Macro and Asset Price Dynamics During the Climate Transition: Evidence from the Oil Sector

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Abstract

This paper analyzes the climate-related transition from brown towards green industries through the lens of the oil sector. We show that the relative valuations of oil firms have decoupled from the oil price around the year 2000, and they have declined by one third with the rise of climate change risk awareness. A macro asset pricing model matches this devaluation and allows us to characterize asset prices, risk premia, and macroeconomic quantities over the transition. The model predicts that carbon premia become *more positive* as the climate transition proceeds.

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1 Introduction

Scientists, business leaders, and policy-makers worldwide predict almost unanimously that the world will be transitioning towards a low-carbon economy in the next 50 years to avoid the worst possible climate change scenarios. This situation presents a unprecedented challenge for the economy, and there is strong agreement that the transition is a new main driver of capital allocation decisions, firms' cash flows and stock market valuations, as well as fossil fuel commodity prices. Furthermore, climate policy risk becomes a key systematic risk factor in this new era. Despite overwhelming interest, the implications of the climate transition for economic and financial market outcomes are not precisely understood at this point. This paper aims to contribute to this understanding by analyzing the effects of the climate transition through the lens of the oil sector, providing a new perspective on this topic.

We start by asking to what extent the effects of the transition are already reflected by current financial market outcomes. To this end we take a close look at the fossil fuel sector, arguing that this sector is the one that is first and most significantly affected prior to other industries. We construct a new measure for climate change risk awareness and analyze how the market valuation of oil firms has changed with increasing awareness, relative to other firms and controlling for a number of factors. Our results show that compared to other firms, the market-to-book ratios of fossil fuel firms have decreased by more than one third in the last 20 years, together with a strong increase in climate change risk awareness. In addition, oil firms' market valuations have decoupled from oil prices in the beginning of the 2000s, with a much weaker relation in recent times compared to before.

These empirical results indicate that the climate transition is significantly reflected by financial market valuations as of today, adding to a vivid debate on the effects on brown compared to green firms in the recent years. Bolton and Kacperczyk (2021) find that stocks of brown firms delivered higher returns than those of green firms in the period from 2005 to 2017 and attribute this to a carbon premium. Pastor, Stambaugh, and Taylor (2021b) argue that brown assets should indeed have higher returns in equilibrium, but that green firms in fact delivered higher *realized* returns between 2013 and 2020 (see also In, Park, and Monk 2018) due to an increased preference for green investments (Pastor, Stambaugh, and Taylor 2021a). Our analysis focuses on the fossil fuel sector, a clearly brown sector, which allows us to avoid classification issues regarding the brown- and green-ness of different industries. We find that the stock market valuations of oil firms have, in fact, steadily declined since the 2000s compared to other firms and decoupled from the oil price, indicating that the market has started pricing the transition away from fossil fuels around that time.

After establishing the status quo, we ask how the dynamics of macroeconomic quantities and asset prices evolve in the *future* as the transition towards a low-carbon world economy proceeds. Important open questions are: How are the valuations of firms (measured by book-to-market ratios or Tobin's Qs) predicted to behave over the transition period, dependent on their carbon intensity? Do risk premia amplify or counteract the cash flow effects of the climate transition? How does the dynamics of capital reallocation between the different sectors evolve? Finally, how does the oil price behave during the different stages of the transition?

We develop a macro asset pricing model for the climate transition to investigate these questions qualitatively and quantitatively. Our model is based on a production economy with a *climate change externality*: Environmental quality, which enters the utility function of households, is negatively affected by permanent changes in temperature, and the global temperature level is influenced by the greenhouse gas emissions of the economy. "Dirty" ("brown", fossil-fuel consuming) firms have a higher emissions intensity than "clean" ("green") firms, and they do not internalize the negative effect of their emissions on the economy, such that a climate change externality arises. To bring the economy closer to the social optimum, the regulator introduces a carbon tax. 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 exogenous regulation shocks, standing for hardly predictable results of political processes, which represent the source of *climate policy risk* in the model.

We initialize the model by considering a special case which represents the 'pre-transition' economy. In this scenario, economic agents believe that there is no causal relation between the economy's greenhouse gas emissions and global temperature levels, such that the climate change externality is neglected and the optimal carbon tax is zero. We use this special case of the model to calibrate it to empirical moments computed for the time before 1995. After that, we change the parameter determining the relation between emissions and global temperature from zero to its actual value, and simulate the model as it converges from the pre-transition world to a new equilibrium with full awareness of climate change risks and eventually optimal carbon taxation.

Evaluating the results of this simulation, we show that the model reproduces the decline in fossil fuel firm valuations in the beginning of the transition period that we find empirically. Our analysis furthermore shows that this result translates to the high-carbon firms, whose Tobin's Qs similarly decline in the beginning of the transition period in the calibrated model. The valuation of clean firms, on the other hand, increases in the short run, consistent with the intuition that low-carbon industries become more profitable relative to dirty industries as the carbon tax increases. The change of valuations triggers a reallocation of capital between the different sectors in the transition period, such that capital is moved from the dirty production sector and the fossil fuel sector towards the clean sector. As a result, valuation ratios in all sectors are predicted to revert again towards the end of the climate transition in all sectors.

We next use the model to analyze climate policy risk premia. Under Epstein and Zin (1991) preferences, the effect of tax-increasing climate policy shocks on the stochastic discount factor depends on their impact 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. In our model calibration, the negative effect on current consumption is quantitatively larger, leading to an increase of the stochastic discount factor overall. Since fossil fuel firms and dirty firms respond negatively to tax-increasing climate policy shocks (and positively to tax-reducing climate policy shocks), the resulting climate policy risk premia are positive. The result implies that dirty assets have higher returns in equilibrium, in line with Bolton and Kacperczyk (2021) and Pastor, Stambaugh, and Taylor (2021b), and alleviates the paradox pointed out by Baker, Hollifield, and Osambela (2019) and Roth Tran (2019) that dirty firms should command negative risk premia in general equilbrium as a hedge against the consequences of climate change. Our model furthermore reveals that climate policy risk premia should become *more positive* over the climate transition.

Climate policy risk premia also prevail when the transition to a low-carbon economy is accomplished, as it will still be the regulator's task to set the carbon tax close to the level that is welfare-optimal for the economy. We show that in the post-transition time, climate policy risk premia are still clearly positive, as a tax-increasing shock will have a negative effect both on current consumption and on future utility when the carbon tax is close to its socially optimal level.

Finally, the model demonstrates that the behavior of oil prices over the transition period resembles the decline and subsequent recovery of fossil-fuel producing and consuming firm valuations. In particular, the production from existing oil wells is relatively rigid in the short run, such that the oil price is mainly driven by the divestment from fossil-fuel consuming firms and the lower resulting demand for oil. Afterwards, the divestment from fossil fuel *producers* eventually results in a decline in oil production, such that the oil price stabilizes again towards the end of the transition period.

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

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

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

2 Climate Transition and Oil Firm Valuations

This section analyzes how the market valuations of fossil fuel firms have been affected by the start of the climate transition. We first introduce our measure of climate change risk awareness and show that it is continuously increased in the past two decades. Second, we provide evidence that the fossil fuel sector is the sector that is most directly and immediately affected by the climate transition, and therefore a perfect laboratory to analyze the effect on firm valuations. Finally, we show that valuations in the oil sector have significantly declined relative to other sectors with the increased awareness for climate change risks.

