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

Michael Donadelli* Patrick Grüning† Steffen Hitzemann‡

January 2025

Abstract

This paper proposes a macro-finance model 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 premia based on stock returns realized since the start of the transition. In contrast, one can very well pin down since when and by how much firm 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 40% since the year 2000 with the proceeding climate transition.

Keywords: climate change, carbon premia, policy risk, macro-finance, oil firms
JEL: E2, E3, G12, Q43

---

*Department of Economics and Management, University of Brescia, and Research Center SAFE, Goethe University Frankfurt. Mailing address: Via S. Faustino 74/b, 25122, Brescia, Italy. E-mail: `michael.donadelli@unibs.it`.

†Research Division, Monetary Policy Department, Bank of Latvia. Mailing address: K. Valdemāra iela 2A, LV-1050 Riga, Latvia. E-mail: `Patrick.Gruening@bank.lv`.

‡Bauer College of Business, University of Houston. Mailing address: 4250 Martin Luther King Blvd, Houston, TX 77204, United States. E-mail: `hitzemann@bauer.uh.edu`.

Previously circulated as: *Understanding Macro and Asset Price Dynamics During the Climate Transition.* We would like to thank Lauren Cohen, Robert Engle, Diego Garcia (discussant), Mathias Kruttli (discussant), Valerio Nispi Landi (discussant), Delphine Lautier (discussant), Sean Myers, Julien Penasse, Rick van der Ploeg, Luca Taschini, Julian Thimme, Nicolas Treich (discussant), Chi-Yang Tsou (discussant), Gauthier Vermandel (discussant), as well as participants of the Central Bank Research Association Annual Meeting, Commodity and Energy Markets Association Annual Meeting at Carnegie Mellon, Financial Management Association Annual Meeting, Global Research Alliance for Sustainable Finance and Investment Annual Conference, J.P. Morgan Center New Directions In Commodities Research Symposium, LTI@UniTO/Bank of Italy Workshop on Long-term investors' trends, Toulouse Conference on the Economics of Energy and Climate, and of several other events for their helpful comments and suggestions. We gratefully acknowledge research and financial support from the Research Center SAFE, funded by the State of Hessen initiative for research LOEWE. The views expressed herein are solely those of the authors and do not necessarily reflect the views of the Bank of Latvia or the Eurosystem.

1 Introduction

Scientists, business leaders, and policy-makers worldwide predict, with very few exceptions, 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 an unprecedented challenge for the world 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 vibrantly 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 realized returns observed 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 biased point 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

Paper	Period	Scope	Brown−Green Returns
In et al. (2019)	2005–2015	US	negative
Görgen et al. (2020)	2010–2017	international	insignificant
Bolton and Kacperczyk (2021)	2005–2017	US	positive
Bauer et al. (2022)	2010–2021	international	negative
Pastor et al. (2022)	2012–2020	US	negative
Bolton and Kacperczyk (2023)	2005–2018	international	positive
Aswani et al. (2024)	2005–2019	US	insignificant
Zhang (2025)	2009–2021	international	negative (US) insignificant (global)

This table summarizes recent papers which compute the difference in realized equity returns between brown and green firms and statistically determine whether average brown-minus-green returns 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 (or "E scores" in the case of Pastor et al. 2022), while we do not list papers that use other criteria such as general ESG scores.

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 for 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 carbon-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

---

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

climate policy shocks on the stochastic discount factor depends on the effect on current consumption 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, all agents (including the policy-maker) 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.[2] 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, for instance resulting from a different riskiness of capital investments in the two sectors due to differential adjustment costs. 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 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 in the median scenario, and carbon emis-

---

[2] We choose the year 1995 as a cut-off date for the pre-transition period since widespread awareness for climate change issues was created with the adoption of the Kyoto Protocol in 1997. Indeed, we show based on a Climate Change Risk Awareness Index (CCRAI) in Section 4.3 and Appendix E that the trend of steadily increasing awareness for climate change started after 1995.

sions reaching their peak around the year 2050. Aggregate output, consumption, and investment fall in the long run 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 combination of 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 simulated economies even if the actual carbon premium is the same. For a climate policy risk premium of 2.31% per year, which we can directly observe in the model environment, the outcomes for average realized brown-minus-green returns range from -7.75% to 6.84% in different simulated 15-year samples. One substantial source of variation is the start of the sample, since starting early in the transition includes a significant devaluation of the brown sector, resulting in large negative realized returns which are, however, not representative of (ex-ante) risk premia. If the initial steep drop is not included, the average brown-minus-green return in the median economy is 2.80% 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 6.84% carbon return observed in the 90% 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 2.31%, which further highlights the possibility of false conclusions.

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.[3] 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 impact on firm valuations, resulting from the combined cash flow and risk premium effects. The start of the climate transition is marked by a disconnect between current cash flows and firm valuations, which is most notably and directly observable in the oil (fossil-fuel-producing) sector as a divergence between firm valuations and oil prices. While oil firm valuations and oil prices move in tandem otherwise, our model-based analysis predicts that they strongly disconnect in the beginning of the climate transition.

We bring our model insights to application and empirically examine equity returns and valuations in the oil (and general fossil-fuel-producing) sector. Analyzing oil firms in particular has the advantage that one avoids classification issues regarding the brown- and green-ness of different firms, as there is no doubt that the oil sector is clearly negatively impacted by increasing climate regulations (van Benthem et al., 2022). 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 different 15-year sample periods can be clearly 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 divergence of oil firm valuations from oil prices, the main driver of short-term cash flows in this sector. We clearly observe such divergence in the data during the 2000s, since when oil firms have lost around 40% in their relative valuations and disconnected from oil prices. This novel empirical fact thus confirms the specific dynamics predicted by our model for the beginning of the climate transition. Moreover, we provide additional support for the climate transition channel by showing that the oil firms' devaluation indeed coincides with the increase in climate change risk awareness and that it is less pronounced for firms that are less exposed to climate transition risk. We also show that the devaluation of fossil fuel firms with the proceeding climate transition is clearly reflected across different valuation measures (market-to-

---

[3] 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.

book ratios, Tobin's q, Peters and Taylor 2017 total q) and when defining the fossil fuel sector more broadly, beyond oil firms.

Literature Our paper contributes to a fast-growing literature on the effects of climate change on the macroeconomy and on asset prices. A large number of papers considers the exposure of equities to climate change risks and analyzes related risk premia. While some studies investigate the pricing of physical climate risk (Balvers et al., 2017; Bansal et al., 2017), a great focus is on climate policy risk and the question whether green or brown firms exhibit larger returns. As revealed by Table 1, the current state of this literature can be best summarized as inconclusive, with different studies finding negative, positive, or insignificant carbon returns over different sample periods and using different methodologies. We show based on our macro-finance model that a variety of different outcomes is expected when considering brown-minus-green returns over relatively short sample periods. Therefore, it is difficult to reliably identify carbon premia from realized returns even when abstracting from additional methodological issues as highlighted by Aswani et al. (2024) or Zhang (2025). Our insights also partly translate to a similar and related debate on the stock returns of firms with low and high sustainability (ESG) ratings (Alves et al., 2024; Lindsey et al., 2024), as carbon emissions are an important component of ESG scores (Berg et al., 2022).[4]

The quantitative macro-finance model for the climate transition presented in this paper builds on advances in the macroeconomics literature on the economic effects of climate change. General equilibrium models, such as the integrated assessment models developed by Nordhaus (1992, 1993, 2008), are used 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 to characterize the optimal environmental policy. Golosov et al. (2014), Cai et al. (2019), and Hambel et al. (2021) build DSGE models that allow to compute the social cost of carbon under uncertainty with different types of modeling assumptions. We extend these approaches by providing a model that reproduces

---

[4] A consequence of our findings is that researchers should give more weight to alternative approaches for identifying risk premia as opposed to the analysis of realized returns. For example, Engle et al. (2020) construct climate change hedging portfolios using a dynamic approach based on climate change news, which could be used to quantify risk premia through the cost of hedging. Gormsen et al. (2023) consider firms' perceived cost of capital as articulated in corporate conference calls, and Giglio et al. (2025) analyze retail investor expectations based on a survey. Eskildsen et al. (2024) evaluate a number of different approaches, including forward-looking stock returns constructed from option prices.

not only macroeconomic and climate change variables, but also explains asset prices in the spirit of the macro-finance literature (e.g., Jermann, 1998; Croce, 2014; Favilukis and Lin, 2016). As such, our framework particularly allows us to analyze the effects of climate policy risk on equity returns and valuations of brown and green firms. Based on simulated samples from our model, we show that it is difficult to properly identify carbon premia by evaluating realized returns, while it is possible to capture the climate transition's impact on firm valuations that results from the combination of cash flow and discount rate effects.

Moreover, by applying the model insights to the stock returns and valuations of oil firms, we contribute to the strand of research investigating the effects of the climate transition on energy firms. As van Benthem et al. (2022) highlight, "[c]ompanies in the energy sector are uniquely affected by this change in financial markets. Oil and gas firms and fossil fuel-based power generators are a major source of carbon emissions, and thus directly exposed to transition risks as policymakers guide the economy towards net-zero targets." Against this background, it is surprising that we are the first to analyze carbon returns and risk premia through the lens of oil firms. While Barnett (2024) focuses on oil price and production dynamics under climate policy uncertainty, Bogmans et al. (2024) examine oil and gas firms' investments, which have significantly declined as a consequence of climate policies and related uncertainty according to their results. We are able to identify a significant drop in relative oil firm valuations and a decoupling from the oil price in the 2000s. Such decline in valuations explains and leads to lower investment in those firms according to q theory, as predicted by our model. Our findings are also consistent with a recent paper by Acharya et al. (2024), who analyze the effects of different types of transition risk on the energy sector in a two-period general equilibrium model.

2 A Macro-Finance 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 impact on environmental quality and household utility.

This effect gives rise to a negative climate externality, which the brown firms do not internalize in a competitive setting. The regulator therefore introduces a carbon tax, and we assume that the implemented tax can deviate from its socially optimal level, to which it slowly converges. The dynamics of the carbon tax drive 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 derive utility from a constant elasticity of substitution (CES) bundle that is composed of a consumption-leisure aggregate $\widetilde{C}_t$ and of environmental quality X_t:

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

Here, θ is the weight of environmental quality in the bundle and φ determines the elasticity of substitution between the consumption-leisure aggregate and environmental quality. Environmental quality is furthermore weighted by productivity A_t to ensure balanced growth in the model, which can be interpreted as an adjustment for the standard of living. The aggregate of consumption C_t and leisure l_t is, as usual, also defined as a CES function,

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

with leisure weight ν and an elasticity of substitution η. 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 discount factor β, risk aversion γ, and intertemporal elasticity of 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),

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

as a CES aggregate with parameter ε. We furthermore introduce a scaling parameter $\bar{A}$ to make model outputs (levels) comparable to empirical figures.

For the production of intermediate goods, 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 CES aggregate of physical capital $K_{b,t}$ and oil O_t,

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

The parameter ι specifies the share of oil in this CES aggregate, and o is the elasticity of substitution parameter. Fossil fuel O_t is produced by the oil sector, which is described in detail below.

Emissions, temperature, and the environment By burning fossil fuels, firms in the brown sector emit greenhouse gases when producing goods. Therefore, the production of the brown firms increases the level of greenhouse gases in the atmosphere, which evolves as

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

In these dynamics, $\rho_{\mathcal{E}}$ 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. 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, and to guarantee balanced growth in the model.

Green firms have a lower emissions intensity than brown firms, and in fact, we assume for simplicity that they do not emit any greenhouse gases.

Global temperature levels are affected by greenhouse gas emissions according to the following dynamics:

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

Here, χ is the climate sensitivity to emissions and ρ_T is the cooling rate similar to Bansal et al. (2017) and Cai et al. (2019). We also incorporate weather shocks ε^T_{t+1} with volatility σ_T 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 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 in the model.

Carbon tax To address this climate change externality, the regulator introduces a tax of $A_t\tau_t$ per unit of greenhouse gas emissions, which increases by default with the economy's standard of living. We allow the implemented tax level τ_t to deviate from the socially optimal tax level τ_t^*,

$$\tau_t = \Theta_t\tau_t^*, \tag{10}$$

driven by the extent of environmental regulation Θ_t. Appendix A.2 formally derives the socially optimal tax level τ_t^* based on the social planner's solution. The stringency of environmental regulation is governed by the process

$$\Theta_{t+1} = (1-\rho_\Theta)(1-\mu_\Theta) + \rho_\Theta \Theta_t + \sigma_\Theta \varepsilon^\Theta_{t+1}. \tag{11}$$

Implemented carbon taxes are therefore affected by climate policy shocks ε^Θ_{t+1}, with volatility σ_Θ, which 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 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

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

with parameter α_o. 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 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 is the capital depreciation rate and $G_{i,t}$ is a Jermann (1998) adjustment cost function of the form $G_{i,t}(I_{i,t}/K_{i,t}) = I_{i,t}/K_{i,t} - \left(a_{0,i} + \frac{a_{1,i}}{1-1/\zeta_i}\left(I_{i,t}/K_{i,t}\right)^{1-1/\zeta_i}\right)$, with sector-specific parameter ζ_i.[5]

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

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

where $\widetilde{w}_t$ is the competitive wage and $\bar{L}_i = \varsigma L_i$ is the amount of labor that does not pay the competitive wage (determined as a fraction ς of the steady state labor demand). 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 productivity A_t of the economy and its long-run trend z_t follow the processes

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

$$z_{t+1} = \rho_z z_t + \sigma_z \varepsilon^z_{t+1}, \tag{18}$$

as in Croce (2014), where μ_A is the average productivity growth rate and ε^A_{t+1} are shocks affecting the level of productivity with volatility σ_A. The trend component z_t has a persistence of ρ_z and is subject to long-run growth shocks ε^z_{t+1} with volatility σ_z. All shocks in our model are i.i.d. standard normal random variables.

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

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

---

[5] As usual, the parameters $a_{0,i}$ and $a_{1,i}$ are set in such way that adjustment costs and their first derivative are zero in the model's steady state.

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

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

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

respectively, 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. The oil firm maximizes

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

and takes the oil price $p_{o,t}$, the rental rate of capital $R^K_{o,t}$, and the labor wages w_t as given. Finally, the capital producers in each sector ($i \in \{b, g, o\}$) maximize

$$\mathbb{E}_t\left[\sum_{t=0}^{\infty}\mathbb{M}_t D^K_{i,t}\right], \quad \text{with} \quad D^K_{i,t} = R^K_{i,t}K_{i,t} - I_{i,t}, \tag{23}$$

taking the capital rental rates $R^K_{i,t}$ as given.

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

$$l_t = 1 - L_{b,t} - L_{g,t} - L_{o,t}, \tag{24}$$

$$Y_t = C_t + I_{b,t} + I_{g,t} + I_{o,t} + \mathcal{G}_t. \tag{25}$$

In the former equation, available hours are normalized to 1, and in the latter equation, we account for government consumption $\mathcal{G}_t = \bar{g}Y_t$ as a fixed share $\bar{g}$ of output. Government consumption has no role in our model other than reducing the amount of output that is used for household consumption or investment.

