningful positive climate policy risk premia. Precisely, as Panel A of Table 6 shows, the brown-minus-green climate policy risk premium is 1.31% in the calibrated model. The table also shows that the overall brown-minus-green risk premium, which also includes premia due to differences in adjustment costs, for example, is 1.58% in the model. If an econometrician were to observed these risk premia directly, she could directly infer their magnitude; in particular, since we use a second-order approximation to the model equilibrium, risk premia themselves do not vary in magnitude over time in our simulations. In contrast, the table also reveals that it is very difficult for an econometrician to infer the underlying risk premia by observing brown-minus-green realized returns over a short simulated sample period of 15 years. The first row of the table shows that even though the underlying risk premia are positive, the observed brown-minus-green returns are on average negative if the sample starts with the beginning of the transition period and thus includes the large devaluation of the brown sector. The large negative initial return leads to an average brown-minus-green realized return of −2.07% measured over 15 years in the median economy. On the contrary, when the econometrician looks at a sample period with a later start date, she will observe positive brown-minus-green returns in most cases, even though a negative observed brown-minus-green return is still possible in the 5% quantile economy. In the median economy, the observed 1.54% brown-minus-green return is very close to the risk premium, but not statistically significant in the simulated sample. In contrast, a 4.57% realized return is observed in the 95% quantile economy, which is statistically significant, but much larger than the actual risk premium. As a result, the econometrician can come to the conclusion that the brown-minus-green risk premium is negative or positive in terms of its point estimate but statistically indistinguishable from zero, or statistically significant and much larger than what it actually is. The drawn conclusion will thus likely suffer either from being a false negative or from providing an upward-biased point

Table 6: Simulated brown-minus-green returns and risk premia during the climate transition. This table reports statistics of realized returns and risk premia for the brown-minus-green equity portolio in the simulated transition from the pre-transition state to the post-transition economy. We simulate 1,000 economies for 15 years at a monthly frequency. The table shows the time-series average of the monthly ex-post realized returns and risk premia (i.e., ex-ante expected returns) for the median economy and the 5% and 95% quantile economies. Early sample start indicates that the returns are averaged over the full 15 simulated years for each economy, while late sample start implies that the first month is excluded. Risk premium is the full risk premium, while the climate policy risk premium is obtained by subtracting the brown-minus-green risk premium obtained from a model simulation in which climate policy shocks are shut down. In brackets, we report p-values of the returns and risk premia for the respective economy.

Panel A: Positive climate policy risk premium ($\text{Corr}(\varepsilon^{\theta}_{t+1}, \varepsilon^{x}_{t+1}) = -0.45$)

	5%	Median	95%
Brown-minus-green returns			
Early sample start	-4.54% [0.24]	-2.07% [0.62]	0.97% [0.81]
Late sample start	-0.94% [0.54]	1.54% [0.38]	4.57% [0.01]
Brown-minus-green risk premia			
Overall risk premium	1.58% [0.00]	1.58% [0.00]	1.58% [0.00]
Climate policy risk premium	1.31% [0.00]	1.31% [0.00]	1.31% [0.00]

Panel B: Close-to-zero climate policy risk premium ($\text{Corr}(\varepsilon^{\theta}_{t+1}, \varepsilon^{x}_{t+1}) = -0.05$)

	5%	Median	95%
Brown-minus-green returns			
Early sample start	-5.50% [0.13]	-3.03% [0.41]	0.01% [1.00]
Late sample start	-2.19% [0.17]	0.29% [0.87]	3.32% [0.07]
Brown-minus-green risk premia			
Overall risk premium	0.38% [0.00]	0.38% [0.00]	0.38% [0.00]
Climate policy risk premium	0.11% [0.00]	0.11% [0.00]	0.11% [0.00]

estimate.

In Panel B, we consider the case with only a small negative correlation between climate policy shocks and long-run growth shocks, where the resulting climate policy risk premia are virtually zero. Even though this is the case, we find that the observed 15-year average brown-minus-green returns in different sample economies are very similar compared to the case with the clearly positive climate transition premium. As a result, the econometrician's inference on whether there is a significant carbon premium and on its size is not substantially different in the case where it is actually present compared to the case where it is close to zero. Generally speaking, our model analysis shows clearly that when attempting to infer climate transition premia from 15 years of brown-minus-green equity returns, the econometrician will very likely fall for a false negative, false positive, or an upward-biased point estimate of the underlying premium.

We finally show that these points, which apply to the return spreads between the brown (i.e., oil-consuming) relative to the green sector, equivalently apply to the oil-producing sector. The reason is that oil-producing firms are affected by climate regulations similarly to oil-consuming firms, with a similar impact on their valuations and returns. Table 7 shows realized returns and risk premia, paralleling the outcomes discussed for the brown sector. In Figure 3, we see that oil firm valuations exhibit a pronounced decrease in the beginning of the transition period due to the impact of the carbon tax on the brown sector, which leads to a much lower demand of oil. While the decline in valuations is immediate, dividends decline only slowly; therefore, the beginning of the climate transition is reflected by a strong disconnect between contemporaneous dividends and valuations in the brown sector and the oil sector.

3.5 Summary and Empirical Implications

The results on realized brown-minus-green returns simulated based on our model show that it is very difficult to infer carbon risk premia through realized returns over relatively short samples. One important confounding factor is that the beginning of the climate transition comes with substantial effects on cash flows, which are reflected by realized returns and make it difficult to distinguish them from risk premia. Quantitatively, the analysis of our calibrated model shows that cash flow effects are indeed so large that one may observe substantial negative average brown-minus-green returns

Table 7: Simulated oil-minus-other returns and risk premia during the climate transition. This table reports statistics of realized returns and risk premia for the oil-minus-other equity portolio in the simulated transition from the pre-transition state to the post-transition economy. We simulate 1,000 economies for 15 years at a monthly frequency. The table shows the time-series average of the monthly ex-post realized returns and risk premia (i.e., ex-ante expected returns) for the median economy and the 5% and 95% quantile economies. Early sample start indicates that the returns are averaged over the full 15 simulated years for each economy, while late sample start implies that the first month is excluded. Risk premium is the full risk premium, while the climate policy risk premium is obtained by subtracting the oil-minus-other risk premium obtained from a model simulation in which climate policy shocks are shut down. In brackets, we report p-values of the returns and risk premia for the respective economy.

Panel A: Positive climate policy risk premium ($\text{Corr}(\varepsilon^{\theta}_{t+1}, \varepsilon^{x}_{t+1}) = -0.45$)

	5%	Median	95%
Oil-minus-other returns			
Early sample start	-6.94% [0.03]	-2.77% [0.44]	2.27% [0.54]
Late sample start	-4.98% [0.12]	-0.87% [0.78]	4.19% [0.20]
Oil-minus-other risk premia			
Overall risk premium	-0.72% [0.00]	-0.72% [0.00]	-0.72% [0.00]
Climate policy risk premium	2.47% [0.00]	2.47% [0.00]	2.47% [0.00]

Panel B: Close-to-zero climate policy risk premium ($\text{Corr}(\varepsilon^{\theta}_{t+1}, \varepsilon^{x}_{t+1}) = -0.05$)

	5%	Median	95%
Oil-minus-other returns			
Early sample start	-8.79% [0.00]	-4.62% [0.17]	0.42% [0.89]
Late sample start	-7.35% [0.02]	-3.24% [0.29]	1.82% [0.57]
Oil-minus-other risk premia			
Overall risk premium	-3.09% [0.00]	-3.09% [0.00]	-3.09% [0.00]
Climate policy risk premium	0.10% [0.00]	0.10% [0.00]	0.10% [0.00]

when the climate policy risk premium is clearly positive, or significantly positive brown-minus-green returns when the actual climate policy risk premium is virtually zero.