2.1 Measuring Climate Change Risk Awareness

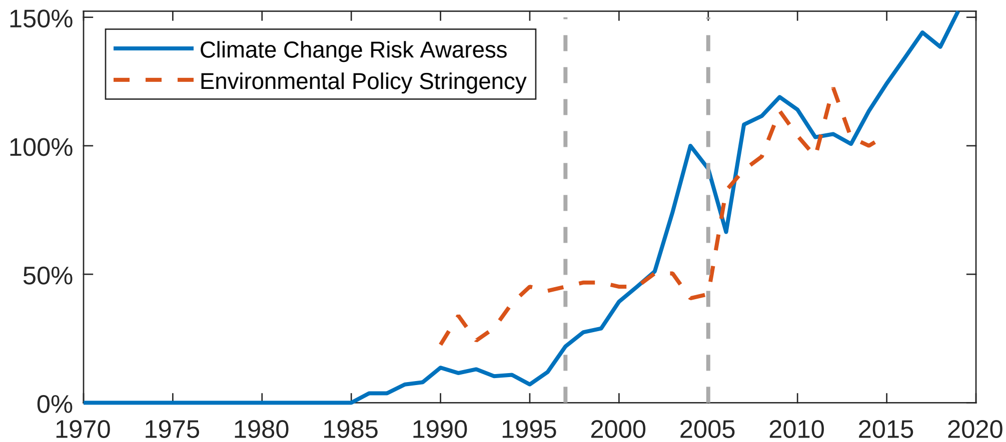
The awareness of climate change and related risks seems to be higher today than ever. In the United States, the *Green New Deal* proposed in a letter with more than 600 signatory organizations has recently received considerable attention and support by the Democratic party. Internationally, movements such as *Fridays for Future*, in which more than 1 million school students go on strike for the climate, are not only very present in the media, but also receive backing by international scientists organized as *Scientists for Future*. A common demand of these initiatives is that fossil fuel extraction should be banned as soon as possible in order to achieve the transition to a clean energy world. While the aforementioned initiatives justifiably argue that the "current measures for protecting the climate and biosphere are deeply inadequate" (Hagedorn et al. 2019), a considerable number of countries and regions around the world have taken first steps towards a world with cleaner energy in the last two decades: As of now, about 20% of worldwide greenhouse gas emissions are covered by a carbon price,[1] while this number was virtually 0% in the year 2000. The number and stringency of other environmental regulations has also increased quite continuously over the last two decades according to measures such as the environmental policy stringency measure provided by the OECD.[2]

To capture the described trend quantitatively, we construct a simple Climate Change Risk

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

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

Figure 1: Climate Change Risk Awareness Index and Environmental Policy Stringency Index. The Climate Change Risk Awareness Index (CCRAI) is constructed based on the number of occurrences of the term *climate change risk* in the literature and in search volumes on Google. The Environmental Policy Stringency Index for the United States is provided by the OECD. The first gray dashed line marks the adoption of the Kyoto Protocol in December 1997, the second one marks February 2005, when the Protocol came into force.



Awareness Index (CCRAI) based on the number of occurrences of the term *climate change risk* in the literature and in search volumes on Google. In particular, we combine data from Google Ngram, which is available on a yearly basis from 1970 to 2008, with data from Google Trends, where monthly data on search volumes is provided starting in 2004. We aggregate the monthly Google Trends data to an annual frequency, and construct 5-year leading moving averages for the Google Ngram data, representing the assumption that it takes about 5 years to write and publish a book. Finally, we combine the two resulting time series by normalizing their value in 2004 to 100%. Figure 1 plots our climate risk awareness index over time, showing a substantial and continuous increase of awareness which started in the second half of the 1990s and continues until today. The start of this trend coincides also quite nicely with the adoption of the Kyoto Protocol in 1997. The figure also compares our measure to the environmental policy stringency in the United States as provided by the OECD, which confirms this general trend from the policy-makers' side.

2.2 Exposure of Oil Firms to the Climate Transition

We argue that the energy sector, and in particular fossil fuel producing firms, are most directly and immediately affected by the transition to a climate-friendly world economy. Intuitively, the simple reason is that the CO_2 emissions generated by burning fossil fuels account for 76% of the anthropogenic greenhouse gas emissions, while the remaining 24% come from other sources such as non-energy related industrial production processes or farming.[3] We provide evidence on the outstanding role of the fossil fuel sector, on the one hand from the perspective of integrated assessment models for climate change, and on the other hand based on an event-study analysis of climate-related policy events.

Evidence from Integrated Assessment Models Climate scientists simulate different climate scenarios within integrated assessment models, which allow to make predictions about the economy and the energy sector in particular if certain climate goals are maintained. The most prominent goal is the 2 degree limit originally introduced by Nordhaus (1975, 1977), under which the world's temperature increase is limited to 2 centigrades compared to pre-industrial levels. The popular TIAM-WORLD model predicts that the composition of worldwide energy consumption dramatically changes over the next 50 years if the 2 degrees limit is maintained (see Appendix Figure A.1): Fossil fuels (oil, coal, and gas) make up about 78% of the world's energy consumption in 2020, while this share is predicted to decrease to about 31% in the next 50 years under a scenario in which global warming stays within the 2 degree range. Fossil fuels will be replaced by renewable energies such as solar and wind, but also by fuels based on biomass, which are approximately carbon-neutral because the plants capture CO_2 while they are growing in a similar amount as the CO_2 that is later emitted through their combustion.

More precisely, the model predicts that the fossil fuel sector is strongly affected by the climate transitions over the next 5 to 10 years already (see Appendix Figure A.2). While the worldwide consumption of oil is predicted to increase by 20% until 2030 under the business-as-usual (BAU) scenario with no additional climate policies, oil consumption will decline if policies are implemented

[3]See `https://www.eia.gov/energyexplained/index.php?page=environment_where_ghg_come_from` for data for the United States.

in line with the 2 degrees goal. Coal consumption is affected even more strongly by the transition towards cleaner energies, as it is the dirtiest of all fossil fuels. Gas consumption increases in the medium run even under reasonably strict climate policy scenarios — although weaker than in the business-as-usual scenario — as gas will partly replace coal-based production of electricity in these scenarios. These outcomes obviously depend considerably on the desired climate scenario: Under a 3 degrees scenario, which is predicted to lead to severe environmental and economical damages, the transition away from fossil fuel energies is much weaker, as the figure depicts. The chances of achieving environmental goals on the one side, and the worsening prospects for the fossil fuel sector on the other side, are therefore critically driven by the speed at which the climate transition progresses.

Event-Study Evidence We demonstrate the strong exposure of fossil fuel firms to announcements about changes in climate policy by providing event-study evidence. We use sectoral returns data and evaluate the performance of these sectors around the dates related to events that provide information about climate policy. The hypothesis for doing this type of event study is that information which points to stricter climate policy in the future and which reaches the market on the event day should have a negative effect on the returns of firms operating in dirty sectors and, in particular, on the returns of fossil fuel firms. We use value-weighted returns data for the 17 industry portfolios, provided by Ken French on his website,[4] for the sectoral returns. For the event dates, we use the events compiled by Barnett (2018) that are associated with stricter climate policy.[5] Moreover, we expand this list by using the dates in the United Nations Framework Convention on Climate Change (UNFCCC) that are provided on `https://unfccc.int/timeline`, which correspond to key milestones in the evolution of international climate policy. Our Appendix Table A contains the dates and short descriptions of all the events we use in our event study.

To compute abnormal returns, we estimate a standard one-factor market model (i.e., the CAPM) for each sector using the 180 trading days before each event (i.e., from -190 to -10

[4] `https://mba.tuck.dartmouth.edu/pages/faculty/ken.french/`.