2.2 Equilibrium

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

$$\mathbb{M}_{t+1} = \beta \left(\frac{C_{t+1}}{C_t}\right)^{-\frac{1}{\eta}} \left(\frac{\widetilde{C}_{t+1}}{\widetilde{C}_t}\right)^{\frac{1}{\eta}-\frac{1}{\varphi}} \left(\frac{\vartheta(A_{t+1}X_{t+1}, \widetilde{C}_{t+1})}{\vartheta(A_t X_t, \widetilde{C}_t)}\right)^{\frac{1}{\varphi}-\frac{1}{\psi}} \left(\frac{V_{t+1}}{\mathbb{E}_t\left[V_{t+1}^{1-\gamma}\right]^{\frac{1}{1-\gamma}}}\right)^{\frac{1}{\psi}-\gamma}, \tag{26}$$

where

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

the household's condition yields that the Euler equation

$$\mathbb{E}_t\left[\mathbb{M}_{t+1} R_{t+1}\right] = 1 \tag{27}$$

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,

$$(1-\nu) C_t^{\frac{1}{\eta}} = \nu \widetilde{w}_t l_t^{\frac{1}{\eta}}. \tag{28}$$

On the firms' side, we obtain that the Euler equation (27) holds for the capital returns in the three sectors ($i \in \{b, g, o\}$),

$$R^k_{i,t+1} = \frac{R^K_{i,t+1} + ((1-\delta) + G'_{i,t+1} \cdot I_{i,t+1}/K_{i,t+1} - G_{i,t+1}) Q_{i,t+1}}{Q_{i,t}}, \tag{29}$$

with the marginal products of capital $R^K_{i,t}$ as well as $Q_{i,t}$, the marginal Tobin's q of each sector, given by

$$R^K_{g,t} = \alpha p_{g,t} \frac{Y_{g,t}}{K_{g,t}}, \quad R^K_{b,t} = \alpha(1-\iota)(p_{b,t} - \tau_t \xi_b) \frac{Y_{b,t}}{Z_t^{1-\frac{1}{o}} K_{b,t}^{\frac{1}{o}}}, \quad R^K_{o,t} = \alpha_o \lambda_{o,t} \frac{N_t}{K_{o,t}}, \quad Q_{i,t} = \frac{1}{1-G'_{i,t}}. \tag{30}$$

The state variable $\lambda_{o,t}$ is a Lagrange multiplier attached to the production for new oil wells in the oil firm's problem (see Appendix A.1 for details).

The wage equations are given by

$$\widetilde{w}_t = (1-\alpha)p_{g,t}\frac{Y_{g,t}}{L_{g,t}} = (1-\alpha)(p_{b,t} - \tau_t\xi_b)\frac{Y_{b,t}}{L_{b,t}} = (1-\alpha_o)\lambda_{o,t}\frac{N_t}{L_{o,t}}. \tag{31}$$

Additionally, the oil price $p_{o,t}$ satisfies the condition

$$p_{o,t} = \alpha\iota(p_{b,t} - \tau_t\xi_b)\frac{Y_{b,t}}{Z_t^{1-\frac{1}{o}} O_t^{\frac{1}{o}}}, \tag{32}$$

as implied by the brown firm's optimization problem, and the intermediate goods prices $p_{i,t}$ fulfill the condition

$$Y_{i,t} = p_{i,t}^{-\varepsilon}\bar{A}^{\varepsilon-1}Y_t. \tag{33}$$

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

$$\tau_t^* = \epsilon_t^S, \tag{34}$$

where ϵ_t^S is a Lagrange multiplier describing the shadow cost of an additional unit of emissions, as defined in Appendix A.2.

The (unlevered) sectoral equity returns in our model differ from the capital returns (29), as wages deviate from the marginal product of labor due to wage rigidities. Sectoral equity returns for $i \in \{b, g, o\}$ are obtained by solving recursively for the firm value $\mathcal{V}_{i,t} = D_{i,t}^{aggr} + \mathbb{E}_t[\mathbb{M}_{t+1}\mathcal{V}_{i,t+1}]$, with aggregate sectoral dividends $D_{i,t}^{aggr}$, and computing $R_{i,t} = \mathcal{V}_{i,t}/(\mathcal{V}_{i,t-1} - D_{i,t-1}^{aggr})$. The aggregate dividends of a sector are given by the sum of the intermediate goods or oil producer's dividends and the capital producer's dividends, $D_{i,t}^{aggr} = D_{i,t} + D_{i,t}^K$, which are each defined in equations (20), (21), (22), and (23). The (unlevered) market return $R_{m,t}$ is obtained analogously for aggregate dividends $D_{m,t} = D_{b,t}^{aggr} + D_{g,t}^{aggr} + D_{o,t}^{aggr}$, and the return $R_{m\backslash o,t}$ without the oil sector is obtained for $D_{m\backslash o,t} = D_{b,t}^{aggr} + D_{g,t}^{aggr}$.

With these conditions and 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 et al.

(2018), which allows us to compute unconditional moments and impulse response functions in closed form.

We furthermore compute the risk-free rate and the levered equity excess returns for the different sectors and the market based on the model solution, as defined by the equations

$$R_t^f = \frac{1}{\mathbb{E}_t[\mathbb{M}_{t+1}]}, \tag{35}$$

$$R_{i,ex,t}^{LEV} = (1 + \overline{DE})(R_{i,t} - R_{t-1}^f), \quad i = b, g, o, m. \tag{36}$$

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. Finally, we explicitly distinguish between returns and risk premia in our analysis of the climate transition, with risk premia being defined as ex-ante expected excess returns,

$$RP_{i,t} = \mathbb{E}_t[R_{i,ex,t+1}^{LEV}], \quad i = b, g, o, m. \tag{37}$$

Under a second-order approximation, risk premia do not vary over time, such that the risk premium at any given point in time is equal to the unconditional risk premium.

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 captured 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 a pre-transition state towards the full model equilibrium, with the carbon tax slowly converging to its optimal level. We analyze the detailed dynamics of macroeconomic quantities and asset prices over the transition in Section 3.4, with a particular focus on brown-minus-green returns, risk premia, and firm valuations. Section 3.5 summarizes the main implications of our results and highlights implications for empirical research.

3.1 Calibration

We explain our parameter choices and report all parameters as annualized values. The preference parameters of our model are set 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 intertemporal elasticity of 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 to match 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 φ between environmental quality and the consumption-leisure bundle to 0.4, making them complements rather than substitutes. While there is no clear guidance in the literature for the precise value of these two parameters, our results in Sections 3.4 and 4.2 demonstrate that the chosen values allow us to reproduce realistic asset price dynamics during 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 and the green intermediate goods sector, and set it to 0.21 to reproduce the investment-output ratio in the model. Capital adjustment costs ζ_i are chosen to produce and match the variation in equity premia across the different sectors in the pre-transition state (see Section 3.3), 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. The average ratio of government consumption to output in the pre-transition period is 21.68%, and we therefore set $\bar{g}$ precisely to 0.2168, close to the value of 0.2 proposed by Sims and Wu (2021).

Regarding the labor market, the leisure share ν in households' utility is calibrated such that the model matches the average work hours of a full-time worker in the U.S. (equal to 21.58% of overall hours), and the elasticity of substitution between consumption and labor η is set to 0.7, following Croce et al. (2021). The wage rigidity parameter ς is chosen to be 5/6, such that one sixth of the wage rate is adjusted to the competitive wage immediately, while the remainder is a moving average

Table 2: Preference and production parameters

Parameter	Symbol	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	φ	0.4
	Labor market	
Leisure share in consumption-leisure bundle	ν	0.1397
Elasticity of substitution between consumption and leisure	η	0.7
Wage rigidity parameter	ς	5/6
	Goods production	
Depreciation rate of capital	δ	0.06
Sectoral 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
Final goods output scaling factor	$\bar{A}$	1.083
Average productivity growth rate	μ_A	0.02
Volatility of productivity growth	σ_A	0.05
Persistence of long-run growth rate	ρ_z	0.8
Volatility of long-run growth rate	σ_z	$0.035\sigma_A$
	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	α_o	0.4
Oil extraction rate	κ_o	0.08
	Government	
Government consumption to output ratio	$\bar{g}$	0.2168

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

of the previous wage rates. Finally, the average growth rate of productivity and its volatility, μ_A 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 persistence parameter ρ_z of the long-run growth rate is set to 0.8 following Croce (2014), and its volatility is 3.5% of the short-term

Table 3: Emissions, temperature, and carbon tax parameters

Parameter	Symbol	Value
Emissions and temperature		
Emissions intensity of brown sector	ξ_b	3.309
Environmental quality level at pre-industrial temperatures	$\bar{X}$	0.1
Temperature sensitivity of environmental quality (scale parameter)	$\kappa_{X,1}$	0.075
Temperature sensitivity of environmental quality (power parameter)	$\kappa_{X,2}$	2
Cooling rate	ρ_T	0.038
Atmosphere recovery rate	$\rho_{\mathcal{E}}$	0.0021
Climate sensitivity to emissions	χ	0.004
Volatility of temperature shocks	σ_T	0.005
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	0.14
Correlation between carbon tax shocks and long-run growth shocks	$\varrho_{\Theta,z}$	$(-0.45, -0.05)$

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

volatility σ_A, consistent with the literature and generating a large 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). The oil share ι is set to 0.06 to generate a realistic magnitude of the oil sector. Oil is produced from wells with an extraction rate κ_o of 8% per year, also as in Gao et al. (2022), and a capital share α_o in oil wells production of 0.4. Second, the brown sector generates greenhouse gas emissions as part of the production process, and a value of $\xi_b = 3.309$ corresponds to the U.S. emissions intensity in 1995 (measured in billion tons of carbon per trillion U.S. dollars), the year in which we initialize the model's pre-transition state. Third, we assume that environmental quality is affected by temperatures above pre-industrial levels as specified by the parameters $\kappa_{X,1} = 0.075$ and $\kappa_{X,2} = 2$. These parameter choices are motivated by the results in Nordhaus (1992). Moreover, the level of environmental quality at pre-industrial temperatures is set to $\bar{X} = 0.1$.

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 $\rho_T = 0.038$ (see Bansal et al., 2017; Cai et al., 2019), the atmosphere recovery rate is $\rho_{\mathcal{E}} = 0.0021$ (Reilly and Richards, 1993), and the climate sensitivity to emissions is $\chi = 0.004$. We set the volatility of temperature shocks σ_T to 0.005 in line with the volatility of the annual global temperature anomaly. Finally, we assume that policy-makers set the carbon tax to the theoretically optimal level in the long-run equilibrium of the model, implying $\mu_\Theta = 0$. Recall that our analysis focuses on the transition of the model towards this long-run equilibrium, with a tax persistence of $\rho_\Theta = 0.95$ and a policy volatility of $\sigma_\Theta = 0.14$.[6] For our simulation of the climate transition in Section 3.4, we furthermore introduce a negative correlation $\varrho_{\Theta,z}$ between carbon tax shocks and long-run growth shocks (-0.45 in the benchmark calibration and -0.05 in an alternative scenario), which we discuss at the end of the next section. The parameters related to the dynamics of emissions, temperatures, 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 $\varepsilon^{\Theta}_{t+1}$. 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 equation (21), leading to a negative effect on brown sector equity returns (see also equation (30)). The tax burden on the brown sector also induces a greater demand for green sector capital, yielding a positive impact on the green sector's equity return. Thus, the returns of green firms increase and the returns of brown firms decline when a

---

[6] The carbon tax in our model is understood as an aggregate of different measures disincentivizing carbon emissions, including emissions trading and command-and-control measures. While the volatility of emission permit prices is typically comparable to that of stocks (see Hitzemann and Uhrig-Homburg, 2018), the volatility of other measures is naturally lower (see Goulder and Schein, 2013), suggesting that the annual carbon pricing volatility is in the range of 10–20%.

positive climate policy shock materializes, in line with intuition. The effect of climate policy shocks on the pricing kernel is more ambiguous and can be well understood based on equation (26). 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.

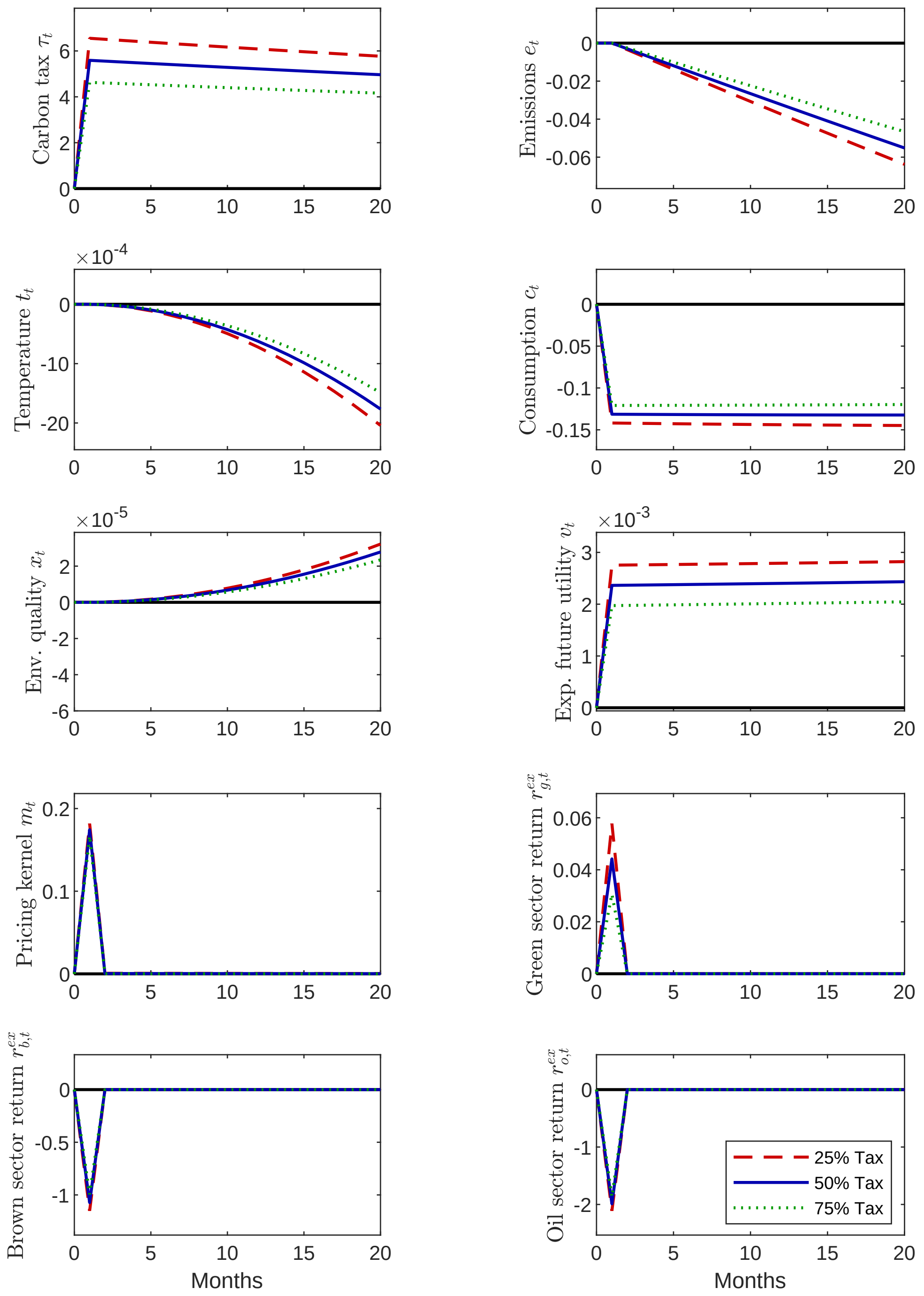
We therefore demonstrate and analyze the precise effects of carbon tax shocks in the calibrated model by means of impulse response functions (see Figure 1). Importantly, we consider the impulse response functions at states where the tax is at 25%, 50%, or 75% of its optimal level, which is representative of the climate transition period.[7] 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. Importantly, 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 and environmental quality 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 et al. (2021) who do, however, not consider climate policy shocks in a general equlibrium sense. Moreover, our result alleviates the theoretical result by Roth Tran (2019) and Baker et al. (2022) 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 in the next sections, we also introduce an exogenously negative correlation between the carbon tax shocks $\varepsilon_{t+1}^{\Theta}$ and long-run economic growth shocks ε_{t+1}^{z}.