There is no simple remedy to this issue. One may attempt to control for cash flow effects using measures of climate change concerns or dividend and earnings information (see Pastor, Stambaugh, and Taylor 2022; Eskildsen et al. 2024); however, realized returns may be driven by changes in long-run cash flow growth expectations, which are difficult to measure and to separate from long-run discount rates (risk premia). It is, of course, possible to circumvent these issues by *not* analyzing realized returns and instead computing forward-looking excess returns, which by definition reflect risk premia. Despite the very large and growing literature on carbon premia, the recent paper by Eskildsen et al. (2024) is the only one taking this approach. The computation of forward-looking returns requires the availability of liquidly traded options on the given stocks and therefore restricts the sample in both the cross-section and time-series, especially in the international setting. If forward-looking returns can reliably be computed, a remaining issue is to identify the part that is actually driven by climate policy risk, as we have shown that there can be positive brown-minus-green risk premia even prior to or generally unrelated to the climate transition.

While providing this negative perspective on the inference carbon risk premia from realized brown-minus-green returns, we also want to highlight that we *can* very well learn when the market started pricing the climate transition and pin down the overall effect on valuations through combined cash flow and risk premium effects. As our analysis shows, the beginning of the climate transition is reflected by a remarkable drop in market valuations of brown sector firms and oil firms. Moreover, the valuations strongly disconnect from current cash flows, which is observable very clearly in both the brown sector and the oil sector.

We use the oil sector as a laboratory in the next section to apply these insights from our model. Focusing on the oil sector allows us to avoid classification issues of brown and green firms; instead, it is clear and obvious that oil-producing firms are strongly affect by the climate transition. While there are lots of papers discussing green and brown (i.e., oil-consuming) firms, the literature has not analyzed the climate transition through the lens of oil firm returns and valuations thus far.

4 New Evidence from the Oil Sector

This section brings the insights from our model to application. While a large number of papers have considered brown-minus-green returns by classifying firms according to their carbon emissions, we provide new evidence by focusing on the oil sector. By definition, the oil sector is brown and strongly negatively affected by stricter climate policies. In Section 4.1, we consider the return spread between oil firms and other firms over 15-year sample periods and show that, as predicted by our model, it can be clearly negative or positive, both before and during the climate transition. Section 4.2 applies the positive model result that we can pin down when the market started pricing the climate transition by means of a notable disconnect of current cash flows and firm valuations. For oil firms, current cash flows are proxied by the current oil price, and we clearly observe such disconnect in the data during the 2000s. In Section 4.3, we provide additional evidence by showing that the devaluation of the oil sector indeed coincides with the increase in climate change risk awareness, and that is less pronounced for firms with fewer stranded assets.

4.1 Return Spread Between Oil Firms and Other Firms

As a variation on the brown-minus-green return exhaustively analyzed in the literature, we investigate the return spread between oil firms and other firms. We run our analysis on the standard CRSP/Compustat dataset from 1950 to 2021, and define oil firms as those where the first two digits of the SIC code start with 13 or 29. We consider the return spread between oil firms and other firms for different 15-year sample periods, both before and during the climate transition. Following Bolton and Kacperczyk (2021), we run a pooled regression, where monthly returns are the dependent variable and an indicator for oil firms is the independent variable. Table 8 presents the results.

As the table shows, realized oil-minus-other firm returns as a special case of brown-minus-green returns attain both significantly negative and positive values when considered over different 15-year sample periods, and this is the case both before and during the climate transition. This observation is exactly in line with our model predictions in Section 3. However, as our model simulations show, it is very likely that these realized returns do not directly translate to underlying risk premia. As

Table 8: Oil-minus-other returns in different 15-year samples. For different 15-year periods both before and during the climate transition, we conduct a pooled regression of stock returns from the CRSP/Compustat universe of firms on an oil firm indicator. The estimated coefficient is reported as the oil-minus-other return. *** indicates significance at the 1% level according to Newey-West standard errors.

Period	Oil-minus-other Return
Pre-Transition Times	
1950–1964	$4.26\%^{***}$
1965–1979	$13.57\%^{***}$
1980–1994	$-10.55\%^{***}$
During Climate Transition	
1995–2009	$5.26\%^{***}$
2000–2014	$4.82\%^{***}$
2005–2019	$-4.72\%^{***}$

an example, we find a highly significant oil-minus-others return of 4.82% in the period from 2000 to 2014. The econometrician may interpret this finding as evidence of a positive carbon premium, in line with the increased exposure of oil firms to climate transition risks in the period after 2000. However, if the econometrician were to use a sample period starting in 2005, she would observe a significantly negative carbon return. In addition, she can also observe significantly positive or negative returns in sample periods prior to 1995, when climate policy risks were very likely not an important risk factor in financial markets. The empirical perspective through the lens of the oil sector therefore confirms and illustrates one of our main model implications, namely that it is extremely difficult to infer carbon risk premia from realized returns observed over a 15-year sample, and the question whether the carbon premium of oil firms is positive or negative remains unanswered.

4.2 Valuation of Oil Firms and the Climate Transition

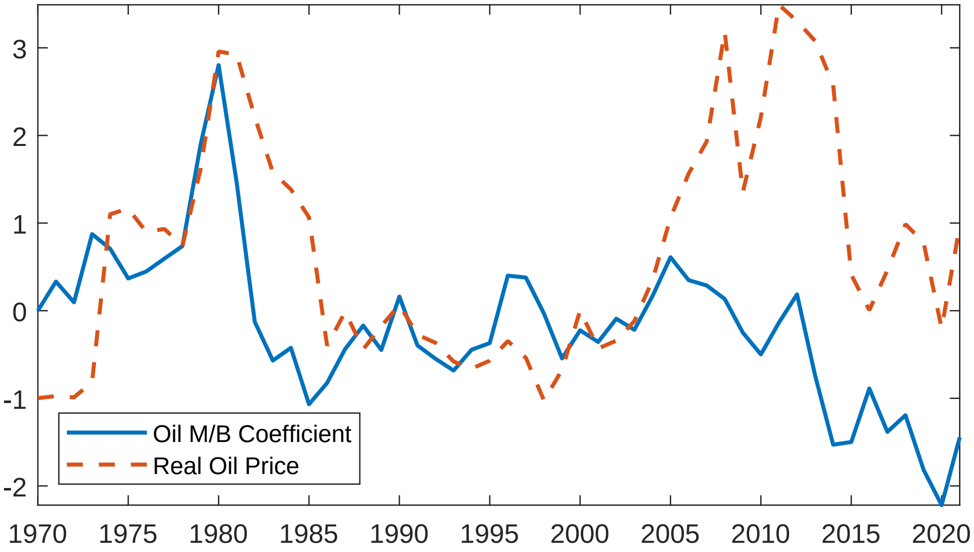
We turn to the questions that can be answered according to our model, namely when the market started pricing the climate transition, and what effect it had on the valuations of affected firms. These questions have not clearly been answered by the literature; in fact, the variety of different sample start dates for the analysis of carbon premia (see Table 1) shows that there is no consensus on when the climate transition started affecting financial market outcomes. Our model predicts that this start date can be well identified by a considerable drop in oil firm valuations, which furthermore get disconnected from the oil price as a proxy of current cash flows.