[5] These are the events labeled with a "+" in the "Shock Sign" column of Figure 17 in Appendix B of Barnett (2018).

days with respect to the day of the event).[6] Therefore, we use only past information to estimate the CAPM with the following regression equation:

$$R_{i,t} = \alpha_i + \beta_i \cdot (R_{M,t} - R_{f,t}) + \varepsilon_{i,t}. \tag{1}$$

The index i in this equation refers to the sector, and $R_{M,t} - R_{f,t}$ is the excess return on the market. We use the estimated intercept coefficient $\hat{\alpha}_i$ and the estimated slope coefficient $\hat{\beta}_i$ to compute predicted returns $\hat{R}_{i,t}$ for -5 to $+20$ trading days with respect to the event and compute abnormal returns for this time window as the difference between the actual observed return and the predicted return,

$$R^A_{i,t} = R_{i,t} - \hat{R}_{i,t}. \tag{2}$$

The cumulative abnormal returns for each sector are then computed by summing up abnormal returns around the event (from -5 to $+20$ trading days).[7] Furthermore, we normalize the cumulative abnormal returns such that they start at zero on day -5 relative to the event. We then compare the cumulative abnormal return for the oil sector with the average cumulative abnormal return of all other sectors, as well as the cumulative market return to obtain the exposure of oil firms relative to the other sectors in the economy.

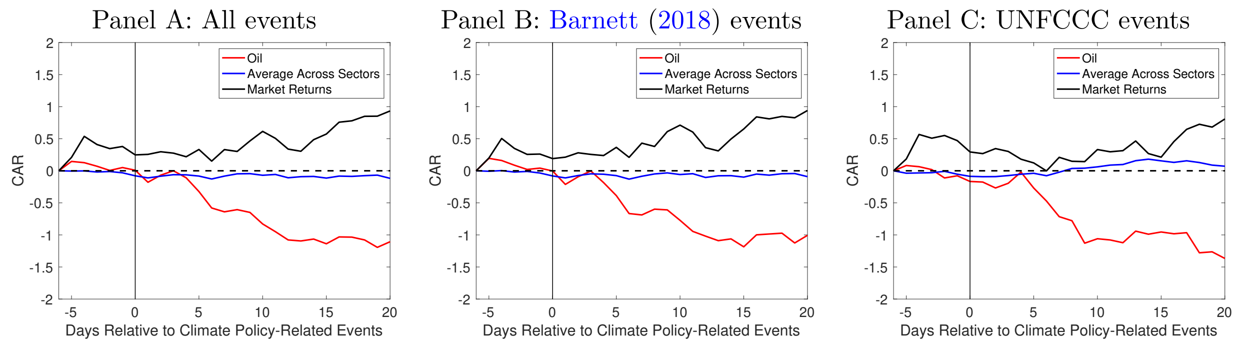
Figure 2 reports the results from our event study. In Panel A, we use all events, i.e., both the "+" events of Barnett (2018) and the UNFCCC timeline events. Panel B contains the results of the event study, only using the "+" events of Barnett (2018), whereas in Panel C we use only the UNFCCC timeline events.

The main take-away from all three figures is that cumulative abnormal returns of the oil sector are considerably lower than the cumulative market returns or the cumulative average return across the other sectors at the end of the event window. Moreover, there is a pronounced decline of the

[6] We have also used the 3-factor Fama-French model to derive abnormal returns as a robustness check and find very similar results in this case, as compared to the results in Figure 2. The graphs are depicted in Appendix Figure A.3.

[7] We have also experimented with the event window as an additional robustness check. In particular, we use an event window that lasts from -15 to $+30$ trading days. The results are then a bit less pronounced, but still hold. Thus, we again find similar graphs, as compared to the graphs in Figure 2. The graphs for value-weighted returns and equal weighted returns are depicted in Appendix Figures A.4 and A.5.

Figure 2: Oil sector's exposure to climate policy events.



oil sector's cumulative abnormal return shortly after the event date (around day 4), which persists and becomes even stronger over the remaining event horizon.[8]

2.3 Valuation of Oil Firms and the Climate Transition

Motivated by the increased climate risk awareness, our event study results, and the fact that the fossil fuel sector is the one that is most directly and immediately affected by the climate transition, we analyze a simple empirical question: Has the market valuation of fossil fuel firms changed, relative to other sectors, together with the increased awareness for climate-related risks? Focusing explicitly on fossil fuel firms provides a simple and clean way to construct a sample of firms that is, almost by definition, much more significantly exposed to climate transition risks compared to other sectors.

We build on CRSP/Compustat data for the period 1970–2018 and follow the methodology of Chen, Hou, and Stulz (2015) and Minton, Stulz, and Taboada (2019) for our analysis. In particular, we use market-to-book ratios ($mtob$) as a valuation measure for firms, and run panel regressions to investigate whether market valuations for a considered set of firms differ significantly from other firms, after taking into account a number of general firm-specific control variables. In our case, the set of firms we consider are fossil fuel firms, i.e., firms with the first two digits of the SIC code starting with 13, 29 (both oil), or 12 (coal). As we want to answer the question whether the valuation of fossil fuel firms has changed together with the increased awareness for

[8] The results are very similar when we use equal-weighted returns instead of value-weighted returns. The resulting graphs are shown in Appendix Figure A.6.

climate change risks, we also introduce the Climate Change Risk Awareness Index (CCRAI) into our regression setup as well as its interaction term with the fossil fuel sector dummy, labeled as *fossil_ia_ccrai*. Note that we do not assume or require the CCRAI to provide a large amount of time-variation around its trend — what we want 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. As control variables, we consider the firm's cash ratio as a measure of liquidity (*cash_ratio*), the firm's amount of debt relative to assets as a measure of leverage (*debt_assets*), the log of firm's total assets as a measure of firm size (*logat*), and the ratio of firm's research and development (R&D) expenditures to sales multiplied by 1000 as a measure of firm innovation capacity (*rd_sale_1000*) in our regressions. Table 1 provides summary statistics on the dependent market-to-book ratios and on our control variables.

Table 1: Firms' summary statistics in our CRSP/Compustat data sample. *mtob* is the firms' market-to-book ratio, *cash_ratio* is the firm's cash ratio as a measure of liquidity, *debt_assets* is the firm's amount of debt relative to assets as a measure of leverage, *logat* is the log of firm's total assets as a measure of firm size, and *rd_sale_1000* is the ratio of firm's research and development (R&D) expenditures to sales multiplied by 1000 as a measure of firm innovation capacity.

	mean	sd	min	p25	p50	p75	max
mtob	3.1183	12.6253	0.0059	0.9653	1.6340	2.9608	1000.0000
cash_ratio	1.5118	10.9443	-0.1198	0.1170	0.3550	1.1230	3031.0580
debt_assets	0.4793	0.2154	-0.3180	0.3178	0.4898	0.6330	11.6930
logat	5.0441	2.1877	-4.7105	3.4797	4.9020	6.5177	13.1841
rd_sale_1000	0.0017	0.1042	0.0000	0.0000	0.0000	0.00002	26.9570

Table 2 presents the panel regression results. The coefficient of *fossil_ia_ccrai* shows the main finding: The market valuation of fossil fuel firms declines, compared to other firms, together with the increasing awareness for climate change risks. The coefficient is highly significant for all specifications of our panel regression with different control variables. In terms of economic significance, a coefficient of -0.0115 for the richest specification (6) means that the market-to-book ratio of fossil fuel firms relative to other firms declines by 1.15 for a 100 points increase in the CCRAI, relative to an average market-to-book ratio of fossil fuel firms of 2.8923.[9] This implies that the valuation of

[9] This value is calculated as 3.1183–0.226 as implied by the average market-to-book ratio of all firms from Table 1 and the coefficient on the fossil_dummy in Table 2, specification (6).