---

[7] 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 et al. (2018) allows us to compute conditional impulse functions around such states of the economy.

Figure 1: Impact of carbon tax shocks on climate, economy, and asset prices



This figure depicts the impact of carbon tax shocks on the climate, economy, and asset prices. Conditional impulse response functions are computed for three states of the carbon tax level: 25%, 50%, and 75% of the optimal carbon tax. Lowercase letters refer to log variables, and the impulse responses are plotted as percentage deviations from the given state in response to a positive one-standard-deviation tax shock materializing at $t = 1$.

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 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 a 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 *perceived* χ is zero for all agents (including the policy-maker), 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 agents perceive the shadow costs of emissions to be zero (see Appendix A.2 and A.3). Furthermore, the temperature anomaly specified by the dynamics (8) is not endogenous anymore from the agents' perspective, but perceived as an exogenous process.

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 does a good job reproducing the size of the different sectors in the economy in terms of output, as well as the overall investment-output ratio. Moreover, it is calibrated to match the average output growth rate and also does reasonably well explaining the volatilities of output, consumption, and investment growth.[8] When it comes to asset prices, the model produces both a low average risk-free rate and high equity premia. As in the data, equity premia differ across the different sectors, which is achieved by calibrating the sectoral adjustment costs accordingly. Remarkably, the model produces

---

[8] While the volatility of consumption growth produced by our model is about 1% higher than in the data, it is also known that the data moment understates the true volatility due to the filtering process applied by the Bureau of Economic Analysis (see Kroencke, 2017).

high equity volatilities through a combination of adjustment costs, wage rigidities, and a non-fundamental volatility component.

Second, we evaluate realized returns of brown-minus-green equity portfolios in the pre-transition economy. Since 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. The moments in Table 4 already indicate that

Table 4: Data and model moments

Moment		Data	Model
	Size of different sectors		
Investment-output ratio	$\mathbb{E}[I/Y]$	15.06	13.89
Brown sector output share	$\mathbb{E}[p_bY_b/Y]$	20.99	24.24
Green sector output share	$\mathbb{E}[p_gY_g/Y]$	76.86	71.55
Oil sector output share	$\mathbb{E}[p_oO/Y]$	2.16	4.20
	Economic growth and volatilities		
Output growth rate	$\mathbb{E}[\Delta y]$	2.29	1.96
Output growth volatility	$\sigma(\Delta y)$	5.81	5.05
Consumption growth volatility	$\sigma(\Delta c)$	3.74	4.70
Investment growth volatility	$\sigma(\Delta i)$	5.86	6.68
	Risk-free rate and equity premia		
Risk-free rate	$\mathbb{E}[r_f]$	0.51	0.45
Market equity premium	$\mathbb{E}[r^{LEV}_{m,ex}]$	8.49	8.57
Brown sector equity premium	$\mathbb{E}[r^{LEV}_{b,ex}]$	10.19	10.49
Green sector equity premium	$\mathbb{E}[r^{LEV}_{g,ex}]$	9.63	9.69
Oil sector equity premium	$\mathbb{E}[r^{LEV}_{o,ex}]$	6.71	3.58
	Equity volatilities		
Market equity volatility	$\sigma(r^{LEV}_{m,ex})$	21.10	15.82
Brown sector equity volatility	$\sigma(r^{LEV}_{b,ex})$	23.38	17.67
Green sector equity volatility	$\sigma(r^{LEV}_{g,ex})$	26.28	16.99
Oil sector equity volatility	$\sigma(r^{LEV}_{o,ex})$	29.07	11.00

This table reports empirical and model-based macroeconomic and asset price moments for the pre-transition economy. Empirical moments are calculated based on U.S. macroeconomic and asset price data for the period 1927–1995. Details on the construction of sectoral shares are provided in Appendix C. Model moments are computed using 1,000 simulations for 69 years, matching the length of the data sample. The model is simulated at a monthly frequency, and all moments are annualized. Lowercase letters refer to log variables.

Table 5: Simulated brown-minus-green returns and risk premia before the climate transition

Panel A: Benchmark Calibration

	10%	Median	90%
Brown-minus-green returns	0.41% [0.07]	0.79% [0.00]	1.21% [0.00]
Brown-minus-green risk premia	0.81%	0.81%	0.81%

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

	10%	Median	90%
Brown-minus-green returns	1.20% [0.02]	2.01% [0.00]	2.85% [0.00]
Brown-minus-green risk premia	2.00%	2.00%	2.00%

This table presents statistics of realized returns and risk premia for the brown-minus-green equity portfolio in the pre-transition economy. We simulate 1,000 economies for 15 years at a monthly frequency. The reported brown-minus-green returns are the annualized time-series averages of the monthly ex-post realized returns ($r_b^{LEV} - r_g^{LEV}$) for the median economy and the 10% and 90% quantile economies. In brackets, we report p-values of the returns for the respective economy. Brown-minus-green risk premia ($RP_b - RP_g$), i.e., annualized ex-ante expected returns, are constant over time and across sample economies under a second-order approximation.

on average over the whole pre-transition period, brown sector equity returns slightly exceed green sector equity returns. In addition, we simulate 15 years of data for 1,000 pre-transition sample economies based on our model at a monthly frequency and report statistics on brown-minus-green equity returns and risk premia in Table 5. Panel A considers the benchmark calibration. While there is no climate policy risk in the pre-transition model by definition, average brown-minus-green equity returns range from 0.41% to 1.21% per year across the different 15-year samples, highlighting that other factors besides climate policy risk can be responsible for a return spread between brown and green equity. Importantly, the brown-minus-green risk premium, which is directly observable in the model, amounts to 0.81% in the pre-transition samples, but this risk premium does, again, not arise due to climate policy risk.

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 returns on brown sector equity may be significantly different from returns 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.[9] We then simulate the transition paths towards the equilibrium of the full model — in which agents understand the relation between emissions and global temperatures as defined through the parameter χ — for 1,000 economies.

3.4.1 Emissions, Temperature, and Macroeconomic Quantities

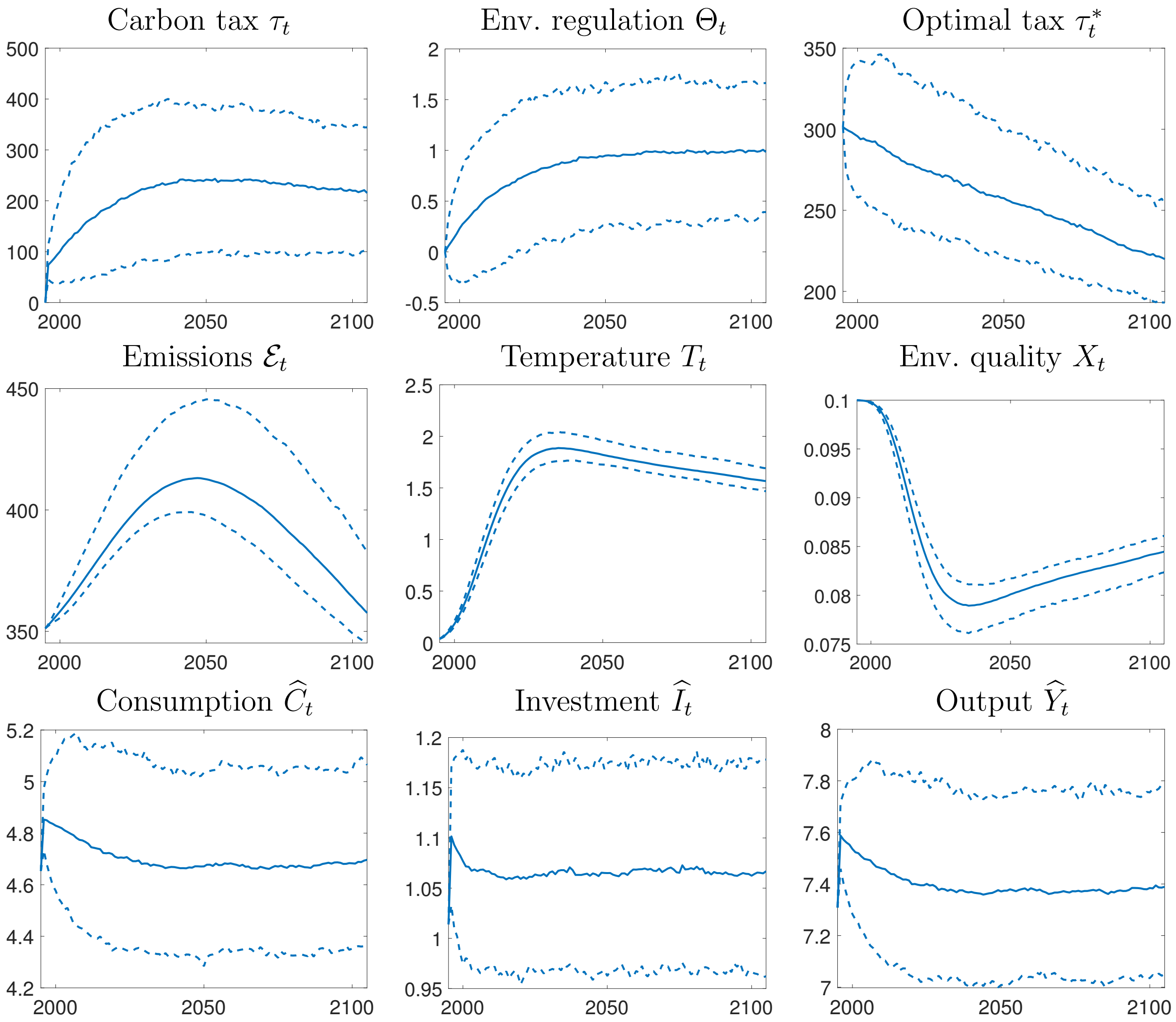
We first discuss the dynamics of temperature, emissions, the carbon tax, and macroeconomic variables during the transition period, which we depict in Figure 2. The figures show the median path of the considered variables as well as 95% confidence bands. In our simulation of the climate transition, the temperature anomaly reaches a value of about 1.9 degrees Celsius on the median transition path, approximately in the year 2040, before it slowly declines. Staying below the 2-degree mark is achieved through a carbon tax which starts at a low value and gradually converges towards the socially optimal tax, exceeding 200 dollars per ton of carbon emissions in 2050.[10] As a result, emissions also reach their peak around the year 2050 and decline quickly after that. On the contrary, a carbon tax at the low end of the confidence band, which stays below 100 dollars

---

[9] We can compute the unconditional mean, which differs from the (deterministic) steady state in the presence of higher-order terms, in closed form under the pruning scheme proposed by Andreasen et al. (2018). Thus, we do not need to rely on a simulation of the pre-transition model for obtaining this starting point.

[10] Our results confirm the finding by Daniel et al. (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 climate and macroeconomic variables



This figure illustrates the dynamics of emissions, temperature, carbon taxes, and macroeconomic variables over the climate transition. The transition dynamics are computed for 110 years (from 1995 to 2105) and 1,000 sample economies at a monthly frequency. The initial point of the simulation is the unconditional mean of the pre-transition economy. Carbon taxes are denominated in U.S. dollars per ton of carbon dioxide, (cumulative) emissions in billion tons of carbon dioxide, and temperatures in degrees Celsius above the pre-industrial level. Consumption, investment, and output are annualized and denominated in trillion U.S. dollars as of 1995 and adjusted for the economy's productivity growth, such that the transition dynamics can be interpreted relative to the balanced growth path. The median path across the 1,000 economies is depicted for the considered variables, alongside 95% confidence bands according to the corresponding quantiles at any given point in time.

per ton for the longest time, translates to a higher and later peak of emissions and to temperatures above the 2-degree mark. In either case, environmental quality declines first and then stabilizes once temperatures do not rise anymore.

In terms of macroeconomic variables, the figures show that aggregate consumption, investment, and output increase in the very beginning of the climate transition, before they enter a long-term decline relative to the balanced growth path. The reason for the initial increase in economic activity is a surge in labor in both the green sector and the brown and oil sectors (see Appendix D for the corresponding transition dynamics).[11] While the increase of green sector labor is permanent due to the rising demand for green goods over the transition, the labor boom in the brown and oil sectors is of short-term nature to compensate for the predictably higher taxation of brown sector output in the future, similar to the "run on oil" highlighted by Barnett (2024). In the longer run, the increasing carbon tax, which is welfare-improving and necessary to prevent catastrophic temperature increases, naturally comes at the cost of a reduction in economic activity relative to the balanced growth path.

3.4.2 Firm Valuations and Capital Flows

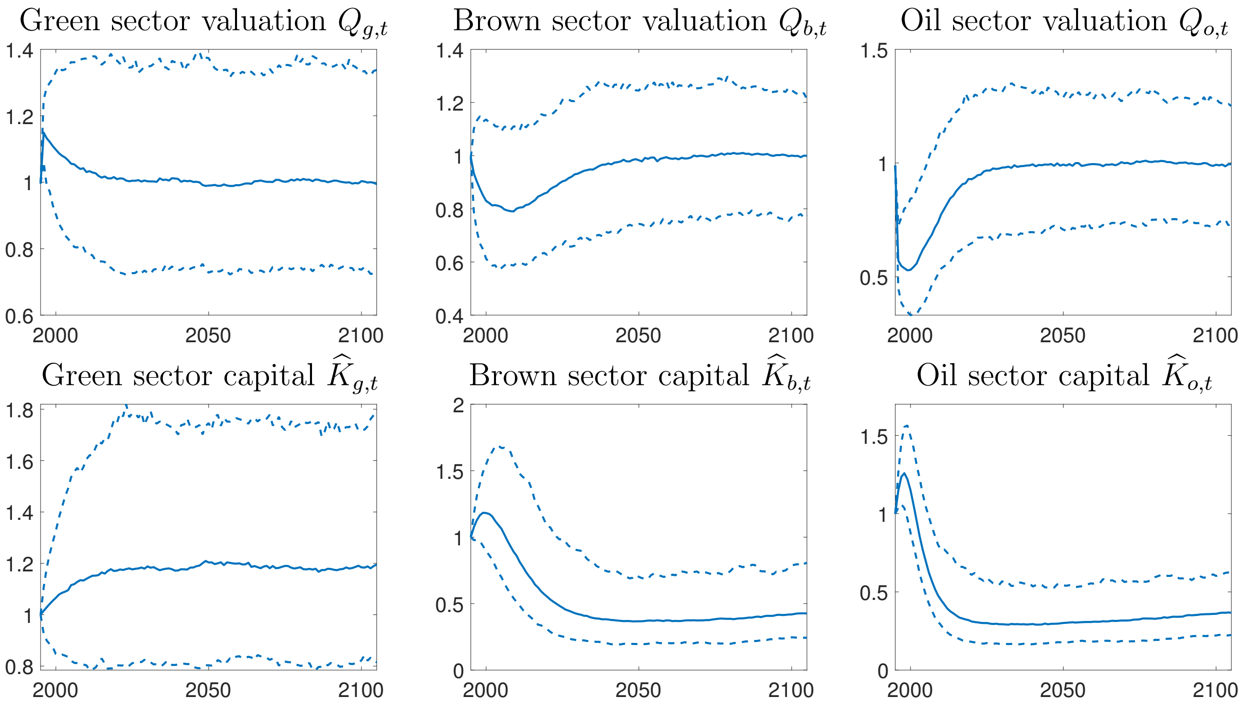
Figure 3 depicts the median transition paths and confidence bands of firm valuations and capital stocks in the economy. In particular, firm valuation dynamics are illustrated in the first row by means of marginal Tobin's qs, and the second row shows sectoral capital stocks, with the initial capital stock in each sector normalized to one. Our simulation predicts, on the one hand, that the valuations of the brown and the oil sector substantially decline in the beginning of the climate transition. The marginal 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. In the longer run, all industry valuations revert back to a marginal Tobin's q of 1 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,[12] and on the other side, capital is flowing to the green sector.