We first measure the relative valuation of oil firms each year by running a panel regression of all CRSP/Compustat firms' valuations on an indicator for the oil sector, its interactions with a time dummy variable for each year, and a number of firm-specific controls. As valuation measures, we use market-to-book ratios in our baseline analysis and subsequently also consider Tobin's q as well as Peters and Taylor's (2017) total q. As control variables, we consider the firms' cash ratio as a measure of liquidity, the firms' amount of debt relative to assets as a measure of leverage, the log of firms' total assets as a measure of firm size, and the ratio of firms' research and development (R&D) expenditures to sales as a measure of firm innovation capacity (see also Chen, Hou, and Stulz 2015 and Minton, Stulz, and Taboada 2019). Appendix Table A.1 provides summary statistics of our valuation measures and control variables, separately for the full sample and the subsample of oil firms.

Figure 4 plots the yearly coefficients on the oil sector indicator, which represent the valuation of oil firms relative to other firms after taking the control variables into account, together with the real oil price over our sample. The figure shows that these valuations were relatively stable from about 1985 to 2005, and declined afterwards to reach their minimum towards the end of our sample. Remarkably, the oil firms' valuations co-move strongly with the oil price until this time as a main driver of oil firms' profits. This pattern has dramatically changed in the beginning of the 2000s, when the oil sector's market valuation decoupled from the oil price and declined irrespective of the dramatic commodity price boom of 2008 and other substantial oil price movements. Put simply, the (real) oil price in 2021 is at the same level as in 1985 or 1974, but the relative valuation of the oil sector is considerably lower compared to these points in time.

This disconnect of oil firm valuations from oil prices is exactly in line with the predictions of our model for the start of the climate transition. Statistically, the correlation between the yearly valuation coefficient and the oil price is 0.52 and significant at the 1% level from the beginning of our sample until the year 2000, and 0.29 and insignificant when computed for the years after 2000. Altogether, these results suggest that the market started pricing the effects of the climate

Figure 4: Regression-implied relative valuation of oil firms compared to the real oil price. We regress the firms' market-to-book ratios on the interaction terms of an indicator for the oil sector with dummies for every single year of our sample. The blue solid line plots the estimated coefficients of these interaction terms. Control variables include the firm's cash ratio as a measure of liquidity, the firm's amount of debt relative to assets as a measure of leverage, the log of firm's total assets as a measure of firm size, and the ratio of firm's research and development (R&D) expenditures to sales as a measure of firm innovation capacity. The red dashed line plots the real oil price, standardized to the same scale. Our sample runs from 1970 to 2021.



transition for oil firms in the 2000s around the year 2005, as reflected by a strong devaluation of oil firms, together with a disconnect of these valuations from the oil price.

4.3 Oil Firm Valuations, Climate Change Awareness, and Stranded Assets

We extend our analysis by asking to what extent the devaluation of oil firms observed in the previous section correlates with measures of the progressing climate transition. For that, we construct a Climate Change Risk Awareness Index (CCRAI) from search volumes and word count data (see Appendix E) and introduce it together with its interaction with the oil firm indicator into our panel regression, replacing the yearly dummy variables. Table 9 presents the regression results. The interaction term of the Climate Change Risk Awareness Index (CCRAI) with the oil indicator shows our main finding: The market valuation of oil firms declines, compared to other firms, together with the progressing climate transition captured by the CCRAI. The related coefficient is highly significant in all specifications and across the different valuation measures. In terms of economic significance, a coefficient of -0.005 in column (1) means that the market-to-book ratio of oil firms relative to other firms declines by 1.00 for a 200 points increase in the CCRAI, relative to an average market-to-book ratio of oil firms of 2.475.[6] This implies that the valuation of oil firms has decreased by more than one third relative to other firms along with the climate transition over the last 20 years. For robustness, we confirm that these results also hold when considering not only oil firms but the whole fossil fuel sector (including coal, SIC code 12), as columns (2), (4), and (6) show.

These results show that oil and fossil fuel firm valuations have substantially declined with the start of the climate transition and decoupled from the oil price around the year 2000, as the previous section reveals. We argue that the economic mechanism behind these results is that due to the climate transition, the demand for oil and fossil fuels in the economy falls, such that oil firms will not be able to capitalize on the full amount of their assets anymore as the economy moves towards greener energies. In other words, a certain amount of fossil fuel firms' assets will remain unexplored and become "stranded". To test this hypothesis, we investigate whether the decline in market valuations of oil and fossil fuel firms is related to the amount of potential stranded assets. We employ a novel dataset from the *2 degrees of separation* initiative, provided by CarbonTracker and the United Nation's Principles for Responsible Investments Association,[7] which provides for a sample of energy firms the percentage of potential capex that become stranded under a 1.6-degree global warming scenario. We match these data to our sample and define fossil fuel firms that are within the lowest two quartiles of potential stranded assets as firms with few stranded assets.

We repeat the panel regressions from above, but additionally include an indicator variable for firms with few stranded assets as well as its interaction with the CCRAI. The results, reported in Table 10, show that the valuations of firms with few stranded assets exhibit a much smaller

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[6] This value is calculated as $2.440 + 0.035$ as implied by the average market-to-book ratio of all firms from Panel A of Table A.1 and the coefficient on 1_{Oil} in Table 9, column (1).

[7] See `https://2degreesseparation.com/`.

Table 9: Relation between climate change risk awareness and oil or fossil fuel firm valuations. We regress the firms' valuation measures on the Climate Change Risk Awareness Index (CCRAI), a dummy for the oil or fossil fuel sector, respectively, and their interaction term. As valuation measures, we use market-to-book ratios and Tobin's q as well as Peters and Taylor's (2017) total q. Control variables include the firms' cash ratio as a measure of liquidity, the firms' amount of debt relative to assets as a measure of leverage, the log of firms' total assets as a measure of firm size, and the ratio of firms' research and development (R&D) expenditures to sales as a measure of firm innovation capacity. Our sample runs from 1970 to 2021. Standard errors double-clustered by firm and year are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

	Market-to-book ratio		Tobin's q		Total q	
	(1)	(2)	(3)	(4)	(5)	(6)
$1_{Oil} \times CCRAI$	-0.005*** (0.002)		-0.015*** (0.002)		-0.002** (0.001)	
$1_{Fossilfuel} \times CCRAI$		-0.005*** (0.002)		-0.015*** (0.002)		-0.002** (0.001)
1_{Oil}	0.035 (0.200)		-0.960*** (0.174)		-0.028 (0.087)	
$1_{Fossilfuel}$		0.014 (0.195)		-0.966*** (0.172)		-0.037 (0.085)
$CCRAI$	0.006*** (0.001)	0.006*** (0.001)	0.012*** (0.002)	0.012*** (0.002)	0.001 (0.001)	0.001 (0.001)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	134015	134015	107440	107440	105244	105244
Adjusted R^2	0.113	0.113	0.245	0.245	0.153	0.153

exposure to the increase in CCRAI compared to oil or fossil fuel firms in general. In particular, the market-to-book ratios of firms with few potential stranded assets decline by a value of 0.40 with a 200 percentage points increase in the CCRAI, compared to a reduction of 1.00 in the market-to-book ratios of all oil firms. The results are similar for Tobin's q and total q, such that valuations of firms with few potential stranded assets do not significantly decline with increasing climate change risk awareness, while they do significantly decline for general oil or fossil fuel firms. The combined evidence provides strong support for the intuition that the climate transition drives the devaluation of the oil sector since it leads to a significant amount of stranded assets.