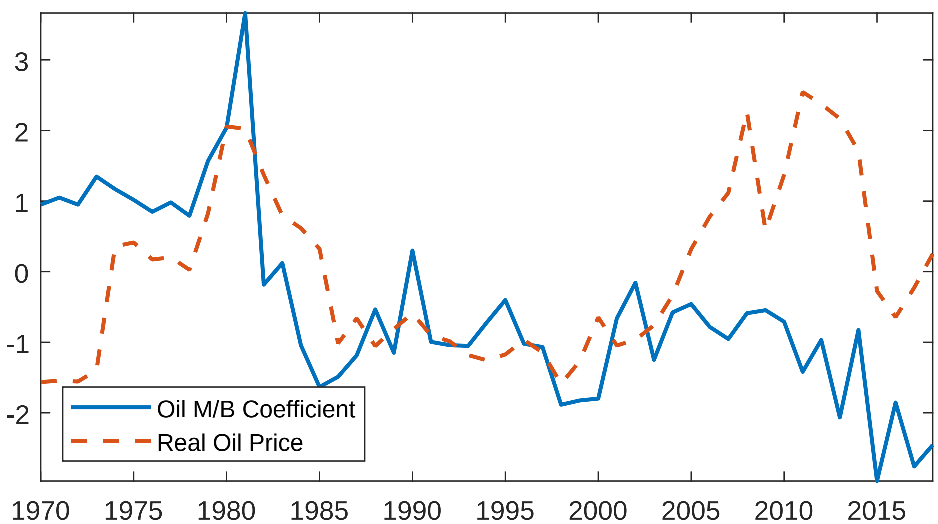
Table 2: Panel regression for fossil-fuel firms. We regress the firms' market-to-book ratio (*mtob*) on the climate change risk awareness index (*ccrai*), a dummy for the fossil fuel sector, and their interaction term (*fossil_ia_ccrai*). Control variables include the firm's cash ratio as a measure of liquidity (*cash_ratio*), the firm's amount of debt relative to assets as a measure of leverage (*debt_assets*), the log of firm's total assets as a measure of firm size (*logat*), and the ratio of firm's research and development (R&D) expenditures to sales multiplied by 1000 as a measure of firm innovation capacity (*rd_sale_1000*). Firm-fixed effects are included. Standard errors are clustered at the firm level. The sample spans the period 1970–2018. *** and ** denote significance at the 1% and the 5% level, respectively.

	(1) mtob	(2) mtob	(3) mtob	(4) mtob	(5) mtob	(6) mtob
fossil_dummy	-0.326	-0.298	-0.226	-0.326	-0.298	-0.226
	(-1.21)	(-1.08)	(-0.79)	(-1.21)	(-1.08)	(-0.79)
ccrai	0.0132***	0.0143***	0.0246***	0.0132***	0.0143***	0.0246***
	(5.19)	(5.68)	(9.33)	(5.18)	(5.67)	(9.32)
fossil_ia_ccrai	-0.0131***	-0.0153***	-0.0115***	-0.0131***	-0.0152***	-0.0115***
	(-3.68)	(-4.31)	(-3.17)	(-3.68)	(-4.31)	(-3.17)
cash_ratio		0.0258**	0.0217**		0.0258**	0.0217**
		(2.29)	(2.25)		(2.29)	(2.25)
debt_assets		5.165***	6.994***		5.167***	6.996***
		(8.55)	(9.91)		(8.56)	(9.91)
logat			-0.615***			-0.615***
			(-14.42)			(-14.42)
rd_sale_1000				0.244	0.391	0.314
				(1.31)	(1.61)	(1.56)
N	163972	163972	163784	163972	163972	163784

fossil fuel firms has decreased by more than one third relative to other firms along with the increase of the climate change risk awareness index over the last 20 years. These results also hold when considering only the oil sector instead of the whole fossil fuel sector (including coal), as Appendix Table A.1 shows.

To understand the dynamics of this devaluation of the oil and overall fossil fuel sector in more detail, we use the same panel regression setup but include yearly dummies for every year in the sample instead of the climate change risk awareness index. Figure 3 plots the related coefficients of the yearly dummies' interaction terms with the oil sector. The plot depicts that the yearly

Figure 3: Coefficients of the year-oil sector interaction dummies based on the panel regression setup, compared to the real oil price. We regress the firms' market-to-book ratio ($mtob$) on the interaction terms of a dummy for the fossil fuel sector and dummies for every single year of our sample. The blue solid line plots the coefficients on these interaction terms. Control variables include the firm's cash ratio as a measure of liquidity, the firm's amount of debt relative to assets as a measure of leverage, the log of firm's total assets as a measure of firm size, and the ratio of firm's research and development (R&D) expenditures to sales multiplied by 1000 as a measure of firm innovation capacity. The red dashed line plots the real oil price. Firm-fixed effects are included. The sample spans the period 1970–2018.



coefficients, which represent the valuation of the oil sector relative to other sectors after taking the control variables into account, were relatively stable from about 1985 to 2005, and declined afterwards to reach the minimum at the end of our sample. Furthermore, the oil sector's valuation is generally strongly driven by the oil price as a main driver of these firms' future profits, as the figure reveals. This pattern has changed, however, in the beginning of the 2000s, when the oil sector's market valuation decoupled from the oil price and declined irrespective of the dramatic commodity price boom of 2008 and other substantial oil price movements. Put simply, we can see that the (real) oil price in 2018 is at the same level as in 1984 or 1975, but the relative valuation of the oil sector is considerably lower compared to these points in time. The decoupling of oil firm valuations from oil prices is reflected by the correlation between the yearly valuation coefficient and the oil price, which is 0.52 and significant at the 1% level from the beginning of our sample until the year 2000, and 0.08 and insignificant when computed for the years after 2000. Altogether, our results suggest that the devaluation of oil firms happening over the same period that the awareness for climate change risks notably increases is more than a coincidence, and indicate that the climate transition has become an important driver of valuations besides the oil price.

3 Macro Asset Pricing Model with Climate Risks

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

3.1 Setup

Production There are two intermediate goods production sectors in the economy, a clean and a dirty one (labeled by c and d, respectively). The final goods producers compose the output from the clean firms and the dirty firms to a final good

$$Y_t = \left(Y_{c,t}^{1-\frac{1}{\varepsilon}} + Y_{d,t}^{1-\frac{1}{\varepsilon}} \right)^{\frac{1}{1-\frac{1}{\varepsilon}}} \tag{3}$$

as a constant elasticity of substitution aggregate with parameter ε. Final goods producers are perfectly competitive and maximize

$$\mathbb{E}_t \left[\sum_{t=0}^{\infty} \mathbb{M}_t (Y_t - p_{c,t} Y_{c,t} - p_{d,t} Y_{d,t}) \right], \tag{4}$$

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

The main difference between the clean and the dirty sector is that the dirty sector uses fossil fuels as part of the production input, while the clean sector does not. In particular, with capital $K_{i,t}$ and labor $L_{i,t}$ allocated to the clean and dirty sector ($i \in \{c, d\}$), the respective production functions are

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

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

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

The quantity of oil O_t is produced by the oil sector, which will be described in detail below. The labor productivity A_t of the economy follows the process

$$\ln(A_{t+1}) = \ln(A_t) + \mu_A + \sigma_A \varepsilon_{t+1}^A \tag{7}$$

with productivity shocks ε_{t+1}^A.