---

[11] The beginning of the climate transition can be interpreted as a long-run shock to carbon taxes, which predictably increase in the subsequence, and leads to an initial increase of economic variables including consumption. In contrast, consumption responds negatively to temporary carbon tax shocks (see Figure 1). The opposite sign of the consumption response to short-run and long-run shocks is also observed for productivity shocks, for example (see Croce, 2014).

[12] In the very short run, brown sector and oil sector capital first increases, accompanying the short-term labor boom discussed in Section 3.4.1.

Figure 3: Transition dynamics of firm valuations and capital



This figure illustrates the dynamics of firm valuations and capital allocation in the green, brown, and oil sectors over the climate transition. The transition dynamics are computed for 110 years (from 1995 to 2105) and 1,000 sample economies at a monthly frequency. The initial point of the simulation is the unconditional mean of the pre-transition economy. Valuations are marginal Tobin's qs, and sectoral capital stocks are normalized to 1 in the beginning of the transition and adjusted for the economy's productivity growth, such that the transition dynamics can be interpreted relative to the balanced growth path. The median path across the 1,000 economies is depicted for the considered variables, alongside 95% confidence bands according to the corresponding quantiles at any given point in time.

The devaluation of the brown and oil sectors results from a combined effect of the climate transition on risk premia and future cash flows. In the literature, there is a great focus on the risk premium component inferred from realized brown-minus-green returns, as discussed in the introduction to this paper. Our results in the next section show, however, that making such inference and therefore disentangling risk premia and cash flow effects in the beginning of the climate transition turns out to be extremely difficult from an econometric point of view. In contrast, we demonstrate in Section 3.4.4 that it is well possible to capture and measure the combined cash flow and risk premium effects of the climate transition, which we particularly highlight at the example of oil firm valuations.

3.4.3 Brown and Green Returns and Risk Premia

We analyze returns and risk premia during the transition period within our simulated model. We start with the benchmark 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 annual brown-minus-green climate policy risk premium is 2.31% in the calibrated model. The table also shows that the overall brown-minus-green risk premium, which also includes premia stemming from other factors such as differential adjustment costs, is 2.85% in the model. While these risk premia are directly observable in the model environment,[13] empirical studies typically attempt to infer carbon premia from realized returns (see Table 1).

Our model simulations reveal, however, that it is very difficult for an econometrician to correctly estimate the underlying risk premia based on monthly brown-minus-green realized returns over a relatively short sample period of 15 years. The first row of Panel A 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 -4.34% per year measured over 15 years in the median economy. On the contrary, when the econometrician examines a sample period with a later start date,[14] she will observe positive brown-minus-green returns in most cases, even though a negative realized brown-minus-green return is still possible in the 10% quantile economy. In the median economy, the observed 2.80% brown-minus-green return is very close to the risk premium, but not statistically significant in the simulated sample. In contrast, a 6.84% realized return is observed in the 90% quantile economy, which is statistically significant, but much larger than the actual risk premium.

---

[13] Risk premia do not vary in magnitude over time in our simulations since we employ a second-order approximation to the model equilibrium. Time-varying risk premia would further complicate the inference of carbon premia from brown-minus-green realized returns.

[14] In our model, the large negative return of the brown sector is realized in the first month of the climate transition, as investors fully anticipate the predictable increase of carbon taxes over time towards the optimal tax level. Therefore, a simulated sample that excludes the very first month of the climate transition does already not contain this large initial negative return. Introducing gradual learning about the transition would lead to a distribution of this initial devaluation over a longer period of time, but yield similar conclusions overall.

Table 6: Simulated brown-minus-green returns and risk premia during the climate transition

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

	10%	Median	90%
Brown-minus-green returns			
Early sample start	-7.75%	-4.34%	-0.33%
	[0.32]	[0.58]	[0.97]
Late sample start	-0.60%	2.80%	6.84%
	[0.83]	[0.37]	[0.04]
Brown-minus-green risk premia			
Overall risk premium	2.85%	2.85%	2.85%
Climate policy risk premium	2.31%	2.31%	2.31%

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

	10%	Median	90%
Brown-minus-green returns			
Early sample start	-9.42%	-6.01%	-2.00%
	[0.20]	[0.41]	[0.79]
Late sample start	-2.79%	0.61%	4.66%
	[0.33]	[0.84]	[0.16]
Brown-minus-green risk premia			
Overall risk premium	0.74%	0.74%	0.74%
Climate policy risk premium	0.20%	0.20%	0.20%

This table presents 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 full model equilibrium. We simulate 1,000 economies for 15 years at a monthly frequency. The reported brown-minus-green returns are the annualized time-series averages of the monthly ex-post realized returns ($r_b^{LEV} - r_g^{LEV}$) for the median economy and the 10% and 90% 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. In brackets, we report p-values of the returns for the respective economy. Brown-minus-green risk premia ($RP_b - RP_g$), i.e., annualized ex-ante expected returns, are constant over time and across sample economies under a second-order approximation. The overall risk premium is the full brown-minus-green risk premium, while the climate policy risk premium is computed as the difference between the full risk premium and the brown-minus-green risk premium obtained when climate policy shocks are shut down. Panel A considers the benchmark case of a strongly negative correlation between carbon tax shocks and long-run growth shocks, yielding substantially positive climate policy risk premia, and Panel B considers the case of a weakly negative correlation, resulting in climate policy risk premia that are positive but close to zero.

As a result, the econometrician may 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 a biased point estimate of the carbon premium.

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 close to zero. Even though this is the case, we find that the observed variation in 15-year average brown-minus-green returns in different sample economies is rather similar compared to the case with the clearly positive climate policy risk premium. As a result, the econometrician's inference on whether there is a significant carbon premium and on its magnitude is not substantially different in the case where its actual size is economically meaningful 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 a biased point estimate of the underlying premium.

3.4.4 Oil Sector Returns and Valuations

The results on return spreads between brown (i.e., oil-consuming) and green firms in the previous section apply analogously to the oil-producing sector. Climate regulations directly affect oil-consuming firms, but also translate to oil-producing firms through the demand channel, with a similar impact on their valuations and returns. Table 7 shows realized returns and risk premia for oil firms relative to other firms, which parallel the outcomes discussed for brown vs. green firms: Observed realized returns can be negative, positive, or close to zero, both in scenarios where the actual climate policy risk premium is substantially positive and when it is close to zero.[15] While these results imply that it is similarly difficult to infer carbon premia from oil firm returns, we finally highlight — at the example of the oil sector — that it is possible to pin down the overall impact of the climate transition on valuations.

---

[15] For the oil sector, climate policy risk premia are positive in the model as for the brown sector, but the overall oil-minus-other risk premium driven by adjustment costs and other factors is negative, in line with the data (see Table 4).

Table 7: Simulated oil-minus-other returns and risk premia during the climate transition

Panel A: Positive climate policy risk premium ($\text{Corr}(\varepsilon_{t+1}^{\Theta}, \varepsilon_{t+1}^{z}) = -0.45$)

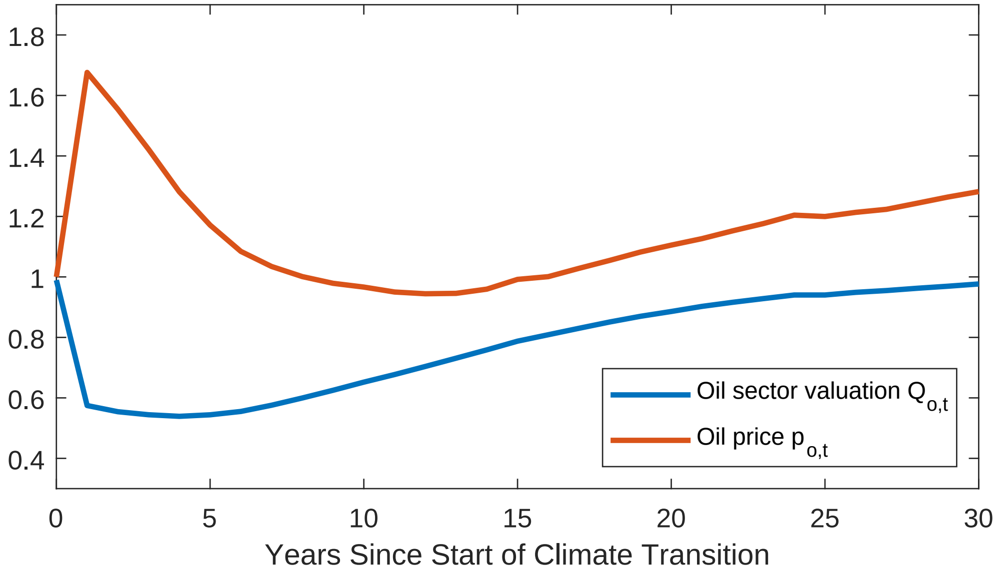
	10%	Median	90%
Oil-minus-other returns			
Early sample start	-12.97% [0.07]	-7.07% [0.32]	-0.37% [0.96]
Late sample start	-8.08% [0.12]	-2.20% [0.68]	4.53% [0.45]
Oil-minus-other risk premia			
Overall risk premium	-2.07%	-2.07%	-2.07%
Climate policy risk premium	4.32%	4.32%	4.32%

Panel B: Close-to-zero climate policy risk premium ($\text{Corr}(\varepsilon_{t+1}^{\Theta}, \varepsilon_{t+1}^{z}) = -0.05$)

	10%	Median	90%
Oil-minus-other returns			
Early sample start	-16.17% [0.02]	-10.27% [0.11]	-3.58% [0.60]
Late sample start	-12.20% [0.02]	-6.31% [0.23]	0.41% [0.94]
Oil-minus-other risk premia			
Overall risk premium	-6.18%	-6.18%	-6.18%
Climate policy risk premium	0.21%	0.21%	0.21%

This table presents 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 full model equilibrium. We simulate 1,000 economies for 15 years at a monthly frequency. The reported oil-minus-other returns are the annualized time-series averages of the monthly ex-post realized returns ($r_o^{LEV} - r_{m\backslash o}^{LEV}$) for the median economy and the 10% and 90% 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. In brackets, we report p-values of the returns for the respective economy. Oil-minus-other risk premia ($RP_o - RP_{m\backslash o}$), i.e., annualized ex-ante expected returns, are constant over time and across sample economies under a second-order approximation. The overall risk premium is the full oil-minus-other risk premium, while the climate policy risk premium is computed as the difference between the full risk premium and the oil-minus-other risk premium obtained when climate policy shocks are shut down. Panel A considers the benchmark case of a strongly negative correlation between carbon tax shocks and long-run growth shocks, yielding substantially positive climate policy risk premia, and Panel B considers the case of a weakly negative correlation, resulting in climate policy risk premia that are positive but close to zero.

Figure 4: Oil firm valuations and oil prices in the beginning of the climate transition



This figure illustrates the dynamics of oil firm valuations (marginal Tobin's qs) and oil prices for the first 30 years of the climate transition. The transition dynamics are computed based on the model for 1,000 sample economies, with the initial point of the simulation being the unconditional mean of the pre-transition economy. We depict the median paths across the 1,000 economies and normalize the initial value of both variables to one.

Oil firm valuations exhibit a pronounced decrease in the beginning of the transition period (see Figure 3) due to the impact of the carbon tax on the brown sector and the resulting lower demand for oil. While the decline in valuations is immediate, oil prices, the main driver of contemporaneous oil sector dividends, are predicted to fall only slowly over the first 10–15 years of the climate transition with the gradual reallocation of production to the green sector. As Figure 4 illustrates, these dynamics result in a remarkable disconnect between oil firm valuations and oil prices in the beginning of the climate transition.[16] In Section 4, we show that this disconnect is clearly observable in the data, marking the beginning of the climate transition being priced by the market. Otherwise, oil prices and oil firm valuations tend to move in tandem, and our model predicts that this behavior is restored after around 15 years.

---

[16] A similar disconnect is observable between brown sector valuations and contemporaneous dividends (see Figure 3 and Appendix Figure D.1 for the corresponding transition dynamics). We empirically pin down this disconnect for the oil sector in this paper, and leave the empirical analysis of the relation between brown sector valuations and dividends for future research.

3.5 Summary and Empirical Implications

The results on realized brown-minus-green returns simulated based on our model demonstrate 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 a substantial devaluation of the brown and oil sectors, which is reflected by (ex-post) realized returns, but not representative of (ex-ante) risk premia. Quantitatively, the analysis of our calibrated model shows that these effects are indeed so large that one may observe substantially negative average brown-minus-green returns when the climate policy risk premium is clearly positive. Similarly, positive cash flow shocks can lead to substantially 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 improve the identification of risk premia by controlling for cash flow effects using measures of climate change concerns or dividend and earnings information (see Pastor et al., 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 of carbon risk premia from realized brown-minus-green returns, our results also highlight that we *can* very well learn when the market started pricing the climate transition and pin down the overall effect on valuations through the combined cash flow and risk premium effects. As our model predicts, 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 materializes in the case of the oil sector as a strong disconnect between oil firm valuations and oil prices (see Figure 4). In the next section, we use the oil sector as a laboratory to apply and validate these insights from our model.[17] 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 affected by the climate transition (see also van Benthem et al., 2022). While there are lots of papers discussing green and brown (i.e., oil-consuming) firms, the literature has not analyzed the climate transition and carbon premia 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 numerous papers consider brown-minus-green returns by classifying firms according to their carbon emissions (see Table 1), we provide new evidence by focusing on the oil sector. By definition, oil-producing firms are strongly negatively affected by stricter climate policies that aim to reduce the use of fossil fuels in the economy, which can, according to theory, lead to substantial climate policy risk premia compared to other firms (see Table 7, Panel A). At the same time, a main prediction of our model is that these premia cannot well be captured via realized returns over short time samples, which strongly deviate from the actual climate policy risk premia in most cases.

We show in Section 4.1 that this prediction is strongly reflected by the data. In particular, we consider the return spread between oil firms and other firms over 15-year sample periods and find that, as predicted by our model, it can be clearly negative or positive, both before and during the climate transition. Section 4.2 then applies our positive model result that one *can* very well pin down when the market started pricing the climate transition through the lens of firm valuations and their disconnect from current cash flows. For oil firms, this disconnect is particularly reflected by a divergence between oil prices and oil firm valuations (see Figure 4), and we clearly observe such a divergence in the data during the 2000s. In Section 4.3, we provide additional support that

---

[17] Our analysis also considers the broader fossil fuel sector, which includes coal-producing firms in addition to oil firms, and our results are confirmed in this broader sample.

the observed devaluation of oil firms is connected with the climate transition by showing that it coincides with the increase in climate change risk awareness and that it is less pronounced for firms with fewer assets affected by the transition.

4.1 Return Spread Between Oil Firms and Other Firms

We investigate the return spread between oil firms and other firms, as a variation on the brown-minus-green return exhaustively analyzed in the literature.[18] Our analysis is based on the standard CRSP/Compustat dataset featuring monthly stock returns from 1950 to 2024, and we define oil firms as those where the first two digits of the SIC code are 13 or 29. To capture the return spread between oil firms and other firms, we regress firms' monthly stock returns on an indicator for oil firms and a standard set of control variables, considering different 15-year subsamples both before and during the climate transition.[19] We run both pooled regressions in line with most of the literature, with standard errors double-clustered by firm and year, and monthly Fama-MacBeth regressions with Newey-West standard errors. Our set of control variables includes the firms' cash ratio as a measure of liquidity, the amount of debt relative to assets as a measure of leverage, the log of total assets as a measure of firm size, and the ratio of research and development (R&D) expenditures to sales as a measure of firm innovation capacity (see also Chen et al., 2015; Minton et al., 2019). Summary statistics of these control variables, separately for the full sample and the subsample of oil firms, are provided in Appendix Table F.1.