Table 10: Relation between climate change risk awareness, potential stranded assets, and oil or fossil fuel firm valuations. We regress the firms' valuation measures on the Climate Change Risk Awareness Index (CCRAI), a dummy for the oil or fossil fuel sector, respectively, their interaction term, as well as a dummy for firms with few potential stranded assets and its interaction term with the CCRAI. Firms with few potential stranded assets are those in the first two quartiles of assets at risk as classified by the *2 degrees of separation* initiative. As valuation measures, we use market-to-book ratios and Tobin's q as well as Peters and Taylor's (2017) total q. Control variables include the firms' cash ratio as a measure of liquidity, the firms' amount of debt relative to assets as a measure of leverage, the log of firms' total assets as a measure of firm size, and the ratio of firms' research and development (R&D) expenditures to sales as a measure of firm innovation capacity. Our sample runs from 1970 to 2021. Standard errors double-clustered by firm and year are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

	Market-to-book ratio		Tobin's q		Total q	
	(1)	(2)	(3)	(4)	(5)	(6)
$1_{Oil} \times CCRAI$	-0.005***		-0.014***		-0.002*	
	(0.002)		(0.002)		(0.001)	
$1_{Fossilfuel} \times CCRAI$		-0.005***		-0.014***		-0.002**
		(0.002)		(0.002)		(0.001)
$1_{Fewassetsatrisk} \times CCRAI$	-0.002	-0.002	-0.005*	-0.005	0.001	0.001
	(0.002)	(0.002)	(0.003)	(0.003)	(0.001)	(0.001)
1_{Oil}	0.034		-0.929***		-0.016	
	(0.202)		(0.172)		(0.088)	
$1_{Fossilfuel}$		0.013		-0.936***		-0.025
		(0.197)		(0.169)		(0.085)
$1_{Fewassetsatrisk}$	0.012	0.022	-1.007***	-1.007***	-0.393***	-0.389***
	(0.245)	(0.245)	(0.162)	(0.163)	(0.100)	(0.098)
$CCRAI$	0.006***	0.006***	0.012***	0.012***	0.001	0.001
	(0.001)	(0.001)	(0.002)	(0.002)	(0.001)	(0.001)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
$1_{Oil} \times CCRAI - 1_{Fewassetsatrisk} \times CCRAI$	-0.003		-0.009		-0.002	
$1_{Fossilfuel} \times CCRAI - 1_{Fewassetsatrisk} \times CCRAI$		-0.003		-0.009		-0.002
p-value	0.304	0.278	0.015	0.012	0.074	0.062
Observations	134015	134015	107440	107440	105244	105244
Adjusted R^2	0.113	0.113	0.245	0.245	0.153	0.153

5 Conclusion

This paper provides an analysis of the climate-related transition towards a low-carbon and less fossil-fuel intense economy and its implications for macroeconomic and financial market outcomes. We propose a macro-finance model for the climate transition that allows us to analyze asset prices in simulated settings, including the disruptive effects in the beginning of the transition as well as climate policy risk premia. As one of the main implications of our model, we show that it is extremely difficult for an econometrician to infer underlying climate transition risk premia based on observed returns over a relatively short sample of 15 years, for example. Due to the volatility of brown-minus-green returns, a variety of different outcomes can be observed, which, however, often give rise to false positive or false negative conclusions on the existence of carbon premia. Similarly, point estimates can be largely biased. These model-based results may explain the vast heterogeneity of conclusions regarding carbon premia in the empirical literature.

We also show that a question which can very well be addressed is *since when* the market started pricing the climate transition. The start of the climate transition is reflected by a substantial decline in brown and oil firm valuations and furthermore, a disconnect of valuations from the firms' contemporaneous cash flows. Using the oil sector as a laboratory, we find that such pattern was precisely and cleanly observable for oil firm valuations around the year 2005. While oil prices, as a proxy for oil firms' cash flows, kept increasing as a result of the commodity boom, relative oil firm valuations first stagnated and then declined by around one third with the climate transition. Realized oil firm stock returns, on the contrary, varied widely in different 15-year sample periods both before and during the climate transition, illustrating nicely the prediction of our model that these should not be over-interpreted to make strong conclusions regarding possible underlying carbon premia.

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A Additional Tables and Figures

Table A.1: Summary statistics of our CRSP/Compustat data sample. Market-to-book ratio, Tobin's q, and Peters and Taylor's (2017) total q are the valuation measures used in our analysis. The firms' cash ratio as a measure of liquidity, the debt-to-asset ratio as a measure of leverage, the log of firms' total assets as a measure of firm size, and the ratio of firms' research and development (R&D) expenditures to sales as a measure of firm innovation capacity are our main control variables. Panel A summarizes our full sample and Panel B the subsample of oil firms. Observations are in firm-years.

Panel A: All Firms

	Mean	SD	5%	25%	50%	75%	95%	N
Market-to-book ratio	2.44	2.47	0.36	0.89	1.52	2.87	10.09	324,298
Tobin's q	2.70	4.28	-0.45	0.37	0.94	2.79	16.59	218,247
Total q	0.97	1.19	-0.25	0.22	0.61	1.23	4.55	225,968
Cash ratio	1.11	1.87	0.00	0.08	0.31	1.09	7.31	363,220
Debt-to-asset ratio	0.60	0.30	0.09	0.37	0.59	0.84	1.25	459,662
Log assets	5.05	2.61	0.38	3.06	5.08	7.05	9.70	461,062
R&D-to-sales ratio	0.19	0.44	0.00	0.00	0.03	0.12	1.85	178,525

Panel B: Oil Firms

	Mean	SD	5%	25%	50%	75%	95%	N
Market-to-book ratio	2.16	2.19	0.36	0.86	1.44	2.43	7.76	17,932
Tobin's q	1.11	1.60	0.10	0.41	0.71	1.20	3.29	16,124
Total q	0.89	0.87	0.09	0.38	0.65	1.08	2.68	15,864
Cash ratio	1.00	1.83	0.00	0.05	0.25	0.85	7.31	22,739
Debt-to-asset ratio	0.51	0.30	0.09	0.29	0.48	0.65	1.25	22,815
Log assets	4.66	2.71	0.38	2.46	4.63	6.69	9.69	22,851
R&D-to-sales ratio	0.07	0.29	0.00	0.00	0.00	0.01	0.21	4,009

B Sectoral Output Construction in U.S. Data

To construct a measure for the output of the brown, green, and oil sectors, we use U.S. data from the Bureau of Economic Analysis. Specifically, we use the gross output by industry data between 1927 and 1995. We let output by all private industries (Line 2) be aggregate output. From these private industries, the gross output of the following industries is summed up to obtain the gross output of the brown sector:

- Agriculture, forestry, fishing, and hunting (Line 3)
- Wood products (Line 14)
- Nonmetallic mineral products (Line 15)
- Primary metals (Line 16)
- Fabricated metal products (Line 17)
- Motor vehicles, bodies and trailers, and parts (Line 21)
- Paper products (Line 29)
- Chemical products (Line 32)
- Plastics and rubber products (Line 33)
- Motor vehicle and parts dealers (Line 36)
- Air transportation (Line 41)
- Water transportation (Line 43)
- Truck transportation (Line 44)

From these private industries, the gross output of the following industries is summed up to obtain the gross output of the oil sector:

- Mining (Line 6)
- Petroleum and coal products (Line 31)

- Pipeline transportation (Line 46)

The green sector's output is then the residual or private industries output (Line 2) minus our measure of brown sector's output and minus our measure of oil sector's output.