By burning fossil fuels, firms in the dirty sector emit ξ_d tons of greenhouse gas for each unit of produced output, contributing to climate change in the long run which reduces the quality of the environment enjoyed by the households. This negative *emissions externality* is addressed by the regulator in form of tax of τ_t on the production output of the dirty firms, as specified below. Such an output-based tax is equivalent to a tax on the amount of greenhouse gas emissions produced by the dirty firm (see Appendix C), and we refer to it as a carbon tax.

Overall, the perfectly competitive intermediate goods firms maximize

$$\mathbb{E}_t \left[\sum_{t=0}^{\infty} \mathbb{M}_t \left(p_{c,t} Y_{c,t} - R_{c,t}^K K_{c,t} - w_t L_{c,t} \right) \right], \tag{8}$$

$$\mathbb{E}_t \left[\sum_{t=0}^{\infty} \mathbb{M}_t \left(p_{d,t} Y_{d,t} - R_{d,t}^K K_{d,t} - w_t L_{d,t} - p_{o,t} O_t - \tau_t Y_{d,t} \right) \right], \tag{9}$$

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

Emissions, temperature, and the environment The production of the dirty firms increases the level of greenhouse gas emissions in the atmosphere, which evolve as

$$\mathcal{E}_{t+1} = (1-\eta)\mathcal{E}_t + \frac{\xi_d}{A_t} \cdot Y_{d,t}, \tag{10}$$

where η specifies the rate at which the atmosphere recovers from greenhouse gases, and ξ_d/A_t is the carbon intensity of the dirty firms' production process (recall that we assume that clean firms do not produce any greenhouse gas emissions). That the dirty firm's carbon intensity declines with productivity A_t is assumed in order to capture that technology progress nowadays usually leads to production emitting less greenhouse gases. The level of greenhouse gas emissions affects the global temperature level, which follows the dynamics

$$T_{t+1} = \nu T_t + \chi \mathcal{E}_{t+1} + \sigma_T T_{t+1} \varepsilon_{t+1}^T. \tag{11}$$

Here, χ is the climate sensitivity to emissions and ν is the carbon retention rate similar to Bansal, Kiku, and Ochoa (2017), and we consider weather shocks ε_{t+1}^T, whose volatility increases with the temperature level T_{t+1}. Note that T_t is should not be seen as the actual temperature in the model, but as the global temperature anomaly, describing how much the temperature is above the pre-industrial long-run temperature value.

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

$$X_t = \frac{\bar{X}}{1 + \kappa_{x,1} T_t^{\kappa_{x,2}}}, \tag{12}$$

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.

Carbon tax We introduce a tax on greenhouse gas emissions into the model that is set by the regulator and evolves as

$$\tau_t = \theta_t \tau_t^*, \tag{13}$$

$$\theta_{t+1} = (1-\rho_\theta)(1-\mu_\theta) + \rho_\theta \theta_t + \sigma_\theta \varepsilon_{t+1}^\theta, \tag{14}$$

where τ_t^* is the theoretically socially optimal tax level, and the process θ_t governs the extent of environmental regulation. The carbon tax accounts for the negative emissions externality in our model and narrows the wedge between the competitive equilibrium and the social planner's solution. While with an optimal carbon tax of τ_t^* the social optimum is attained under perfect competition, we assume that the *implemented* tax τ_t is affected by policy shocks ε_{t+1}^θ. 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 after policy shocks.

Oil sector The oil sector is populated by a perfectly competitive representative firm that extracts oil from its oil wells at a constant rate and builds new oil wells using physical capital and labor as inputs. It sells its whole oil production to the dirty intermediate goods firms. The clean firms do not use any oil in their production function. Therefore, the oil wells accumulate according to

$$U_{t+1} = (1-\kappa_o)U_t + N_t, \tag{15}$$

where N_t are new oil wells produced according to the following technology

$$N_t = (A_t L_{o,t})^{1-\tau} K_{o,t}^\tau. \tag{16}$$

The oil production is extracted at the constant rate κ_o and we assume that holding an inventory of oil commodities is not possible. Therefore, the quantity of oil consumed by the dirty firms O_t is equal to the quantity of oil extracted by the oil firm E_t as follows

$$O_t = E_t = \kappa_o U_t. \tag{17}$$

This implies that the oil firm maximizes its firm value by choosing the amount of physical capital rented out ($K_{o,t}$) and labor ($L_{o,t}$), taking the oil price ($p_{o,t}$), the rental rate of capital ($R^K_{o,t}$), and the labor wages (ω_t) as given. The oil firm value is given by

$$\mathbb{E}_t\left[\sum_{t=0}^{\infty}\mathbb{M}_t\left(p_{o,t}O_t - R^K_{o,t}K_{o,t} - w_tL_{o,t}\right)\right]. \tag{18}$$

Capital The capital stock in each of the three sectors, $i \in \{c, d, o\}$, follows a law of motion of the form

$$K_{i,t+1} = (1-\delta)K_{i,t} + I_{i,t} - G_{i,t}K_{i,t}, \tag{19}$$

where δ is the capital depreciation rate and $G_{i,t}$ is the following Jermann (1998) adjustment cost function

$$G_{i,t}(I_{i,t}/K_{i,t}) = I_{i,t}/K_{i,t} - \left(a_{0,i} + \frac{a_{1,i}}{1-\frac{1}{\zeta}}\left(I_{i,t}/K_{i,t}\right)^{1-\frac{1}{\zeta}}\right). \tag{20}$$

The capital depreciation rate δ and the adjustment cost parameter ζ are assumed to be the same for all three sectors.

Households and market clearing Finally, the households in our model consume a CES bundle of final goods C_t and environmental quality X_t,

$$v(C_t, X_t) = \left[(1-\theta)C_t^{1-\frac{1}{\rho}} + \theta(A_tX_t)^{1-\frac{1}{\rho}}\right]^{\frac{1}{1-\frac{1}{\rho}}}. \tag{21}$$

Here, θ is the weight on environmental quality in the bundle and ρ determines the elasticity of substitution between consumption of final goods and environmental quality. The households therefore maximize Epstein and Zin (1991) utility

$$V_t = \left[(1-\beta)v(C_t, X_t)^{1-\frac{1}{\psi}} + \beta\left(\mathbb{E}_t[V_{t+1}^{1-\gamma}]\right)^{\frac{1-\frac{1}{\psi}}{1-\gamma}}\right]^{\frac{1}{1-\frac{1}{\psi}}} \tag{22}$$

with risk aversion γ and elasticity of intertemporal substitution ψ over this bundle. Since labor is demanded by all three sectors in the economy, the labor market clears when the following condition is satisfied

$$1-\ell = L_{c,t} + L_{d,t} + L_{o,t}, \tag{23}$$

where ℓ determines the exogenously fixed leisure share of households. As usual, final goods are both consumption and investment goods, and the market has to clear according to the condition

$$Y_t = C_t + I_{c,t} + I_{d,t} + I_{o,t}. \tag{24}$$

3.2 Equilibrium

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

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

with

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

the household's condition yields that the Euler equation

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

holds for the returns R_{t+1} of all assets traded in the economy. The following variable, essentially describing the effect of preferences for the early or late resolution of uncertainty in the pricing kernel, is of interest to us later in the analysis of the impulse response functions. Thus, we define it here as follows:

$$\tilde{V}_t = \frac{V_{t+1}}{\mathbb{E}_t\left[V_{t+1}^{1-\gamma}\right]^{\frac{1}{1-\gamma}}}. \tag{27}$$

From the firms' side, we obtain that (26) holds for the investment returns in the three sectors ($i \in \{c,d,o\}$),

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

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

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

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

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

We furthermore obtain the condition

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

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

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

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

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

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

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

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

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

We assume an average debt-to-equity ratio $\overline{DE}$ of 1, in line with Croce (2014).