Table 8 presents the results. As the table reports, realized oil-minus-other stock returns attain both substantial 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 (see Table 7), it is very likely that these realized returns do not directly translate to underlying risk premia. As an

---

[18] Oil(-producing) firms are, like brown (oil-consuming) firms, strongly negatively exposed to climate policies that aim to reduce the amount of carbon emissions produced by the economy (van Benthem et al., 2022). We do not claim or require for our analysis that oil firms are "brown" in all respects. For example, it is well-known that oil firms tend to have low scope-1 emissions and that these firms significantly contribute to green innovation (Cohen et al., 2024).

[19] Following Eskildsen et al. (2024), we winsorize realized returns at the 0.1% and 99.9% level, and valuation measures (considered in Sections 4.2 and 4.3) as well as control variables at the 1% and 99% level.

Table 8: Oil-minus-other returns in different 15-year samples

Pre-transition times				
Period	Oil-minus-other return			
1950–1964	0.75%	3.89%	0.34%	3.16%
1965–1979	16.81%*	18.33%**	12.17%**	12.51%**
1980–1994	−13.92%*	−13.59%*	−9.70%	−9.06%
During climate transition				
Period	Oil-minus-other return			
1995–2009	6.81%	6.18%	5.79%	5.02%
2000–2014	0.35%	−1.07%	4.29%	3.05%
2005–2019	−8.86%*	−11.62%**	−4.64%	−7.48%
2010–2024	−5.69%	−8.87%	−3.17%	−6.53%
Regression	Pooled	Pooled	Fama-MacBeth	Fama-MacBeth
Controls	No	Yes	No	Yes

This table reports results from a regression of annualized monthly stock returns from the CRSP/Compustat universe of firms on an oil firm indicator and a standard set of control variables for different 15-year periods before and during the climate transition, using both pooled and Fama-MacBeth regressions. The estimated coefficient on the oil firm indicator is reported as the oil-minus-other return. Our set of control variables includes the firms' cash ratio, the amount of debt relative to assets, the log of total assets, and the ratio of research and development (R&D) expenditures to sales. We report results with and without controlling for these variables. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively, according to standard errors double-clustered by firm and year (for pooled regressions) and Newey-West standard errors (for Fama-MacBeth regressions).

example, we find a significantly negative oil-minus-other return of −11.62% in the period from 2005 to 2019. The econometrician may interpret this finding as evidence of a negative carbon premium; however, a significantly negative return is not confirmed in any of the other 15-year subsamples during the climate transition (since 1995). In addition, one can also observe significantly negative or positive 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. Consequently, 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 addressed 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) suggests that there is no consensus on when the climate transition started affecting financial market outcomes. Our model predicts that this start date is strongly reflected by a considerable drop in oil firm valuations, which furthermore get disconnected from the oil price as a proxy of current cash flows.

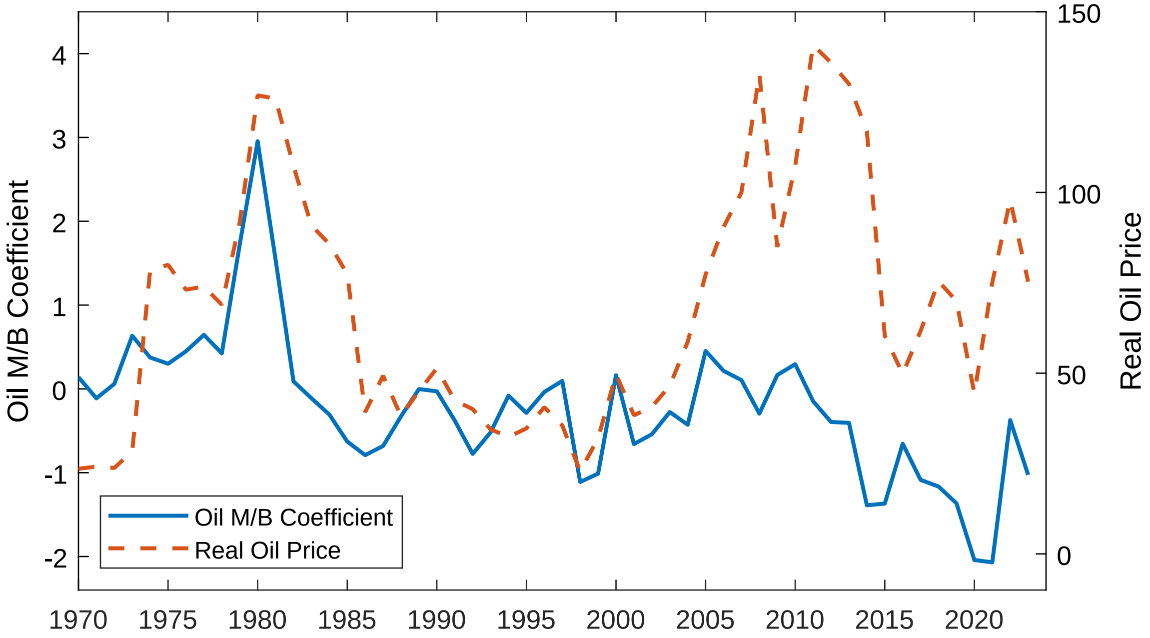
We consider the relative valuation of oil firms based on the CRSP/Compustat sample at an annual frequency by running Fama-MacBeth regressions of firm valuations on an indicator for the oil sector and the same set of control variables as in Section 4.1. We use market-to-book ratios as our baseline valuation measure and additionally consider Tobin's q as well as Peters and Taylor's (2017) total q in Section 4.3.[20] Appendix Table F.1 provides summary statistics of the valuation measures, separately for the full sample and the subsample of oil firms.

To begin with, Figure 5 depicts the yearly coefficients on the oil sector indicator from the baseline Fama-MacBeth regression over our sample period, together with the real oil price. Intuitively, the coefficients provide a measure for the valuation of oil firms relative to other firms after taking the controls into account. The figure shows that oil firm valuations were rather stable between 1985 and 2005, and declined afterwards to reach their lowest levels towards the end of our sample. It is also clearly observable that the oil firm valuations co-move strongly with the oil price for the most part as a main driver of oil firms' profits. This pattern is dramatically disrupted in the 2000s, when the oil sector's market valuation decoupled from the oil price and declined irrespective of the commodity price boom of 2008 and other substantial oil price movements. Put simply, the (real) oil price observed 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.

---

[20] In line with the literature, we remove firm-year observations from our sample that have book equity smaller than ten thousand dollars or gross property, plant, and equipment below five million dollars. We also discard observations with missing or negative values for stockholders' equity, sales, or total assets.

Figure 5: Relative valuation of oil firms and real oil prices



This figure illustrates the relative valuation of oil firms over time, as obtained from a Fama-MacBeth regression of firms' market-to-book ratios on an oil firm indicator and a standard set of control variables. Our set of control variables includes the firms' cash ratio, the amount of debt relative to assets, the log of total assets, and the ratio of research and development (R&D) expenditures to sales. The blue solid line plots the estimated yearly coefficients on the oil sector indicator (left axis). The red dashed line plots the real oil price (right axis). Our sample runs from 1970 to 2024.

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 (see Figure 4). Statistically, the correlation between the yearly valuation coefficient and the real oil price is 0.66 and significant at the 1% level from the beginning of our sample until the year 2000, and 0.34 and insignificant when computed for the years after 2000. Altogether, our results suggest that the market started pricing the effects of the climate 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 Assets at Risk

We extend our analysis by investigating to what extent the observed devaluation of oil firms is explained by the progressing climate transition. In our macro-finance model presented in Section 2, the climate-related transition towards a low-carbon economy is triggered and driven by the surge in economic agents' awareness for the relation between greenhouse gas emissions and climate change. Following this theoretical foundation, we construct a Climate Change Risk Awareness Index (CCRAI) from internet search volumes and word count data, which strongly co-moves with Ardia et al.'s (2023) news-based measure and captures the trend of increasing climate risk awareness.[21] Details on the construction of our index and its co-movement with other established measures are provided in Appendix E. We perform a panel regression of firm valuations on the indicator for oil firms, the CCRAI, and the interaction between the two, as well as the set of control variables from the previous section.

Table 9 presents the results. The interaction term of the CCRAI with the oil firm indicator reveals our main finding: The market valuation of oil firms significantly declines, relative to other firms, together with the progressing climate transition captured by the CCRAI. In terms of the economic magnitude of the effect, a coefficient of -0.474 in column (1) means that the market-to-book ratio of oil firms relative to other firms declines by 0.948 for a 200 points increase in the CCRAI, relative to an average market-to-book ratio of oil firms of 2.376. This implies that the valuation of oil firms has decreased by at least 40% relative to other firms along with the climate transition over the last 20 years.[22]

---

[21] Ardia et al. (2023) compute a Media Climate Change Concerns index at daily frequency from 2010 to 2018. For our purposes, we require a lower-frequency measure covering a much longer sample period. Note also that we do not assume or require the CCRAI to provide a large amount of time-variation around its trend — what we aim to capture is exactly the trend of increasing climate risk awareness and its importance for firm valuations in the medium- to long-run, irrespective of potential temporary attention fluctuations.

[22] The average market-to-book ratio is calculated as $2.49–0.114 = 2.376$ as implied by the average market-to-book ratio of all firms from Panel A of Appendix Table F.1 and the coefficient on 1_{Oil} in Table 9, column (1). The value of the CCRAI is 100 in the year 2004 by construction (see Appendix E), and it increases to values clearly exceeding 300 at the end of our sample. A 200 points increase and the corresponding 40% devaluation are therefore a conservative estimate of the decline in valuations associated with the climate transition.

Table 9: Relation of oil or fossil fuel firm valuations to climate change risk awareness

	Market-to-book ratio				Tobin's q	Total q
	(1) Baseline	(2) Fossil fuel	(3) No IT	(4) Assets at risk	(5)	(6)
$1_{Oil} \times CCRAI$	-0.474**		-0.447**	-0.475**	-2.347***	-0.383***
	(0.183)		(0.177)	(0.185)	(0.487)	(0.120)
$1_{Fossilfuel} \times CCRAI$		-0.486**				
		(0.182)				
$1_{Fewassetsatrisk} \times CCRAI$				0.219*		
				(0.124)		
1_{Oil}	-0.114		0.018	-0.106	-1.475***	-0.055
	(0.155)		(0.147)	(0.155)	(0.321)	(0.105)
$1_{Fossilfuel}$		-0.099				
		(0.154)				
$1_{Fewassetsatrisk}$				-0.579***		
				(0.175)		
$CCRAI$	0.642***	0.643***	0.618***	0.641***	1.803***	0.221**
	(0.174)	(0.175)	(0.167)	(0.174)	(0.464)	(0.087)
Control variables	Yes	Yes	Yes	Yes	Yes	Yes
Observations	183647	183647	159555	183647	180442	175108
Adjusted R^2	0.082	0.082	0.086	0.082	0.163	0.120

This table reports results from a panel regression of firms' valuation measures on the Climate Change Risk Awareness Index (CCRAI), an oil or fossil fuel firm indicator, and their interaction term, as well as a standard set of control variables. Column (4) additionally includes an indicator that is one for oil firms within the lowest cross-sectional quartile of capital expenditures at risk, and its interaction with the CCRAI. As valuation measures, we use market-to-book ratios in columns (1)–(4), Tobin's q in column (5), and Peters and Taylor's (2017) total q in column (6). Our set of control variables includes the firms' cash ratio, the amount of debt relative to assets, the log of total assets, and the ratio of research and development (R&D) expenditures to sales. Detailed results including coefficients on control variables are reported in Appendix Tables F.2–F.7. Our sample runs from 1970 to 2024. Standard errors double-clustered by firm and year are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

In column (2), we test whether these results also hold when considering not only oil firms but the whole fossil fuel sector (including coal, SIC code 12), and confirm that this is the case. Our third specification in column (3) addresses the potential concern that rather than reflecting a decline in oil firm valuations, our results could be driven by the strong increase in IT firm valuations in the recent decades, which are part of the "other" firms. When excluding IT firms from our sample (following the classification of Ward, 2020), the effect remains strong and becomes only marginally smaller in magnitude. In column (4), we ask whether the devaluation is less pronounced for oil firms who are less exposed to the climate transition. 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,[23] which provides for a sample of energy firms the percentage of capital expenditures that are at risk under a 1.6-degree global warming scenario. We match the dataset to our sample and add an indicator for oil firms that are in the lowest cross-sectional quartile of capital expenditures at risk to our regression, as well as its interaction with the CCRAI. The regression results show that the valuations of firms with few assets at risk exhibit a much smaller 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 assets at risk decline by a value of 0.512 ($= (0.475 - 0.219) \times 2$) with a 200 percentage points increase in the CCRAI, compared to a reduction of 0.948 in the market-to-book ratios of all oil firms. Finally, in columns (5) and (6) we repeat our baseline regression from column (1) for Tobin's q and total q as valuation measures. The results unanimously confirm that oil firm valuations have declined relative to other firms with increasing climate change risk awareness.

In sum, these results demonstrate 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. The observed dynamics are consistent with the predictions of our macro-finance model in Section 3. While the effects of the climate transition cannot be well identified based on realized returns of oil firms compared to other firms, they can be uncovered through the lens of market valuations, which decline as a result of the combined cash flow and risk premium effects.

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 a simulated environment, including the disruptive effects in the beginning of the transition as

---

[23] Data from the *2 degrees of separation* initiative are provided on the website `https://2degreesseparation.com/`.

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 policy risk premia based on realized 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 conclusions on the existence of carbon premia. Similarly, point estimates can be largely biased. These model-based results provide, in addition to differences in empirical methodologies across different studies, an explanation for the vast heterogeneity of conclusions regarding carbon premia in the empirical literature.

We also demonstrate 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 by a disconnect of valuations from the firms' contemporaneous cash flows. Using the oil sector as a laboratory, we find that such pattern is 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 40% with the climate transition. Our results thus provide a market-informed benchmark about when the climate transition first affected stock prices. 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 the possible underlying carbon premia.

The macro-finance model for the climate transition presented in this paper, which quantitatively reproduces the dynamics of emissions and temperatures, macroeconomic variables, and asset prices, is a novelty to the literature. While we particularly highlight the assessment of carbon returns and risk premia based on this framework, it enables a quantitative theoretical analysis of many important macro-finance questions related to the climate transition. For example, the model allows for a formal analysis of physical climate risk and climate policy risk, and how the interaction of both types of risk drives economic and financial market outcomes. Our framework can also readily be adapted to examine the dynamic effects of different types of transition risk, combining our approach with the recent work of Acharya et al. (2024), to mention only two possible avenues for future research.

References

Acemoglu, D., Aghion, P., Bursztyn, L. and Hemous, D. (2012). The environment and directed technical change. American Economic Review, **102** (1), 131–166.

Acharya, V. V., Giglio, S., Pastore, S., Stroebel, J., Tan, Z. and Yong, T. (2024). Climate transition risks and the energy sector. Working Paper.

Alves, R., Krüger, P. and van Dijk, M. (2024). Drawing up the bill: Are ESG ratings related to stock returns around the world? Working Paper.

Andreasen, M. M., Fernández-Villaverde, J. and Rubio-Ramírez, J. F. (2018). The pruned state-space system for non-linear DSGE models: Theory and empirical applications. Review of Economic Studies, **85** (1), 1–49.

Ardia, D., Bluteau, K., Boudt, K. and Inghelbrecht, K. (2023). Climate change concerns and the performance of green versus brown stocks. Management Science, **69** (12), 7607–7632.

Aswani, J., Raghunandan, A. and Rajgopal, S. (2024). Are carbon emissions associated with stock returns? Review of Finance, **28** (1), 75–106.