C Model Equilibrium Conditions

C.1 Competitive Equilibrium with Carbon Tax

Final goods producer The final goods firm in the model solves the problem

$$\max_{\{Y_{i,t}\}} \mathbb{E}_t \left[\sum_{t=0}^{\infty} \mathbb{M}_t (Y_t - p_{b,t} Y_{b,t} - p_{g,t} Y_{g,t}) \right], \tag{C.1}$$

which leads to the equilibrium condition

$$Y_{i,t} = p_{i,t}^{-\varepsilon} Y_t, \tag{C.2}$$

in line with Equation (31).

Intermediate goods firms The green and brown intermediate goods producers, $i \in \{b, g\}$, optimize (20) and (21), respectively, subject to the production functions in Equation (5), as well as the laws of motion (7) and (8), leading to the problem

$$\begin{aligned} \max_{\{Y_{i,t};L_{i,t};K_{i,t};O_t;T_{t+1};\mathcal{E}_{t+1}\}} \mathbb{E}_t \Bigg[\sum_{t=0}^{\infty} \mathbb{M}_t \Bigg(& p_{i,t} Y_{i,t} - R^K_{i,t} K_{i,t} - w_t L_{i,t} - \mathbb{1}_{\{i=b\}} p_{o,t} O_t - \mathbb{1}_{\{i=b\}} \tau_t Y_{i,t} \\ & - \mathbb{1}_{\{i=g\}} \lambda_{g,t} \left(Y_{g,t} - (A_t L_{g,t})^{1-\alpha} K^{\alpha}_{g,t} \right) \\ & - \mathbb{1}_{\{i=b\}} \lambda_{b,t} \left(Y_{b,t} - (A_t L_{b,t})^{1-\alpha} \left((1-\iota) K_{b,t}^{1-\frac{1}{o}} + \iota O_t^{1-\frac{1}{o}} \right)^{\frac{\alpha}{1-\frac{1}{o}}} \right) \\ & - \phi_{i,t} A_t (\nu T_t + \chi \mathcal{E}_{t+1} + \sigma_T T_{t+1} \varepsilon^T_{t+1} - T_{t+1}) \\ & - \epsilon_{i,t} A_t (\xi_b / A_t Y_{b,t} + (1-\eta) \mathcal{E}_t - \mathcal{E}_{t+1}) \Bigg) \Bigg] \end{aligned} \tag{C.3}$$

with Lagrange multipliers $\lambda_{i,t}$, $\phi_{i,t}A_t$, and $\epsilon_{i,t}A_t$. Setting the first derivative by $Y_{i,t}$ to zero yields

$$0 = p_{g,t} - \lambda_{g,t}, \tag{C.4}$$

$$0 = p_{b,t} - \tau_t - \lambda_{b,t} - \epsilon_{b,t}\xi_b. \tag{C.5}$$

We set the first derivative by T_{t+1} to zero and obtain

$$0 = -\nu\mathbb{E}_t[\mathbb{M}_{t+1}\phi_{i,t+1}A_{t+1}] + \phi_{i,t}A_t \tag{C.6}$$

Setting the first derivative by $\mathcal{E}_{t+1}$ to zero yields

$$0 = -\chi\phi_{i,t}A_t - (1-\eta)\mathbb{E}_t[\mathbb{M}_{t+1}\epsilon_{i,t+1}A_{t+1}] + \epsilon_{i,t}A_t. \tag{C.7}$$

Finally, setting the first derivative by $L_{i,t}$ to zero gives us

$$\lambda_{i,t}(1-\alpha)\frac{Y_{i,t}}{L_{i,t}} = \widetilde{w}_t, \tag{C.8}$$

the first order condition with respect to $K_{g,t}$ is

$$\lambda_{g,t}\alpha\frac{Y_{g,t}}{K_{g,t}} = R^K_{g,t}, \tag{C.9}$$

and the first order condition with respect to $K_{b,t}$ is

$$\lambda_{b,t}\alpha(1-\iota)\frac{Y_{b,t}}{Z_t^{1-\frac{1}{o}}K_{b,t}^{\frac{1}{o}}} = R^K_{b,t}. \tag{C.10}$$

The first order condition for O_t is (for the brown firm only)

$$\lambda_{b,t}\alpha\iota\frac{Y_{b,t}}{Z_t^{1-\frac{1}{o}}O_t^{\frac{1}{o}}} = p_{o,t}. \tag{C.11}$$

Oil firm The oil producer optimizes (22), subject to the production function (13), as well as the laws of motion (12) and (14), leading to the problem

$$\max_{\{N_t;L_{o,t};K_{o,t};U_{t+1}\}} \mathbb{E}_t\Bigg[\sum_{t=0}^{\infty}\mathbb{M}_t\Bigg(p_{o,t}\kappa_o U_t - R^K_{o,t}K_{o,t} - w_t L_{o,t} \\ - \lambda_{o,t}(N_t - (A_t L_{o,t})^{1-\tau}K^{\tau}_{o,t}) \\ - \phi_{o,t}(U_{t+1} - (1-\kappa_o)U_t - N_t)\Bigg)\Bigg] \tag{C.12}$$

The first derivative with respect to N_t implies

$$\lambda_{o,t} = \phi_{o,t}. \tag{C.13}$$

The first order condition for the labor demand $(L_{o,t})$ gives

$$\lambda_{o,t}(1-\tau)\frac{N_t}{L_{o,t}} = w_t, \tag{C.14}$$

whereas the first order condition with respect to $K_{o,t}$ implies the following condition

$$\lambda_{o,t}\tau\frac{N_t}{K_{o,t}} = R^K_{o,t}. \tag{C.15}$$

Finally, the first order condition with respect to the number of oil wells (U_{t+1}) yields

$$0 = \kappa_o\mathbb{E}_t[\mathbb{M}_{t+1}p_{o,t+1}] - \phi_{o,t} + (1-\kappa_o)\mathbb{E}_t[\mathbb{M}_{t+1}\phi_{o,t+1}]. \tag{C.16}$$

Capital producer Finally, the representative capital producer solves for each of the three sectors, $i \in \{b, g, o\}$, the problem

$$\max_{\{K_{i,t+1},I_{i,t}\}} \mathbb{E}_t\Bigg[\sum_{t=0}^{\infty}\mathbb{M}_t(R^K_{i,t}K_{i,t} - I_{i,t} - Q_{i,t}(K_{i,t+1} - (1-\delta)K_{i,t} - I_{i,t} + G_{i,t}K_{i,t}))\Bigg]. \tag{C.17}$$

Setting the first derivatives with respect to $K_{i,t+1}$ and $I_{i,t}$ to zero yields

$$\mathbb{E}_t\left[\mathbb{M}_{t+1}\left(\frac{R^K_{i,t+1} + ((1-\delta) + G'_{i,t+1}\frac{I_{i,t+1}}{K_{i,t+1}} - G_{i,t+1})Q_{i,t+1}}{Q_{i,t}}\right)\right] = 1 \tag{C.18}$$

and

$$Q_{i,t} = \frac{1}{1 - G'_{i,t}}. \tag{C.19}$$

C.2 Social Planner Solution

In the competitive equilibrium, firms do not internalize the negative effect of their emissions on the environmental quality X. Consequently, $\phi_{i,t}$ and $\epsilon_{i,t}$ result to zero according to (C.6) and (C.7).