4 Implications of the Calibrated Model

We analyze the implications of our model for the climate-related transition to a low-carbon economy. While the model's steady state describes the post-transition economy, in which the carbon tax fully accounts for the climate externaility, we particularly inspect the model's predictions during the slow convergence towards this state from a pre-transition scenario. After explaining the model calibration in the next section, we specify this pre-transition state in Section 4.2. The subsequent sections then simulate the climate transition and analyze the dynamics of firm valuations, capital reallocation, climate policy risk premia, as well as the behavior of oil prices during the transition period.

4.1 Calibration

We choose the preference parameters of our model in line with the recent asset pricing literature (e.g., Bansal and Yaron 2004; Croce 2014), with a relative risk aversion γ of 10 and an elasticity of intertemporal substitution ψ of 2, yielding a preference for the early resolution of uncertainty. The time discount factor β is set to 0.96. Environmental quality accounts for an important part of household utility as specified by a share θ of 0.3 in the household's consumption bundle. We further set the elasticity of substitution ρ between environmental quality and goods consumption to 0.375, making them complements rather than substitutes.

The basic parameters of the production sector in our economy are also chosen in accordance with

Croce (2014): In particular, we set the depreciation rate of capital δ to 0.06 and the capital share of production α to 0.31, and these values are identical for the clean, the dirty, and the oil sector. In line with standard practice, the steady-state labor supply is normalized to be one third of the total time endowment, and we accordingly set ℓ to 2/3. The average growth rate of productivity and its volatility, μ and σ_A, are calibrated to match the mean and standard deviation of the output growth rate in the pre-transition period from 1960–1995, as described in detail in Section 4.2. Similarly, the capital adjustment cost elasticity is chosen to be $\zeta = 12$ to let the model produce a relatively high investment growth volatility. We finally assume that there is a high elasticity of substitution between clean and dirty sector output in line with Acemoglu et al. (2012), which is accounted for by setting ε to 3. All of these parameters are summarized in Table 3.

Table 3: Preference and production parameters. This table reports parameters describing the household's preferences, the labor market, and the production sectors in the model. The model is calibrated at an annual frequency.

Parameter		Value
Preferences		
Subjective discount factor	β	0.96
Relative risk aversion	γ	10
Intertemporal elasticity of substitution	ψ	2
Environmental quality share in utility bundle	θ	0.3
Elasticity of substitution between env. quality and consumption	ρ	0.375
Labor market		
Leisure share	ℓ	2/3
Final goods production		
Depreciation rate of capital	δ	0.06
Capital adjustment costs	ζ	12
Capital share of intermediate goods production	α	0.31
Average productivity growth rate	μ	0.0227
Volatility of productivity growth	σ_A	0.0317
Elasticity of substitution between clean and dirty sector output	ε	3
Oil production and input		
Oil share in dirty sector's production function	ι	0.06
Elasticity of substitution between capital and oil	o	0.5
Capital share of oil wells production	τ	0.4
Oil extraction rate	κ_o	0.025

The clean and the dirty sector differ along three dimensions. First, the dirty sector uses oil as

Table 4: Emissions, temperature, and carbon tax parameters. This table reports parameters describing the emissions and temperature dynamics and the carbon tax set by the regulator. The model is calibrated at an annual frequency.

Parameter		Value
Emissions and Temperature		
Emissions intensity of dirty sector	ξ_d	0.2
Environmental quality level at pre-industrial temperature level	$\bar{X}$	0.1
Temperature-sensitivity of environmental quality	$\kappa_{x,1}$	0.0144
Temperature-sensitivity of environmental quality	$\kappa_{x,2}$	2
Carbon retention rate	ν	0.966
Atmosphere recovery rate	η	0.02
Climate sensitivity to emissions	χ	0.1
Volatility of temperature shocks	σ_T	0.0714
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	0.025

an input in addition to capital and labor, with an elasticity of substitution between physical capital and oil of $o = 0.5$ and a share ι of oil of 6% in the oil-capital CES bundle. Oil is produced by the oil sector with an extraction rate κ_o of 2.5% and a capital share τ in oil wells production of 40%. Second, the dirty sector generates a significant amount of greenhouse gas emissions as part of the production process, $\xi_d = 0.2$, while the clean sector's emissions intensity is 0. Third, we assume that environmental quality is affected by temperature levels beyond pre-industrial levels with parameters $\kappa_{x,1} = 0.0144$ and $\kappa_{x,2} = 2$. These two parameter choices are motivated by the results in Nordhaus (1992). Moreover, the level of environmental quality at pre-industrial temperatures is assumed to be $\bar{X} = 0.1$.

Further parameters driving the overall emissions in the atmosphere as well as the global temperature dynamics are chosen in line with Bansal, Kiku, and Ochoa (2017). Specifically, the carbon retention rate is $\nu = 0.966$, the atmosphere recovery rate is $\eta = 0.02$, and the climate sensitivity to emissions is $\chi = 0.1$. We set the volatility of temperature shocks σ_T to 0.0714 to match the observed volatility of the annual global temperature anomaly for the period 1960–1995. Finally, we assume that policy-makers set the carbon tax to the theoretically optimal level in the steady state of the model, $\mu_\theta = 0$; recall that our analysis focuses on the transition of the model towards this steady state. The parameters related to the sectors' emissions, the temperature dynamics, and the carbon tax are summarized in Table 4.

4.2 State of the Pre-Transition Economy

We start investigating our model by considering a variant of it in which agents disregard the effect of emissions on the global temperature level, which we assume to be the case for the time before the climate transition. Considering this particular case allows us to evaluate the fit of the model to U.S. macroeconomic data and global temperature data from 1960 to 1995, when there was almost no awareness for climate change related issues. Furthermore, we will use the resulting steady state of this model variant as the initial point for our analysis of the climate transition.

Technically, the described pre-transition economy is characterized by the assumption that the agents' *perceived* χ is zero, such that they do not suspect any relation between emissions and global temperatures. Under this assumption, the optimal carbon tax also results to zero as the shadow costs of emissions become zero in the social planner economy (see Appendix C). Furthermore, the global temperature anomaly as specified by the dynamics (11) is not endogenous to the model anymore, but perceived as an exogenous process by the agents.

Table 5: Model moments. This table reports the simulated business cycle moments for the pre-transition economy. The moments are computed using a simulation of the economy for 20,000 years. All values are given in percentage points. The data column is based on U.S. macroeconomic data and global temperature data for the period 1960–1995. Details on the construction of the sectoral output data are given in Appendix B.