Baker, S. D., Hollifield, B. and Osambela, E. (2022). Asset prices and portfolios with externalities. Review of Finance, **26** (6), 1433–1468.

Balvers, R., Du, D. and Zhao, X. (2017). Temperature shocks and the cost of equity capital: Implications for climate change perceptions. Journal of Banking and Finance, **77**, 18–34.

Bansal, R., Kiku, D. and Ochoa, M. (2017). Price of long-run temperature shifts in capital markets. Working Paper.

— and Yaron, A. (2004). Risks for the Long Run: A Potential Resolution of Asset Pricing Puzzles. Journal of Finance, **59**, 1481–1509.

Barnett, M. (2024). A run on fossil fuel? Climate change and transition risk. Working Paper.

Bauer, M. D., Huber, D., Rudebusch, G. D. and Wilms, O. (2022). Where is the carbon premium? Global performance of green and brown stocks. Journal of Climate Finance, **1**, 100006.

Berg, F., Kölbel, J. F. and Rigobon, R. (2022). Aggregate confusion: The divergence of ESG ratings. Review of Finance, **26** (6), 1315–1344.

Binder, M. (2001). Dirty industries in decline: An introduction to the case studies. In M. Binder, M. Jänicke and U. Petschow (eds.), Green Industrial Restructuring, Springer, Berlin, Heidelberg.

Bogmans, C., Pescatori, A. and Prifti, E. (2024). The impact of climate policy on oil and gas investment: Evidence from firm-level data. European Economic Review, **165**, 104750.

Bolton, P. and Kacperczyk, M. T. (2021). Do investors care about carbon risk? Journal of Financial Economics, **142**, 517–549.

— and — (2023). Global pricing of carbon-transition risk. Journal of Finance, **78** (6), 3677–3754.

Botta, E. and Koźluk, T. (2014). Measuring environmental policy stringency in OECD countries: A composite index approach. OECD Economics Department Working Paper.

Cai, Y., Judd, K. L. and Lontzek, T. S. (2019). The social cost of carbon with economic and climate risks. Journal of Political Economy, **127** (6), 2684–2734.

Chen, J., Hou, K. and Stulz, R. M. (2015). Are firms in "boring" industries worth less? Working Paper.

Cohen, L., Gurun, U. G. and Nguyen, Q. H. (2024). The ESG-innovation disconnect: Evidence from green patenting. Working Paper.

Croce, M., Nguyen, T. T. and Raymond, S. (2021). Persistent government debt and aggregate risk distribution. Journal of Financial Economics, **140** (2), 347–367.

Croce, M. M. (2014). Long-Run Productivity Risk: A New Hope for Production-Based Asset Pricing? Journal of Monetary Economics, **66**, 13–31.

Daniel, K. D., Litterman, R. B. and Wagner, G. (2019). Declining CO_2 price paths. Proceedings of the National Academy of Sciences, **116** (42), 20886–20891.

Engle, R. F., Giglio, S., Kelly, B., Lee, H. and Stroebel, J. (2020). Hedging climate change news. Review of Financial Studies, **33** (3), 1184–1216.

Epstein, L. G. and Zin, S. E. (1991). Substitution, risk aversion, and the temporal behavior of consumption and asset returns: An empirical analysis. Journal of Political Economy, **99** (2), 263–286.

Eskildsen, M., Ibert, M., Jensen, T. I. and Pedersen, L. H. (2024). In search of the true greenium. Working Paper.

Favilukis, J. and Lin, X. (2016). Wage Rigidity: A Quantitative Solution to Several Asset Pricing Puzzles. Review of Financial Studies, **29** (1), 148–192.

Gao, L., Hitzemann, S., Shaliastovich, I. and Xu, L. (2022). Oil volatility risk. Journal of Financial Economics, **144** (2), 456–491.

Giglio, S., Maggiori, M., Stroebel, J., Tan, J., Utkus, S. and Xu, X. (2025). Four facts about ESG beliefs and investor portfolios. Journal of Financial Economics, **164**, 103984.

Golosov, M., Hassler, J., Krusell, P. and Tsyvinski, A. (2014). Optimal taxes on fossil fuel in general equilibrium. Econometrica, **82** (1), 41–88.

Gormsen, N. J., Huber, K. and Oh, S. (2023). Climate capitalists. Working Paper.

Goulder, L. H. and Schein, A. R. (2013). Carbon taxes versus cap and trade: A critical review. Climate Change Economics, **4** (3), 1–28.

Görgen, M., Jacob, A., Nerlinger, M., Riordan, R., Rohleder, M. and Wilkens, M. (2020). Carbon risk. Working Paper.

Hambel, C., Kraft, H. and Schwartz, E. (2021). Optimal carbon abatement in a stochastic equilibrium model with climate change. European Economic Review, **132**, 103642.

Hitzemann, S. and Uhrig-Homburg, M. (2018). Equilibrium price dynamics of emission permits. Journal of Financial and Quantitative Analysis, **53** (4), 1653–1678.

In, S. Y., Park, K. Y. and Monk, A. (2019). Is 'being green' rewarded in the market?: An empirical investigation of decarbonization and stock returns. Working Paper.

Jermann, U. J. (1998). Asset pricing in production economies. Journal of Monetary Economics, **41** (2), 257–275.

Kroencke, T. A. (2017). Asset pricing without garbage. Journal of Finance, **72** (1), 47–98.

Lindsey, L. A., Pruitt, S. and Schiller, C. (2024). The cost of ESG investing. Working Paper.

Minton, B. A., Stulz, R. M. and Taboada, A. G. (2019). Are the largest banks valued more highly? Review of Financial Studies, **32** (12), 4604–4652.

Nordhaus, W. D. (1992). The 'DICE' model: Background and structure of a dynamic integrated climate-economy model of the economics of global warming. Cowles Foundation Discussion Paper No. 1009.

— (1993). Optimal greenhouse-gas reductions and tax policy in the "DICE" model. American Economic Review, Papers and Proceedings, **83** (2), 313–317.

— (2008). A Question of Balance: Weighing the Options on Global Warming Policies. Yale University Press.

Pastor, L., Stambaugh, R. F. and Taylor, L. A. (2021). Sustainable investing in equilibrium. Journal of Financial Economics, **142** (2), 550–571.

—, — and — (2022). Dissecting green returns. Journal of Financial Economics, **146** (2), 403–424.

Peters, R. H. and Taylor, L. A. (2017). Intangible capital and the investment-q relation. Journal of Financial Economics, **123** (2), 251–272.

Reilly, J. and Richards, K. (1993). Climate change damage and the trace gas index issue. Environmental and Resource Economics, **3** (1), 41–61.

Roth Tran, B. (2019). Divest, disregard, or double down? Philanthropic endowment investments in objectionable firms. American Economic Review: Insights, **1** (2), 241–256.

Sims, E. and Wu, J. C. (2021). Evaluating central banks' tool kit: Past, present, and future. Journal of Monetary Economics, **118**, 135–160.

van Benthem, A., Crooks, E., Giglio, S., Schwob, E. and Stroebel, J. (2022). The effect of climate risks on the interactions between financial markets and energy companies. Nature Energy, **7**, 690–697.

Ward, C. (2020). Is the IT revolution over? An asset pricing view. Journal of Monetary Economics, **114**, 283–316.

Zhang, S. (2025). Carbon returns across the globe. Journal of Finance, **80** (1), 615–645.

Appendix

A Model Equilibrium Conditions

A.1 Competitive Equilibrium

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

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

which leads to the equilibrium condition

$$Y_{i,t} = p_{i,t}^{-\varepsilon} \bar{A}^{\varepsilon - 1} Y_t, \tag{A.2}$$

in line with equation (33).

Intermediate goods firms The brown and green intermediate goods producers, $i \in \{b, g\}$, maximize the value functions (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

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

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

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

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

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

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

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

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

From equations (A.6) and (A.7), it follows that $\phi_{i,t}$ and $\epsilon_{i,t}$ result to zero in the competitive equilibrium.

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

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

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

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

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

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

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

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

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

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

The first derivative with respect to N_t implies

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

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

$$(1-\alpha_o)\lambda_{o,t}\frac{N_t}{L_{o,t}} = \widetilde{w}_t, \tag{A.14}$$

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

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

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

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

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

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

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

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

and

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

A.2 Social Planner Solution

In the competitive equilibrium, firms do not internalize the negative effect of their emissions on the environmental quality X_t. Accordingly, $\phi_{i,t}$ and $\epsilon_{i,t}$ result to zero according to equations (A.6) and (A.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. As a consequence, the social planner optimizes the production sector according to the problem

$$\begin{aligned}
\max_{\{Y_t;Y_{i,t};L_{i,t};K_{i,t};T_{t+1};\mathcal{E}_{t+1};O_t;U_{t+1};N_t\}} \mathbb{E}_t\Bigg[\sum_{t=0}^{\infty}\mathbb{M}_t\Bigg(Y_t - \lambda_{X,t}A_t\left(\bar{X} - \frac{\bar{X}}{1+\kappa_{X,1}T_t^{\kappa_X,2}}\right) \\
- \sum_{i\in\{b,g\}}(R^K_{i,t}K_{i,t} - w_t L_{i,t}) - \mu_t^S(Y_t - p_{g,t}Y_{g,t} - p_{b,t}Y_{b,t}) \\
- \lambda_{g,t}\left(Y_{g,t} - (A_tL_{g,t})^{1-\alpha}K^{\alpha}_{g,t}\right) - \lambda_{b,t}\left(Y_{b,t} - (A_tL_{b,t})^{1-\alpha}\left((1-\iota)K_{b,t}^{1-\frac{1}{o}} + \iota O_t^{1-\frac{1}{o}}\right)^{\frac{\alpha}{1-\frac{1}{o}}}\right) \\
+ p_{o,t}\kappa_o U_t - R^K_{o,t}K_{o,t} - w_tL_{o,t} - \lambda_{o,t}(N_t - (A_tL_{o,t})^{1-\alpha_o}K^{\alpha_o}_{o,t}) - \phi_{o,t}(U_{t+1} - (1-\kappa_o)U_t - N_t) \\
- \phi_t^S A_t((1-\rho_T)T_t + \rho_T\chi\mathcal{E}_{t+1} + \sigma_T\varepsilon^T_{t+1} - T_{t+1}) \\
- \epsilon_t^S A_t\Big(\xi_b/A_t \cdot Y_{b,t} + (1-\rho_{\mathcal{E}})\mathcal{E}_t - \mathcal{E}_{t+1}\Big)\Bigg)\Bigg].
\end{aligned} \tag{A.20}$$

We denote the shadow cost of temperature ϕ_t^S and the shadow cost of emissions ϵ_t^S in the social planner problem with a superscript S, indicating that they are different from the competitive equilibrium and do not result to zero.

We obtain the first order conditions with respect to $Y_{i,t}$, which (noting that $\mu_t^S = 1$) are

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

$$0 = p_{b,t} - \lambda_{b,t} - \epsilon_t^S \xi_b, \tag{A.22}$$

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

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

and with respect to T_{t+1},

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

The fact that the shadow price of environmental quality is taken into account in the social planner optimum is reflected by equation (A.24) for the shadow cost of temperature. This price is, on the other hand, determined by the household's first order condition in the standard two-goods problem, i.e.,

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

The shadow cost of temperature ϕ_t^S is then reflected by the shadow cost of emissions ϵ_t^S in equation (A.23), and ultimately internalized by the brown firm according to equation (A.22).

A.3 Optimal Carbon Tax

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

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

In comparison, we obtain

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

in the social planner solution. It directly follows that for a carbon tax of $\tau_t^* = \epsilon_t^S$ the social optimum is achieved in a competitive setting.

B Normalized Equilibrium Conditions

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

We denote the normalized version of a generic variable Z_t by $\hat{Z}_t$. The following list comprises the definitions of the normalized variables:

$$\begin{aligned}
&\hat{C}_t = \frac{C_t}{A_t};\ \ \hat{\widetilde{C}}_t = \frac{\widetilde{C}_t}{A_t};\ \ \hat{Y}_t = \frac{Y_t}{A_t};\ \ \hat{Y}_{g,t} = \frac{Y_{g,t}}{A_t};\ \ \hat{Y}_{b,t} = \frac{Y_{b,t}}{A_t};\ \ \hat{Z}_t = \frac{Z_t}{A_t};\ \ \hat{O}_t = \frac{O_t}{A_t};\\
&\hat{K}_{g,t} = \frac{K_{g,t}}{A_t};\ \ \hat{K}_{b,t} = \frac{K_{b,t}}{A_t};\ \ \hat{K}_{o,t} = \frac{K_{o,t}}{A_t};\ \ \hat{w}_t = \frac{w_t}{A_t};\ \ \hat{\widetilde{w}}_t = \frac{\widetilde{w}_t}{A_t};\ \ \Delta a_t = \ln\left(\frac{A_{t+1}}{A_t}\right);\\
&\hat{U}_t = \frac{U_t}{A_t};\ \ \hat{N}_t = \frac{N_t}{A_t};\ \ \hat{E}_t = \frac{E_t}{A_t};\ \ \hat{I}_{g,t} = \frac{I_{g,t}}{A_t};\ \ \hat{I}_{b,t} = \frac{I_{b,t}}{A_t};\ \ \hat{I}_{o,t} = \frac{I_{o,t}}{A_t};\ \ \hat{V}_t = \frac{V_t}{A_t};\\
&\hat{\vartheta}_t = \frac{\vartheta(A_t X_t, \widetilde{C}_t)}{A_t};\ \ \hat{\mathbb{E}}_t[V_{t+1}^{1-\gamma}] = \frac{\mathbb{E}_t[V_{t+1}^{1-\gamma}]}{A_t^{1-\gamma}};\ \ \hat{D}_{g,t} = \frac{D_{g,t}}{A_t};\ \ \hat{D}_{b,t} = \frac{D_{b,t}}{A_t};\\
&\hat{D}_{o,t} = \frac{D_{o,t}}{A_t};\ \ \hat{D}_{a,t} = \frac{D_{a,t}}{A_t};\ \ \hat{V}_{g,t} = \frac{V_{g,t}}{A_t};\ \ \hat{V}_{b,t} = \frac{V_{b,t}}{A_t};\ \ \hat{V}_{o,t} = \frac{V_{o,t}}{A_t};\ \ \hat{V}_{a,t} = \frac{V_{a,t}}{A_t}.
\end{aligned} \tag{B.1}$$

The following variables do not need to be normalized:

$$\begin{aligned}
&\{\lambda_{g,t}; \lambda_{b,t}; \lambda_{o,t}; \lambda_{X,t}; X_t; L_{g,t}; L_{b,t}; L_{o,t}; p_{g,t}; p_{b,t}; p_{o,t}; R^k_{g,t}; R^k_{b,t}; R^k_{o,t}; R^K_{g,t}; R^K_{b,t}; R^K_{o,t}; \mathbb{M}_t; T_t;\\
&\mathcal{E}_t; \Theta_t; \tau_t; \phi_{g,t}; \phi_{b,t}; \phi^S_t; \epsilon_{g,t}; \epsilon_{b,t}; \epsilon^S_t; R_{g,t}; R_{b,t}; R_{o,t}; G_{g,t}; G_{b,t}; G_{o,t}; Q_{g,t}; Q_{b,t}; Q_{o,t}; R^f_t; R_{m,t}\}.
\end{aligned} \tag{B.2}$$

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

$$\hat{Y}_t = \left((\bar{A}\hat{Y}_{g,t})^{1-\frac{1}{\epsilon}} + (\bar{A}\hat{Y}_{b,t})^{1-\frac{1}{\epsilon}}\right)^{\frac{1}{1-\frac{1}{\epsilon}}}, \tag{B.3}$$

$$\hat{Y}_{i,t} = p_{i,t}^{-\epsilon}\bar{A}^{\varepsilon-1}\hat{Y}_t. \tag{B.4}$$