That is different in the social planner problem, where the shadow price of environmental quality, $\lambda_{X,t}A_t$, is accounted for, as if firms pay households a price of $\lambda_{X,t}A_t$ for every unit of environmental quality that they destroy. The social planner therefore optimizes the production sector according to

$$\begin{aligned}\max_{\{Y_t;Y_{i,t};L_{i,t};K_{i,t};T_{t+1};\mathcal{E}_{t+1};O_t;U_{t+1};N_t\}} \mathbb{E}_t\Bigg[\sum_{t=0}^{\infty}\mathbb{M}_t\Bigg(Y_t - \lambda_{X,t}A_t\left(\bar{X} - \frac{\bar{X}}{1+\kappa_{X,1}T_t^{\kappa_X,2}}\right)\\ - \sum_{i\in\{b,g\}}(R^K_{i,t}K_{i,t} - w_tL_{i,t}) - \mu^S_t(Y_t - p_{g,t}Y_{g,t} - p_{b,t}Y_{b,t})\\ - \lambda_{g,t}\left(Y_{g,t} - (A_tL_{g,t})^{1-\alpha}K^{\alpha}_{g,t}\right) - \lambda_{b,t}\left(Y_{b,t} - (A_tL_{b,t})^{1-\alpha}\left((1-\iota)K_{b,t}^{1-\frac{1}{o}} + \iota O_t^{1-\frac{1}{o}}\right)^{\frac{\alpha}{1-\frac{1}{o}}}\right)\\ + p_{o,t}\kappa_oU_t - R^K_{o,t}K_{o,t} - w_tL_{o,t} - \lambda_{o,t}(N_t - (A_tL_{o,t})^{1-\tau}K^{\tau}_{o,t}) - \phi_{o,t}(U_{t+1} - (1-\kappa_o)U_t - N_t)\\ - \phi^S_tA_t(\nu T_t + \chi\mathcal{E}_{t+1} + \sigma_TT_{t+1}\varepsilon^T_{t+1} - T_{t+1})\\ - \epsilon^S_tA_t\Big(\xi_b/A_tY_{b,t} + (1-\eta)\mathcal{E}_t - \mathcal{E}_{t+1}\Big)\Bigg)\Bigg].\end{aligned} \tag{C.20}$$

We obtain the first order condition with respect to $Y_{i,t}$, which (noting that $\mu^S_t = 1$) is

$$0 = p_{g,t} - \lambda_{g,t}, \tag{C.21}$$

$$0 = p_{b,t} - \lambda_{b,t} - \epsilon^S_t\xi_b, \tag{C.22}$$

as well as with respect to $\mathcal{E}_{t+1}$,

$$-\chi\phi_t^S A_t - (1-\eta)\mathbb{E}_t[\mathbb{M}_{t+1}\epsilon_{t+1}^S A_{t+1}] + \epsilon_t^S A_t = 0, \tag{C.23}$$

and T_{t+1}, which yields

$$-\mathbb{E}_t\left[\mathbb{M}_{t+1}\left(\lambda_{X,t+1}A_{t+1}X_{t+1}\frac{\kappa_{X,1}\kappa_{X,2}T_{t+1}^{\kappa_{X,2}-1}}{1+\kappa_{X,1}T_{t+1}^{\kappa_{X,2}}}\right)\right] - \nu\mathbb{E}_t[\mathbb{M}_{t+1}\phi_{t+1}^S A_{t+1}] + \phi_t^S A_t = 0. \tag{C.24}$$

The main difference to the first order conditions for the competitive equilibrium is that the shadow price of environmental quality is taken into account when computing the shadow cost of temperature. This price is, on the other hand, determined by the household's first order condition in the standard two-good problem, i.e.,

$$\lambda_{X,t} = \frac{\theta}{1-\theta}\left(\frac{A_t X_t}{C_t}\right)^{-\frac{1}{\rho}}. \tag{C.25}$$

C.3 Optimal Carbon Tax

Given the competitive equilibrium and the social planner solution, we obtain the optimal carbon tax as follows. In our model specification, we have $\epsilon_{b,t} \equiv 0$, which yields

$$p_{g,t} = \lambda_{g,t} \qquad \text{and} \qquad p_{b,t} = \lambda_{b,t} + \tau_t \tag{C.26}$$

in the competitive equilibrium and

$$p_{g,t} = \lambda_{g,t} \qquad \text{and} \qquad p_{b,t} = \lambda_{b,t} + \epsilon_t^S \xi_b \tag{C.27}$$

in the social planner solution, where the superscript S indicates the shadow cost of emissions computed based on the social planner problem. Therefore, for a carbon tax of $\tau_t^* = \epsilon_t^S \xi_b$, the social optimum is achieved in a competitive setting.

D Normalized Equilibrium Conditions

Since labor productivity is growing in our model, many other variables are also growing. Therefore, the variables need to be normalized before solving the model numerically. The purpose of this appendix is to describe the normalizations necessary and to supply the normalized equilibrium equations that are used in `dynare`.

We denote the normalized version of variable X_t by $\hat{X}_t$. The following list comprises the definitions of the normalized variables:

$$\hat{C}_t = \frac{C_t}{A_t};\ \ \hat{Y}_t = \frac{Y_t}{A_t};\ \ \hat{Y}_{g,t} = \frac{Y_{g,t}}{A_t};\ \ \hat{Y}_{b,t} = \frac{Y_{b,t}}{A_t};\ \ \hat{Z}_t = \frac{Z_t}{A_t};\ \ \hat{O}_t = \frac{O_t}{A_t};\ \ \hat{K}_{g,t} = \frac{K_{g,t}}{A_t}; \tag{D.1}$$

$$\hat{K}_{b,t} = \frac{K_{b,t}}{A_t};\ \ \hat{K}_{o,t} = \frac{K_{o,t}}{A_t};\ \ \hat{\omega}_t = \frac{\omega_t}{A_t};\ \ \Delta a_t = \ln\left(\frac{A_{t+1}}{A_t}\right);\ \ \hat{U}_t = \frac{U_t}{A_t};\ \ \hat{N}_t = \frac{N_t}{A_t}; \tag{D.2}$$

$$\hat{E}_t = \frac{E_t}{A_t};\ \ \hat{I}_{g,t} = \frac{I_{g,t}}{A_t};\ \ \hat{I}_{b,t} = \frac{I_{b,t}}{A_t};\ \ \hat{I}_{o,t} = \frac{I_{o,t}}{A_t};\ \ \hat{V}_t = \frac{V_t}{A_t};\ \ \hat{\mathbb{E}}_t[V_{t+1}^{1-\gamma}] = \frac{\mathbb{E}_t[V_{t+1}^{1-\gamma}]}{A_t^{1-\gamma}}. \tag{D.3}$$

The following variables do not need to be normalized:

$$\lambda_{g,t}; \lambda_{b,t}; \lambda_{o,t}; \lambda_{X,t}; X_t; L_{g,t}; L_{b,t}; L_{o,t}; p_{g,t}; p_{b,t}; p_{o,t}; R^K_{g,t}; R^K_{b,t}; R^K_{o,t}; \mathbb{M}_t; T_t; \mathcal{E}_t; \theta_t; \tau_t; \tag{D.4}$$

$$\phi_{g,t}; \phi_{b,t}; \phi^S_t; \epsilon_{g,t}; \epsilon_{b,t}; \epsilon^S_t; R_{g,t}; R_{b,t}; R_{o,t}; G_{g,t}; G_{b,t}; G_{o,t}; Q_{g,t}; Q_{b,t}; Q_{o,t}; R^f_t; R^M_t. \tag{D.5}$$