Moment	Data	Model
$\mathbb{E}[I/Y]$	12.80	19.54
$\mathbb{E}[p_cY_c/(p_cY_c + p_dY_d + p_oO)]$	74.74	69.92
$\mathbb{E}[p_dY_d/(p_cY_c + p_dY_d + p_oO)]$	20.87	25.56
$\mathbb{E}[p_oO/(p_cY_c + p_dY_d + p_oO)]$	4.39	4.51
$\mathbb{E}[\Delta y]$	2.27	2.27
$\sigma(T)$	14.59	14.58
$\sigma(\Delta y)$	2.20	2.20
$\sigma(\Delta c)$	1.21	2.01
$\sigma(\Delta i)$	8.62	2.97

Table 5 reports the simulated moments for this pre-transition economy and its empirical counterparts based on U.S. macroeconomic data and global temperature data from 1960 to 1995. The model is calibrated to match the average output growth rate and the volatility of output growth. Furthermore, the volatility of the annual global temperature volatility is reproduced by the model. Our calibration lets the model also reproduce the low consumption growth volatility observed in the US macroeconomic data relatively well. Investment growth volatility in the model does not fully reach the empirical counterpart, but it is reasonably large. The aggregate investment to output ratio is roughly 20% in the model, whereas it is just below 13% in the data. The relative importance of the dirty goods sector to the clean goods sector, as well the size of the oil sector are also quite nicely reproduced by the model.

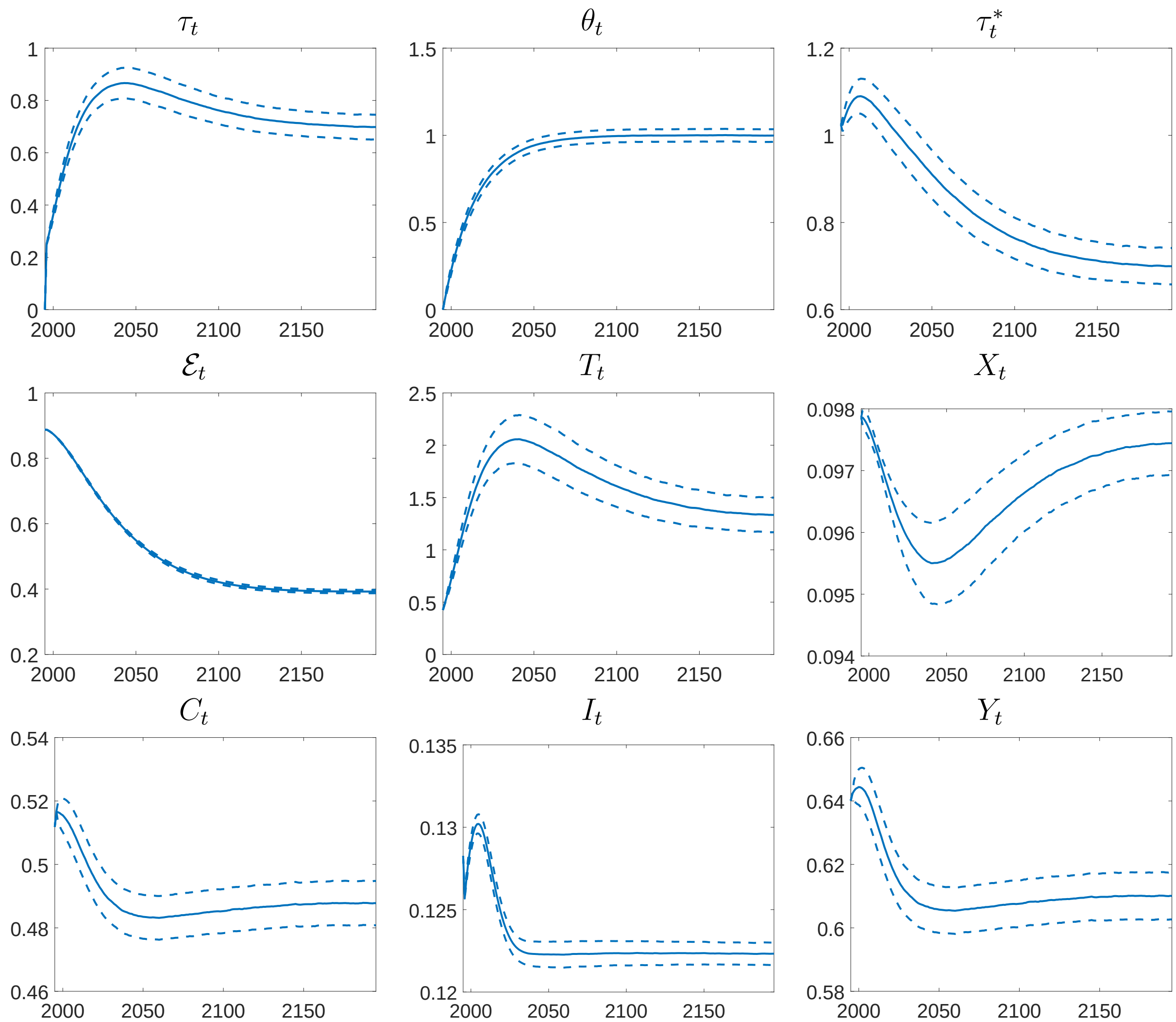
4.3 Simulating the Climate Transition

Using the steady state of the pre-transition model variant analyzed in Section 4.2 as an initial point, we simulate the transition towards the steady state of the full model — in which agents understand the relation of emissions and global temperatures as defined through the parameter χ — for 200 years and 1000 economies. Figure 4 plots the average path of key macroeconomic quantities during the transition period, as well as confidence bands around it. The average path is computed as the average across all 1000 economies at any given point in time.

The simulation of the climate transition reveals that the temperature anomaly converges to a value of around 2, which it reaches approximately in the year 2050. Therefore, the economy is able to constrain the temperature increase to roughly 2 degrees Celsius over pre-industrial levels by setting the carbon tax optimally. The figure nicely demonstrates in the first panel, which depicts the implemented carbon tax, that the carbon tax actually takes longer than the temperature to reach its new steady state at the socially optimal level. Emissions, on the other hand, decrease relatively quickly from the beginning of the transition period. Due to the increasing temperatures, environmental quality declines first and stabilizes once temperatures do not rise anymore.

The figures also show that aggregate consumption, investment, and output all decline during the climate transition. This behavior reflects the fact that increasing the carbon tax, which is welfare-improving and necessary to prevent catastrophic temperature increases, naturally comes at the cost of a reduction in economic growth.

Figure 4: Transition dynamics of macroeconomic quantities. The transition dynamics are computed for 200 years and 1000 sample economies. The initial point of the simulation is the steady state of the pre-transition economy. The mean path across the 1000 economies is depicted for key macroeconomic variables, alongside confidence bands computed as mean path plus/minus one half times the standard deviation of observations across paths at any given point in time.