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

$$\Delta a_t = \mu_A + \sigma_A \varepsilon^A_t, \tag{B.5}$$

$$\hat{K}_{i,t+1}e^{\Delta a_{t+1}} = (1-\delta)\hat{K}_{i,t} + \hat{I}_{i,t} - G_{i,t}\hat{K}_{i,t}, \tag{B.6}$$

$$G_{i,t} = \frac{\hat{I}_{i,t}}{\hat{K}_{i,t}} - \left(a_{0,i} + \frac{a_{1,i}}{1-\frac{1}{\zeta}} \left(\frac{\hat{I}_{i,t}}{\hat{K}_{i,t}} \right)^{1-\frac{1}{\zeta}} \right), \tag{B.7}$$

$$\hat{Y}_{g,t} = L_{g,t}^{1-\alpha}\hat{K}_{g,t}^{\alpha}, \tag{B.8}$$

$$\hat{Y}_{b,t} = L_{b,t}^{1-\alpha}\hat{Z}_{t}^{\alpha}, \tag{B.9}$$

$$\hat{Z}_t = \left((1-\iota)\hat{K}_{b,t}^{1-\frac{1}{o}} + \iota\hat{O}_t^{1-\frac{1}{o}} \right)^{\frac{1}{1-\frac{1}{o}}}, \tag{B.10}$$

$$0 = p_{g,t} - \lambda_{g,t}, \tag{B.11}$$

$$0 = p_{b,t} - \tau_t\xi_b - \lambda_{b,t} - \epsilon_{b,t}\xi_b, \tag{B.12}$$

$$0 = -(1-\rho_T)\mathbb{E}_t[\mathbb{M}_{t+1}\phi_{i,t+1}e^{\Delta a_{t+1}}] + \phi_{i,t}, \tag{B.13}$$

$$0 = -\chi\phi_{i,t} - (1-\rho_{\mathcal{E}})\mathbb{E}_t[\mathbb{M}_{t+1}\epsilon_{i,t+1}e^{\Delta a_{t+1}}] + \epsilon_{i,t}, \tag{B.14}$$

$$\hat{\widetilde{w}}_t = \lambda_{i,t}(1-\alpha)\frac{\hat{Y}_{i,t}}{L_{i,t}}, \tag{B.15}$$

$$R_{g,t}^{K} = \lambda_{g,t}\alpha\frac{\hat{Y}_{g,t}}{\hat{K}_{g,t}}, \tag{B.16}$$

$$R_{b,t}^{K} = \lambda_{b,t}\alpha(1-\iota)\frac{\hat{Y}_{b,t}}{\hat{Z}_t^{1-\frac{1}{o}}\hat{K}_{b,t}^{\frac{1}{o}}}, \tag{B.17}$$

$$p_{o,t} = \lambda_{b,t}\alpha\iota\frac{\hat{Y}_{b,t}}{\hat{Z}_t^{1-\frac{1}{o}}\hat{O}_t^{\frac{1}{o}}}. \tag{B.18}$$

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

$$\hat{K}_{o,t+1}e^{\Delta a_{t+1}} = (1-\delta)\hat{K}_{o,t} + \hat{I}_{o,t} - G_{o,t}\hat{K}_{o,t}, \tag{B.19}$$

$$G_{o,t} = \frac{\hat{I}_{o,t}}{\hat{K}_{o,t}} - \left(a_{0,o} + \frac{a_{1,o}}{1-\frac{1}{\zeta}} \left(\frac{\hat{I}_{o,t}}{\hat{K}_{o,t}} \right)^{1-\frac{1}{\zeta}} \right), \tag{B.20}$$

$$\hat{U}_{t+1}e^{\Delta a_{t+1}} = (1-\kappa_o)\hat{U}_t + \hat{N}_t, \tag{B.21}$$

$$\hat{N}_t = L_{o,t}^{1-\alpha_o}\hat{K}_{o,t}^{\alpha_o}, \tag{B.22}$$

$$\hat{O}_t = \hat{E}_t, \tag{B.23}$$

$$\hat{E}_t = \kappa_o\hat{U}_t, \tag{B.24}$$

$$\lambda_{o,t} = \phi_{o,t}, \tag{B.25}$$

$$\hat{\tilde{w}}_t = \lambda_{o,t}(1-\alpha_o)\frac{\hat{N}_t}{L_{o,t}}, \tag{B.26}$$

$$R^K_{o,t} = \lambda_{o,t}\alpha_o\frac{\hat{N}_t}{\hat{K}_{o,t}}, \tag{B.27}$$

$$0 = \kappa_o\mathbb{E}_t[\mathbb{M}_{t+1}p_{o,t+1}] - \phi_{o,t} + (1-\kappa_o)\mathbb{E}_t[\mathbb{M}_{t+1}\phi_{o,t+1}]. \tag{B.28}$$

The asset pricing equations in normalized form look as follows:

$$1 = \mathbb{E}_t[\mathbb{M}_{t+1}R^k_{i,t+1}], \tag{B.29}$$

$$R^k_{i,t+1} = \frac{R^K_{i,t+1} + ((1-\delta) + G'_{i,t+1}\frac{\hat{I}_{i,t+1}}{\hat{K}_{i,t+1}} - G_{i,t+1})Q_{i,t+1}}{Q_{i,t}}, \tag{B.30}$$

$$Q_{i,t} = \frac{1}{1-G'_{i,t}}, \tag{B.31}$$

$$\hat{D}_{g,t} = p_{g,t}\hat{Y}_{g,t} - R^K_{g,t}\hat{K}_{g,t} - \hat{w}_tL_{g,t}, \tag{B.32}$$

$$\hat{D}_{b,t} = p_{b,t}\hat{Y}_{b,t} - R^K_{b,t}\hat{K}_{b,t} - \hat{w}_tL_{b,t} - p_{o,t}\hat{O}_t - \tau_t\xi_b\hat{Y}_{b,t}, \tag{B.33}$$

$$\hat{D}_{o,t} = p_{o,t}\hat{O}_t - R^K_{o,t}\hat{K}_{o,t} - \hat{w}_tL_{o,t}, \tag{B.34}$$

$$\hat{D}_{a,t} = \hat{D}_{g,t} + \hat{D}_{b,t} + \hat{D}_{o,t}, \tag{B.35}$$

$$\hat{V}_{i,t} = \hat{D}_{i,t} + \mathbb{E}_t[\mathbb{M}_{t+1}\hat{V}_{i,t+1}e^{\Delta a_{t+1}}], \quad i = g,b,o, \tag{B.36}$$

$$\hat{V}_{a,t} = \hat{D}_{a,t} + \mathbb{E}_t[\mathbb{M}_{t+1}\hat{V}_{a,t+1}e^{\Delta a_{t+1}}], \tag{B.37}$$

$$R_{i,t} = \frac{\hat{V}_{i,t}e^{\Delta a_t}}{\hat{V}_{i,t-1} - \hat{D}_{i,t-1}}, \quad i = g,b,o, \tag{B.38}$$

$$R_{m,t} = \frac{\hat{V}_{a,t}e^{\Delta a_t}}{\hat{V}_{a,t-1} - \hat{D}_{a,t-1}}. \tag{B.39}$$

The household and aggregate equations in normalized form look as follows:

$$\hat{V}_t = \left[(1-\beta)\hat{C}_t^{1-\frac{1}{\psi}} + \beta\left(\hat{\mathbb{E}}_t[V^{1-\gamma}_{t+1}]\right)^{\frac{1-\frac{1}{\psi}}{1-\gamma}}\right]^{\frac{1}{1-\frac{1}{\psi}}}, \tag{B.40}$$

$$\hat{\mathbb{E}}_t[V^{1-\gamma}_{t+1}] = \mathbb{E}_t[(\hat{V}_{t+1}e^{\Delta a_{t+1}})^{1-\gamma}], \tag{B.41}$$

$$\mathbb{M}_{t+1} = \beta \left(e^{\Delta a_{t+1}}\right)^{-\frac{1}{\psi}} \left(\frac{\hat{C}_{t+1}}{\hat{C}_t}\right)^{-\frac{1}{\eta}} \left(\frac{\hat{\tilde{C}}_{t+1}}{\hat{\tilde{C}}_t}\right)^{\frac{1}{\eta}-\frac{1}{\varphi}} \left(\frac{\hat{\vartheta}_{t+1}}{\hat{\vartheta}_t}\right)^{\frac{1}{\varphi}-\frac{1}{\psi}} \left(\frac{\hat{V}_{t+1}e^{\Delta a_{t+1}}}{\left(\hat{\mathbb{E}}_t[V_{t+1}^{1-\gamma}]\right)^{\frac{1}{1-\gamma}}}\right)^{\frac{1}{\psi}-\gamma}, \tag{B.42}$$

$$\hat{\vartheta}_t = \left((1-\theta)(\hat{\tilde{C}}_t)^{1-\frac{1}{\varphi}} + \theta(X_t)^{1-\frac{1}{\varphi}}\right)^{\frac{1}{1-\frac{1}{\varphi}}}, \tag{B.43}$$

$$\hat{\tilde{C}}_t = \left[(1-\nu)\hat{C}_t^{1-\frac{1}{\eta}} + \nu(l_t)^{1-\frac{1}{\eta}}\right]^{\frac{1}{1-\frac{1}{\eta}}}, \tag{B.44}$$

$$\ell_t = 1 - L_{g,t} - L_{b,t} - L_{o,t}, \tag{B.45}$$

$$\hat{Y}_t = \hat{C}_t + \hat{I}_{g,t} + \hat{I}_{b,t} + \hat{I}_{o,t} + \bar{g}\hat{Y}_t, \tag{B.46}$$

$$(\hat{C}_t)^{\frac{1}{\eta}} = \frac{\nu}{1-\nu}\hat{\tilde{w}}_t(l_t)^{\frac{1}{\eta}}, \tag{B.47}$$

The environmental equations in normalized forms are as follows:

$$\mathcal{E}_{t+1} = (1-\rho_{\mathcal{E}})\mathcal{E}_t + \xi_b\hat{Y}_{b,t}, \tag{B.48}$$

$$T_{t+1} = (1-\rho_T)T_t + \rho_T\chi\mathcal{E}_{t+1} + \sigma_T\varepsilon_{t+1}^T, \tag{B.49}$$

$$\tau_t = \Theta_t\tau_t^*, \tag{B.50}$$

$$\tau_t^* = \epsilon_t^S, \tag{B.51}$$

$$0 = -\rho_T\chi\phi_t^S - (1-\rho_{\mathcal{E}})\mathbb{E}_t[\mathbb{M}_{t+1}\epsilon_{t+1}^S e^{\Delta a_{t+1}}] + \epsilon_t^S, \tag{B.52}$$

$$0 = -\mathbb{E}_t\left[\mathbb{M}_{t+1}\lambda_{X,t+1}X_{t+1}e^{\Delta a_{t+1}}\frac{\kappa_{X,1}\kappa_{X,2}T_{t+1}^{\kappa_{X,2}-1}}{1+\kappa_{X,1}T_{t+1}^{\kappa_{X,2}}}\right] - (1-\rho_T)\mathbb{E}_t[\mathbb{M}_{t+1}\phi_{t+1}^S e^{\Delta a_{t+1}}] + \phi_t^S, \tag{B.53}$$

$$X_t = \frac{\bar{X}}{1+\kappa_{X,1}T_t^{\kappa_{X,2}}}, \tag{B.54}$$

$$\lambda_{X,t} = \frac{\theta}{1-\theta}\left(\frac{X_t}{\hat{C}_t}\right)^{-\frac{1}{\varphi}}, \tag{B.55}$$

$$\Theta_{t+1} = (1-\rho_\Theta)(1-\mu_\Theta) + \rho_\Theta\Theta_t + \sigma_\Theta\varepsilon_{t+1}^\Theta. \tag{B.56}$$

C Sectoral Output Construction for 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. Following the classification by Binder (2001) and including the transportation sector, we classify the following of these industries as constituents 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:

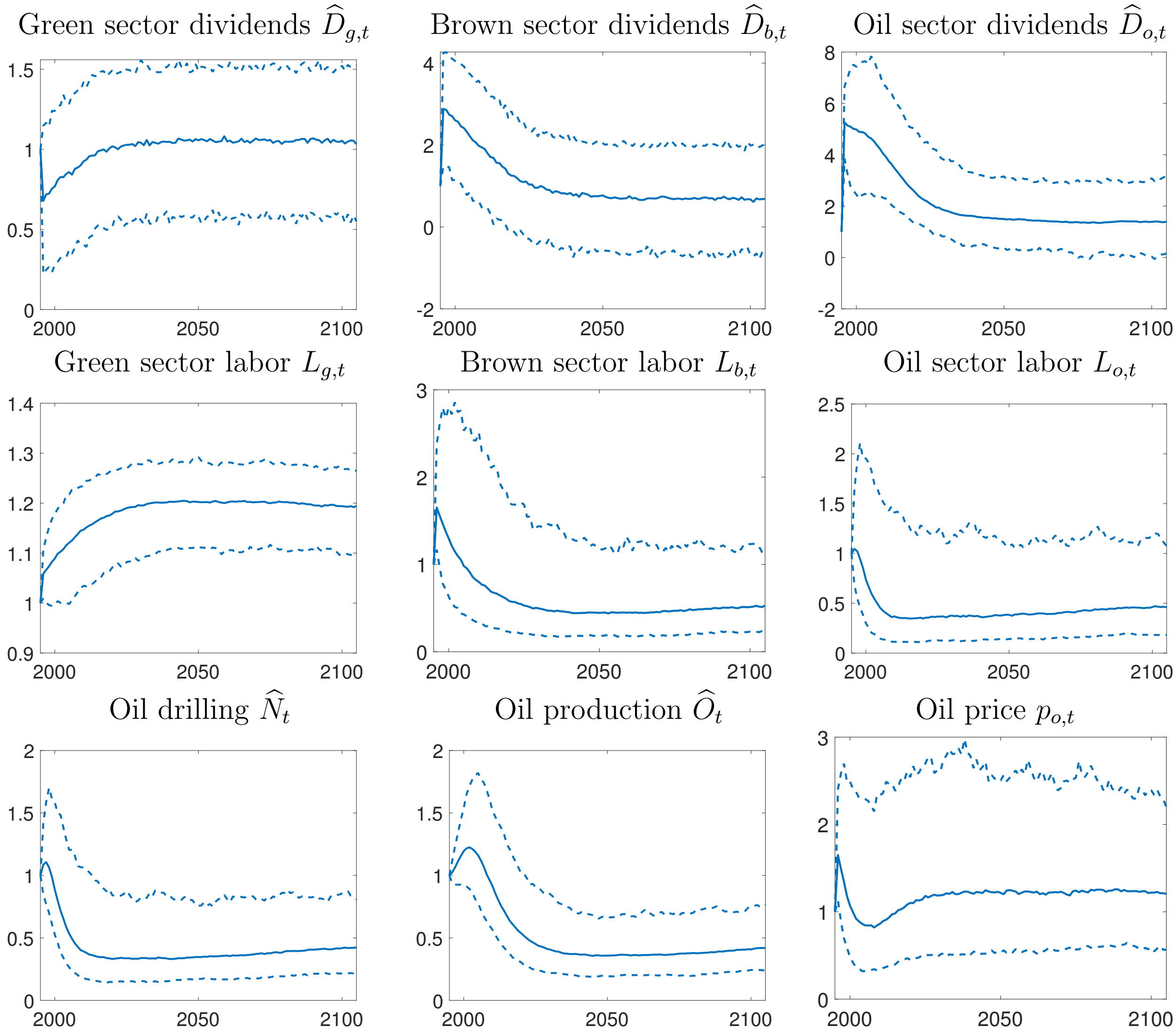
- Mining (Line 6)
- Petroleum and coal products (Line 31)