The normalized equilibrium conditions in the final goods sector are given by:

$$\hat{Y}_t = \left(\hat{Y}_{g,t}^{1-\frac{1}{\epsilon}} + \hat{Y}_{b,t}^{1-\frac{1}{\epsilon}}\right)^{\frac{1}{1-\frac{1}{\epsilon}}}, \tag{D.6}$$

$$\hat{Y}_{i,t} = p_{i,t}^{-\epsilon}\hat{Y}_t. \tag{D.7}$$

The normalized equilibrium conditions in the intermediate goods sectors (green and brown sector) are the following ones:

$$\Delta a_t = \mu_A + \sigma_A \varepsilon^A_t, \tag{D.8}$$

$$\hat{K}_{i,t+1}e^{\Delta a_{t+1}} = (1-\delta)\hat{K}_{i,t} + \hat{I}_{i,t} - G_{i,t}\hat{K}_{i,t}, \tag{D.9}$$

$$G_{i,t} = \frac{\hat{I}_{i,t}}{\hat{K}_{i,t}} - \left(a_{0,i} + \frac{a_{1,i}}{1-\frac{1}{\zeta}} \left(\frac{\hat{I}_{i,t}}{\hat{K}_{i,t}} \right)^{1-\frac{1}{\zeta}} \right), \tag{D.10}$$

$$\hat{Y}_{g,t} = L_{g,t}^{1-\alpha} \hat{K}_{g,t}^{\alpha}, \tag{D.11}$$

$$\hat{Y}_{b,t} = L_{b,t}^{1-\alpha} \hat{Z}_{t}^{\alpha}, \tag{D.12}$$

$$\hat{Z}_t = \left((1-\iota) \hat{K}_{b,t}^{1-\frac{1}{o}} + \iota \hat{O}_t^{1-\frac{1}{o}} \right)^{\frac{1}{1-\frac{1}{o}}}, \tag{D.13}$$

$$0 = p_{g,t} - \lambda_{g,t}, \tag{D.14}$$

$$0 = p_{b,t} - \tau_t - \lambda_{b,t} - \epsilon_{b,t}\xi_b, \tag{D.15}$$

$$0 = -\nu \mathbb{E}_t[\mathbb{M}_{t+1}\phi_{i,t+1}e^{\Delta a_{t+1}}] + \phi_{i,t}, \tag{D.16}$$

$$0 = -\chi\phi_{i,t} - (1-\eta)\mathbb{E}_t[\mathbb{M}_{t+1}\epsilon_{i,t+1}e^{\Delta a_{t+1}}] + \epsilon_{i,t}, \tag{D.17}$$

$$\hat{\omega}_t = \lambda_{i,t}(1-\alpha)\frac{\hat{Y}_{i,t}}{L_{i,t}}, \tag{D.18}$$

$$R_{g,t}^{K} = \lambda_{g,t}\alpha\frac{\hat{Y}_{g,t}}{\hat{K}_{g,t}}, \tag{D.19}$$

$$R_{b,t}^{K} = \lambda_{b,t}\alpha(1-\iota)\frac{\hat{Y}_{b,t}}{\hat{Z}_t^{1-\frac{1}{o}}\hat{K}_{b,t}^{\frac{1}{o}}}, \tag{D.20}$$

$$p_{o,t} = \lambda_{b,t}\alpha\iota\frac{\hat{Y}_{b,t}}{\hat{Z}_t^{1-\frac{1}{o}}\hat{O}_t^{\frac{1}{o}}}. \tag{D.21}$$

The oil sector's normalized equilibrium conditions are given by:

$$\hat{K}_{o,t+1}e^{\Delta a_{t+1}} = (1-\delta)\hat{K}_{o,t} + \hat{I}_{o,t} - G_{o,t}\hat{K}_{o,t}, \tag{D.22}$$

$$G_{o,t} = \frac{\hat{I}_{o,t}}{\hat{K}_{o,t}} - \left(a_{0,o} + \frac{a_{1,o}}{1-\frac{1}{\zeta}} \left(\frac{\hat{I}_{o,t}}{\hat{K}_{o,t}} \right)^{1-\frac{1}{\zeta}} \right), \tag{D.23}$$

$$\hat{U}_{t+1}e^{\Delta a_{t+1}} = (1-\kappa_o)\hat{U}_t + \hat{N}_t, \tag{D.24}$$

$$\hat{N}_t = L_{o,t}^{1-\tau}\hat{K}_{o,t}^{\tau}, \tag{D.25}$$

$$\hat{O}_t = \hat{E}_t, \tag{D.26}$$

$$\hat{E}_t = \kappa_o\hat{U}_t, \tag{D.27}$$

$$\lambda_{o,t} = \phi_{o,t}, \tag{D.28}$$

$$\hat{\omega}_t = \lambda_{o,t}(1-\tau)\frac{\hat{N}_t}{L_{o,t}}, \tag{D.29}$$

$$R^K_{o,t} = \lambda_{o,t}\tau\frac{\hat{N}_t}{\hat{K}_{o,t}}, \tag{D.30}$$

$$0 = \kappa_o \mathbb{E}_t[\mathbb{M}_{t+1}p_{o,t+1}] - \phi_{o,t} + (1-\kappa_o)\mathbb{E}_t[\mathbb{M}_{t+1}\phi_{o,t+1}]. \tag{D.31}$$

The asset pricing equations in normalized form look as follows:

$$1 = \mathbb{E}_t[\mathbb{M}_{t+1}R_{i,t+1}], \tag{D.32}$$

$$R_{i,t+1} = \frac{R^K_{i,t+1} + ((1-\delta) + G'_{i,t+1}\frac{\hat{I}_{i,t+1}}{\hat{K}_{i,t+1}} - G_{i,t+1})Q_{i,t+1}}{Q_{i,t}}, \tag{D.33}$$

$$Q_{i,t} = \frac{1}{1-G'_{i,t}}. \tag{D.34}$$

The other equations in normalized form look as follows:

$$\hat{V}_t = \left[(1-\beta)\hat{C}_t^{1-\frac{1}{\psi}} + \beta\left(\hat{\mathbb{E}}_t[V^{1-\gamma}_{t+1}]\right)^{\frac{1-\frac{1}{\psi}}{1-\gamma}}\right]^{\frac{1}{1-\frac{1}{\psi}}}, \tag{D.35}$$

$$\hat{\mathbb{E}}_t[V^{1-\gamma}_{t+1}] = \mathbb{E}_t[(\hat{V}_{t+1}e^{\Delta a_{t+1}})^{1-\gamma}], \tag{D.36}$$

$$\mathbb{M}_{t+1} = \beta\left(\frac{\hat{C}_{t+1}}{\hat{C}_t}e^{\Delta a_{t+1}}\right)^{-\frac{1}{\psi}}\left(\frac{\vartheta(X_{t+1}/\hat{C}_{t+1})}{\vartheta(X_t/\hat{C}_t)}\right)^{\frac{1}{\rho}-\frac{1}{\psi}}\left(\frac{\hat{V}_{t+1}e^{\Delta a_{t+1}}}{\left(\hat{\mathbb{E}}_t[V^{1-\gamma}_{t+1}]\right)^{\frac{1}{1-\gamma}}}\right)^{\frac{1}{\psi}-\gamma}, \tag{D.37}$$