- Pipeline transportation (Line 46)

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

D Simulating the Climate Transition: Additional Variables

Figure D.1: Transition dynamics of additional variables



Green sector dividends $\widehat{D}_{g,t}$

Brown sector dividends $\widehat{D}_{b,t}$

Oil sector dividends $\widehat{D}_{o,t}$

Green sector labor $L_{g,t}$

Brown sector labor $L_{b,t}$

Oil sector labor $L_{o,t}$

Oil drilling $\widehat{N}_t$

Oil production $\widehat{O}_t$

Oil price $p_{o,t}$

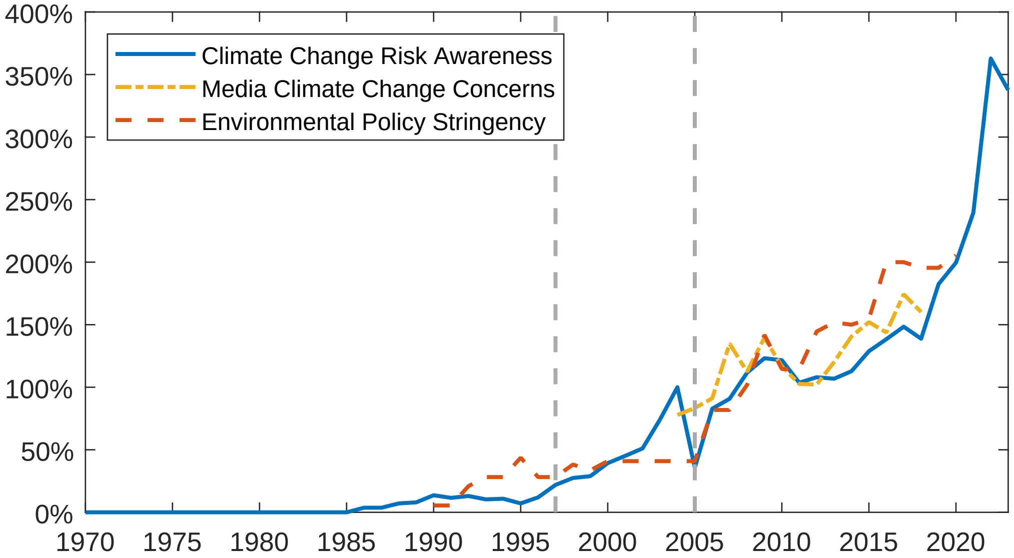
This figure illustrates the dynamics of additional variables (dividends, labor, and oil-sector variables) over the climate transition. The transition dynamics are computed for 110 years (from 1995 to 2105) and 1,000 sample economies at a monthly frequency. The initial point of the simulation is the unconditional mean of the pre-transition economy. All variables are normalized to 1 at the start of the transition, and we adjust dividends as well as oil drilling and production for the economy's productivity growth, such that the transition dynamics can be interpreted relative to the balanced growth path. The median path across the 1,000 economies is depicted for the considered variables, alongside 95% confidence bands according to the corresponding quantiles at any given point in time.

E Measuring Climate Change Risk Awareness

We construct a simple Climate Change Risk Awareness Index (CCRAI) that provides us with a measure of economic agents' 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 moving averages for the Google Ngram data. Finally, we combine the two resulting time series by normalizing their value in 2004 to 100% and using the literature-based measure before 2004 and the search-volume-based measure after 2004.

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

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, for the sample period from 1970 to 2024. The Environmental Policy Stringency Index for the United States is provided by the OECD from 1990 to 2020, and the Media Climate Change Concerns measure is computed and provided by Ardia et al. (2023). 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.

today. The initial increase in climate change risk awareness 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. (2023), 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.[24] Our climate change risk awareness index co-moves strongly with the measure from Ardia et al. (2023) 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 clearly reflected by the policy-makers' side, supporting our modeling approach for the climate transition.

---

[24] 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).

F Additional Tables

Table F.1: Summary statistics of CRSP/Compustat data sample

Panel A: Full Sample

	Mean	SD	10%	25%	50%	75%	90%	Observations
Market-to-book ratio	2.49	3.10	0.60	0.94	1.54	2.71	5.01	223,435
Tobin's q	4.21	9.91	-0.09	0.40	1.02	3.29	10.17	180,985
Total q	1.23	2.33	-0.07	0.22	0.62	1.29	2.84	185,357
Cash ratio	1.14	2.39	0.04	0.11	0.36	1.05	2.76	183,965
Debt-to-asset ratio	0.55	0.24	0.22	0.37	0.55	0.72	0.89	223,110
Log assets	6.06	2.14	3.38	4.41	5.89	7.53	8.99	223,435
R&D-to-sales ratio	0.11	0.66	0.00	0.00	0.00	0.02	0.12	223,435

Panel B: Oil Firms

	Mean	SD	10%	25%	50%	75%	90%	Observations
Market-to-book ratio	2.20	2.72	0.61	0.94	1.47	2.37	4.00	10,110
Tobin's q	1.19	2.79	0.21	0.41	0.69	1.15	2.09	9,947
Total q	0.93	1.27	0.19	0.37	0.63	1.04	1.82	9,748
Cash ratio	0.92	2.28	0.03	0.11	0.31	0.74	1.90	9,993
Debt-to-asset ratio	0.50	0.20	0.21	0.37	0.52	0.64	0.75	10,103
Log assets	6.01	2.54	2.69	4.00	5.88	7.85	9.54	10,110
R&D-to-sales ratio	0.00	0.08	0.00	0.00	0.00	0.00	0.00	10,110

This table reports summary statistics of the CRSP/Compustat data sample used in our empirical analysis. 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 the full sample and Panel B the subsample of oil firms. Observations are in firm-years.

Table F.2: Relation of oil firm valuations to climate change risk awareness

	Market-to-book ratio				
	(1)	(2)	(3)	(4)	(5)
$1_{Oil} \times CCRAI$	-0.448**	-0.583***	-0.545***	-0.496***	-0.474**
	(0.174)	(0.194)	(0.191)	(0.185)	(0.183)
1_{Oil}	0.005	-0.130	-0.137	-0.134	-0.114
	(0.143)	(0.156)	(0.154)	(0.156)	(0.155)
$CCRAI$	0.574***	0.656***	0.598***	0.674***	0.642***
	(0.135)	(0.160)	(0.157)	(0.178)	(0.174)
Cash ratio		0.118***	0.256***	0.251***	0.214***
		(0.021)	(0.019)	(0.019)	(0.018)
Debt-to-asset ratio			3.368***	3.572***	3.514***
			(0.354)	(0.371)	(0.372)
Log assets				-0.086***	-0.076***
				(0.025)	(0.024)
R&D-to-sales ratio					0.327***
					(0.056)
Observations	223435	183965	183647	183647	183647
Adjusted R^2	0.023	0.039	0.075	0.078	0.082

This table reports results from a panel regression of firms' market-to-book ratios on the Climate Change Risk Awareness Index (CCRAI), an oil firm indicator, and their interaction term, as well as a standard set of control variables. Our set of control variables includes the firms' cash ratio, the amount of debt relative to assets, the log of total assets, and the ratio of research and development (R&D) expenditures to sales. Our sample runs from 1970 to 2024. Standard errors double-clustered by firm and year are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table F.3: Relation of fossil fuel firm valuations to climate change risk awareness

	Market-to-book ratio				
	(1)	(2)	(3)	(4)	(5)
$1_{Fossilfuel} \times CCRAI$	-0.457***	-0.590***	-0.555***	-0.508***	-0.486**
	(0.170)	(0.190)	(0.190)	(0.184)	(0.182)
$1_{Fossilfuel}$	0.028	-0.105	-0.124	-0.119	-0.099
	(0.141)	(0.153)	(0.153)	(0.154)	(0.154)
$CCRAI$	0.576***	0.658***	0.600***	0.676***	0.643***
	(0.136)	(0.160)	(0.157)	(0.178)	(0.175)
Cash ratio		0.118***	0.256***	0.251***	0.214***
		(0.021)	(0.019)	(0.019)	(0.018)
Debt-to-asset ratio			3.371***	3.573***	3.515***
			(0.354)	(0.371)	(0.372)
Log assets				-0.086***	-0.076***
				(0.025)	(0.024)
R&D-to-sales ratio					0.327***
					(0.056)
Observations	223435	183965	183647	183647	183647
Adjusted R^2	0.023	0.039	0.075	0.078	0.082

This table reports results from a panel regression of firms' market-to-book ratios on the Climate Change Risk Awareness Index (CCRAI), a fossil fuel firm indicator, and their interaction term, as well as a standard set of control variables. Our set of control variables includes the firms' cash ratio, the amount of debt relative to assets, the log of total assets, and the ratio of research and development (R&D) expenditures to sales. Our sample runs from 1970 to 2024. Standard errors double-clustered by firm and year are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table F.4: Relation of oil firm valuations to climate change risk awareness: Excluding IT firms from the sample

	Market-to-book ratio				
	(1)	(2)	(3)	(4)	(5)
$1_{Oil} \times CCRAI$	-0.409**	-0.551***	-0.517***	-0.471**	-0.447**
	(0.167)	(0.189)	(0.185)	(0.180)	(0.177)
1_{Oil}	0.107	-0.036	-0.004	-0.004	0.018
	(0.138)	(0.150)	(0.145)	(0.147)	(0.147)
$CCRAI$	0.541***	0.629***	0.576***	0.651***	0.618***
	(0.127)	(0.155)	(0.151)	(0.171)	(0.167)
Cash ratio		0.121***	0.249***	0.243***	0.203***
		(0.019)	(0.018)	(0.018)	(0.016)
Debt-to-asset ratio			3.292***	3.500***	3.445***
			(0.326)	(0.343)	(0.343)
Log assets				-0.084***	-0.074***
				(0.024)	(0.023)
R&D-to-sales ratio					0.329***
					(0.055)
Observations	199133	159787	159555	159555	159555
Adjusted R^2	0.022	0.041	0.078	0.081	0.086

This table reports results from a panel regression of firms' market-to-book ratios on the Climate Change Risk Awareness Index (CCRAI), an oil firm indicator, and their interaction term, as well as a standard set of control variables. We exclude IT firms from our overall sample, which are classified in line with Ward (2020). Our set of control variables includes the firms' cash ratio, the amount of debt relative to assets, the log of total assets, and the ratio of research and development (R&D) expenditures to sales. Our sample runs from 1970 to 2024. Standard errors double-clustered by firm and year are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table F.5: Relation of oil firm valuations to climate change risk awareness: Accounting for assets at risk

	Market-to-book ratio				
	(1)	(2)	(3)	(4)	(5)
$1_{Oil} \times CCRAI$	-0.438**	-0.577***	-0.543***	-0.498**	-0.475**
	(0.176)	(0.197)	(0.193)	(0.187)	(0.185)
$1_{Fewassetsatrisk} \times CCRAI$	-0.019	0.039	0.230*	0.224*	0.219*
	(0.123)	(0.117)	(0.129)	(0.124)	(0.124)
1_{Oil}	0.010	-0.124	-0.126	-0.126	-0.106
	(0.143)	(0.156)	(0.154)	(0.156)	(0.155)
$1_{Fewassetsatrisk}$	-0.489***	-0.449***	-0.703***	-0.546***	-0.579***
	(0.144)	(0.150)	(0.179)	(0.177)	(0.175)
$CCRAI$	0.574***	0.656***	0.598***	0.674***	0.641***
	(0.135)	(0.160)	(0.157)	(0.178)	(0.174)
Cash ratio		0.118***	0.256***	0.251***	0.214***
		(0.021)	(0.019)	(0.019)	(0.018)
Debt-to-asset ratio			3.369***	3.572***	3.514***
			(0.354)	(0.371)	(0.372)
Log assets				-0.086***	-0.076***
				(0.025)	(0.024)
R&D-to-sales ratio					0.327***
					(0.056)
Observations	223435	183965	183647	183647	183647
Adjusted R^2	0.023	0.039	0.075	0.078	0.082

This table reports results from a panel regression of firms' market-to-book ratios on the Climate Change Risk Awareness Index (CCRAI), an oil firm indicator, their interaction term, an indicator for firms having few carbon assets at risk and its interaction with the Climate Change Risk Awareness Index (CCRAI), as well as a standard set of control variables. The *Fewassetsatrisk* indicator is one for firms that are in the lowest cross-secctional quartile of capital expenditures at risk according to the *2 degrees of separation* initiative dataset provided by CarbonTracker. Our set of control variables includes the firms' cash ratio, the amount of debt relative to assets, the log of total assets, and the ratio of research and development (R&D) expenditures to sales. Our sample runs from 1970 to 2024. Standard errors double-clustered by firm and year are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table F.6: Relation of oil firm valuations to climate change risk awareness: Tobin's q

	Tobin's q				
	(1)	(2)	(3)	(4)	(5)
$1_{Oil} \times CCRAI$	-2.722***	-2.182***	-2.226***	-2.408***	-2.347***
	(0.574)	(0.506)	(0.507)	(0.499)	(0.487)
1_{Oil}	-1.457***	-1.539***	-1.523***	-1.535***	-1.475***
	(0.344)	(0.315)	(0.317)	(0.320)	(0.321)
$CCRAI$	2.827***	2.131***	2.200***	1.894***	1.803***
	(0.595)	(0.480)	(0.482)	(0.477)	(0.464)
Cash ratio		1.345***	1.191***	1.206***	1.087***
		(0.116)	(0.117)	(0.118)	(0.115)
Debt-to-asset ratio			-3.649***	-4.445***	-4.640***
			(0.553)	(0.602)	(0.589)
Log assets				0.338***	0.368***
				(0.067)	(0.067)
R&D-to-sales ratio					0.966***
					(0.165)
Observations	180985	180444	180442	180442	180442
Adjusted R^2	0.057	0.150	0.155	0.159	0.163

This table reports results from a panel regression of firms' Tobin's q on the Climate Change Risk Awareness Index (CCRAI), an oil firm indicator, and their interaction term, as well as a standard set of control variables. Our set of control variables includes the firms' cash ratio, the amount of debt relative to assets, the log of total assets, and the ratio of research and development (R&D) expenditures to sales. Our sample runs from 1970 to 2024. Standard errors double-clustered by firm and year are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

Table F.7: Relation of oil firm valuations to climate change risk awareness: Total q

	Total q				
	(1)	(2)	(3)	(4)	(5)
$1_{Oil} \times CCRAI$	-0.406***	-0.313**	-0.323**	-0.374***	-0.383***
	(0.128)	(0.121)	(0.122)	(0.119)	(0.120)
1_{Oil}	-0.095	-0.050	-0.046	-0.047	-0.055
	(0.107)	(0.105)	(0.107)	(0.104)	(0.105)
$CCRAI$	0.472***	0.290***	0.310***	0.207**	0.221**
	(0.085)	(0.078)	(0.078)	(0.087)	(0.087)
Cash ratio		0.274***	0.226***	0.230***	0.247***
		(0.026)	(0.024)	(0.024)	(0.025)
Debt-to-asset ratio			-1.116***	-1.307***	-1.281***
			(0.126)	(0.141)	(0.141)
Log assets				0.081***	0.077***
				(0.013)	(0.013)
R&D-to-sales ratio					-0.138***
					(0.022)
Observations	185357	175407	175108	175108	175108
Adjusted R^2	0.016	0.103	0.113	0.118	0.120

This table reports results from a panel regression of firms' Peters and Taylor (2017) total q on the Climate Change Risk Awareness Index (CCRAI), an oil firm indicator, and their interaction term, as well as a standard set of control variables. Our set of control variables includes the firms' cash ratio, the amount of debt relative to assets, the log of total assets, and the ratio of research and development (R&D) expenditures to sales. Our sample runs from 1970 to 2024. Standard errors double-clustered by firm and year are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.