$$1-\ell = L_{g,t} + L_{b,t} + L_{o,t}, \tag{D.38}$$

$$\hat{Y}_t = \hat{C}_t + \hat{I}_{g,t} + \hat{I}_{b,t} + \hat{I}_{o,t}, \tag{D.39}$$

$$\mathcal{E}_{t+1} = (1-\eta)\mathcal{E}_t + \xi_b\hat{Y}_{b,t}, \tag{D.40}$$

$$T_{t+1} = \nu T_t + \chi\mathcal{E}_{t+1} + \sigma_T T_{t+1}\varepsilon^T_{t+1}, \tag{D.41}$$

$$\tau_t = \theta_t\tau^*_t, \tag{D.42}$$

$$\tau^*_t = \epsilon^S_t\xi_b, \tag{D.43}$$

$$0 = -\chi\phi^S_t - (1-\eta)\mathbb{E}_t[\mathbb{M}_{t+1}\epsilon^S_{t+1}e^{\Delta a_{t+1}}] + \epsilon^S_t, \tag{D.44}$$

$$0 = -\mathbb{E}_t\left[\mathbb{M}_{t+1}\lambda_{X,t+1}X_{t+1}e^{\Delta a_{t+1}}\frac{\kappa_{x,1}\kappa_{x,2}T^{\kappa_{x,2}-1}_{t+1}}{1+\kappa_{x,1}T^{\kappa_{x,2}}_{t+1}}\right] - \nu\mathbb{E}_t[\mathbb{M}_{t+1}\phi^S_{t+1}e^{\Delta a_{t+1}}] + \phi^S_t, \tag{D.45}$$

$$X_t = \frac{\bar{X}}{1+\kappa_{x,1}T^{\kappa_{x,2}}_t}, \tag{D.46}$$

$$\lambda_{X,t} = \frac{\theta}{1-\theta}\left(\frac{X_t}{\hat{C}_t}\right)^{-\frac{1}{\rho}}, \tag{D.47}$$

$$\theta_{t+1} = (1-\rho_\theta)(1-\mu_\theta) + \rho_\theta\theta_t + \sigma_\theta\varepsilon^{\theta}_{t+1}. \tag{D.48}$$

E Measuring Climate Change Risk Awareness

The awareness of climate change and related risks seems to be higher today than ever. In the United States, the *Green New Deal* proposed in a letter with more than 600 signatory organizations has recently received considerable attention and support by the Democratic party. Internationally, movements such as *Fridays for Future*, in which more than 1 million school students go on strike for the climate, are not only very present in the media, but also receive backing by international scientists organized as *Scientists for Future*. A common demand of these initiatives is that fossil fuel extraction should be banned as soon as possible in order to achieve the transition to a clean energy world. While the aforementioned initiatives justifiably argue that the "current measures for protecting the climate and biosphere are deeply inadequate" (Hagedorn et al. 2019), a considerable number of countries and regions around the world have already taken first steps towards a world with cleaner energy in the last two decades: As of now, about 20% of worldwide greenhouse gas emissions are covered by a carbon price,[8] while this number was virtually 0% in the year 2000. The number and stringency of other environmental regulations has also increased quite continuously over the last two decades according to measures such as the environmental policy stringency measure provided by the OECD.[9]

Papers analyzing the performance of brown and green stocks typically focus on sample periods that roughly coincide with these developments. Bolton and Kacperczyk (2021) consider the period from 2005 to 2017, and Pastor, Stambaugh, and Taylor (2022) focus on the years 2013–2020. Görgen

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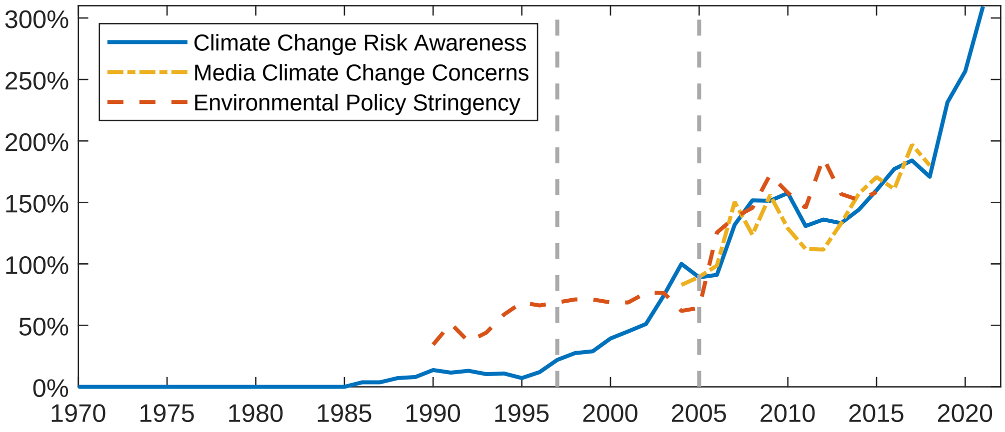
[8] This includes fixed carbon taxes as well as price-flexible emission trading systems, see World Bank (2019).

[9] The Environmental Policy Stringency Index assigns a score to each country for the "degree to which environmental policies put an explicit or implicit price on polluting or environmentally harmful behaviour" (see `https://stats.oecd.org/Index.aspx?DataSetCode=EPS`). The highest degree of stringency corresponds to a score of 6, and a score of 0 describes the lowest stringency. The index is a weighted average of scores achieved in different categories, such as the use of market-based instruments like emissions trading and non-market instruments like R&D subsidies for renewables, as detailed by Botta and Koźluk (2014).

Figure E.1: Climate Change Risk Awareness Index and other measures of climate change concerns. The Climate Change Risk Awareness Index (CCRAI) is constructed based on the number of occurrences of the term *climate change risk* in the literature and in search volumes on Google. The Environmental Policy Stringency Index for the United States is provided by the OECD from 1990 to 2005, and the Media Climate Change Concerns measure is computed and provided by Ardia et al. (2021). The first gray dashed line marks the adoption of the Kyoto Protocol in December 1997, the second one marks February 2005, which is when the Protocol came into force.



et al. (2020) have a sample period from 2010 to 2017, and the earlier paper by In, Park, and Monk (2018) considers the time from 2005 to 2015.

Instead of choosing a pre-specified time period that defines the beginning of the climate transition, we construct a simple CCRAI that provides us with a measure for the awareness of climate change risks. To do so, we combine data on occurrences of the term *climate change risk* in the literature from Google Ngram with search volumes data on the same term provided by Google Trends. The Google Ngram data are available on a yearly basis from 1970 to 2008, while monthly data on search volumes are provided starting in 2004. We aggregate the monthly Google Trends data to an annual frequency, and construct 5-year leading moving averages for the Google Ngram data. Finally, we combine the two resulting time series by normalizing their value in 2004 to 100%.

Figure E.1 plots our climate risk awareness index over time. We observe a substantial and continuous increase of awareness which started in the second half of the 1990s and continues until today. The suggested start of the climate transition also coincides with the adoption of the Kyoto Protocol in 1997. We furthermore compare our measure to the Media Climate Change Concerns index from Ardia et al. (2021), which is computed based on a textual analysis of U.S. newspaper articles, and to the environmental policy stringency in the U.S. as provided by the OECD. Our climate change risk awareness index correlates quite strongly with the measure from Ardia et al. (2021) during the period of its availability, confirming the validity of our approach. In addition, the environmental policy stringency index shows that the general trend in the awareness for climate change is also reflected by the policy-makers' side.