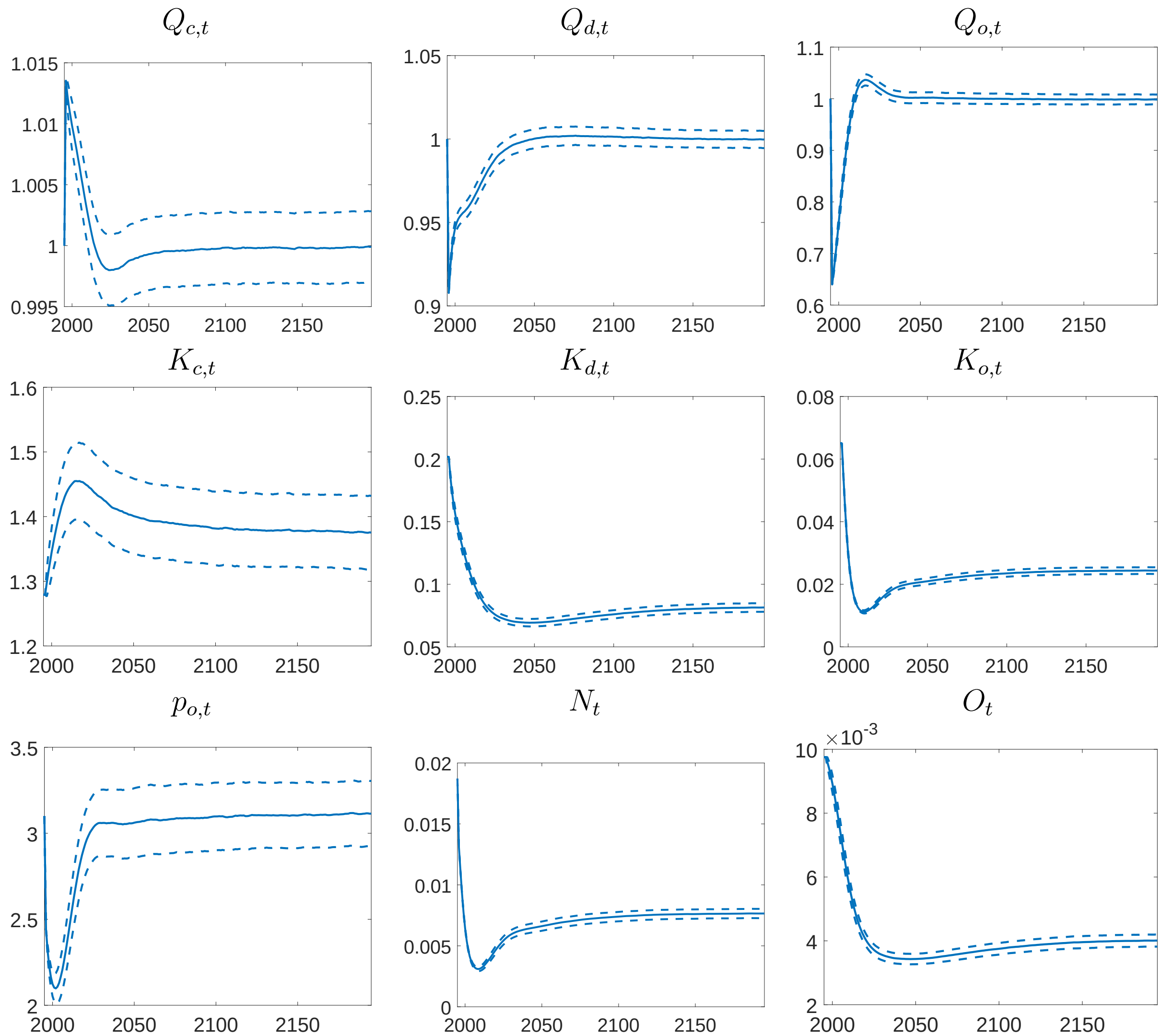


4.4 Predictions for the Transition Period

We pin down the model's main predictions for the climate transition period regarding the behavior of firm valuations and capital reallocation, climate policy risk premia, as well as the dynamics of the oil sector. We particularly analyze the mean transition paths of the respective variables as well as conditional impulse response functions around states that are attained during the transition period.

Firm valuations and capital reallocation We first address the question how the climate transition affects the valuations of clean, dirty, and fossil fuel firms, as measured by Tobin's Qs in our model. Figure 5 depicts the average transition paths and confidence bands of key asset prices in the economy, showing the behavior of Tobin's Qs in the first row.

Figure 5: Transition dynamics of asset prices. The transition dynamics are computed for 200 years and 1000 sample economies. The initial point of the simulation is the steady state of the pre-transition economy. The mean path across the 1000 economies is depicted for key asset pricing variables, alongside confidence bands computed as mean path plus/minus one half times the standard deviation of observations across paths at any given point in time.



Our analysis reveals that the valuations of the dirty and the oil sector substantially decline in the beginning of the climate transition. The dirty sector's valuation stays below 1 during the entire transition period, whereas the oil sector's valuation reverts relatively quickly back to the steady state. Therefore, the model reproduces our empirical finding of Section 2 that fossil-fuel firms lost value relative to other firms in the economy, particularly in the early 2000s. The Tobin's Q of the clean sector slightly increases, on the other hand, consistent with the intuition that low-carbon industries become more profitable relative to fossil-fuel consumption industries as the carbon tax increases.

Importantly, all industry valuations revert back to a Tobin's Q of 1 in the longer run as capital is being reallocated in line with the q theory. In particular, the lower valuations of the dirty and fossil fuel sector lead to a divestment of capital (see second row of Figure 5), and some capital is flowing to the clean sector. As a result of this reallocation, the relative market valuation of dirty and fossil fuel firms starts increasing again later in the climate transition, and the clean sector's valuation declines eventually.

We can also provide a quantification of the extent of revaluation of firms and reallocation of capital. The introduction of the carbon tax leads to a prompt devaluation in the oil sector of roughly one third[10], which in turn triggers a reduction of capital in use by the oil sector of about 70%, a reduction of capital in use by the dirty sector of around 60%, and an increase in capital in use by the clean sector of about 7.5% in the long run (at the end of transition period after 200 years). Furthermore, it allows to constrain the temperature increase to about 2 degrees Celsius above pre-industrial times in the year 2050, with a visible decline afterwards to around 1.5 degrees Celsius in 2200.

Climate policy risk premia An important question is whether the described decline in valuations for the dirty sector and the oil sector is amplified by climate policy risk premia, as these sectors are particularly exposed to the risk of stricter regulations and accordingly higher carbon taxes. To understand climate policy risk premia in our model, we depict the impulse response functions of main macroeconomic aggregates as well as of clean and dirty sector quantities in re-

[10] Recall that the decline we found in the data amounts to about one third as well. Therefore, the model can reproduce our empirical findings, and a significant devaluation of the oil sector is produced by our model.

sponse to shocks to the implemented carbon tax in Figure 6. We consider the conditional impulse responses not only around the socially optimal 100% carbon tax case, but also particularly focus on the state in which only a 50% carbon tax is implemented, as attained during the transition period. Finally, we also analyze impulse responses around a 110% carbon tax case, which could be attained after the transition if the regulator accidentally sets the tax too high. The discussion about the 100% and 110% carbon tax cases is relegated to the next section so that we concentrate here on the 50% carbon tax case.

The first observation to be made is that for a carbon tax level of 50%, the stochastic discount factor slightly increases in response to a higher carbon tax. Overall, a higher carbon tax yields two effects: On the one hand, the consumption of the final good becomes more expensive, such that current household consumption declines. On the other hand, the negative climate externality is partly closed, leading to an increase in future utility. In our model calibration, the former effect on the stochastic discount factor outweighs the latter one, such that the pricing kernel reacts negatively overall to carbon tax increases.

When climate policy is tightened, emissions and temperatures decrease, and the clean sector's output and physical capital increase at expense of the dirty sector, whose output and physical capital decrease due to the increased tax burden the dirty firms face. In line with these economic fundamentals, the excess returns of clean firms increase and the excess returns of dirty firms decrease.

Taking this together with the response of the stochastic discount factor, we obtain negative climate policy risk premia for the clean sector and positive climate policy risk premia for the dirty sector. This result, which implies that climate policy risk premia slightly amplify the devaluation of dirty and oil firms rather than amplifying it, is in line with Bolton and Kacperczyk (2021) and Pastor, Stambaugh, and Taylor (2021b). On the other hand, the result alleviates the intuition provided by Baker et al. (2019) and Roth Tran (2019) that dirty firms should paradoxically have negative risk premia as they provide a hedge against the consequences of climate change.

It is important to emphasize that the sign of carbon risk premia in the beginning of the climate transition is determined by the calibration of our model. In particular, it depends on how much the household decreases its consumption of the final good in response to a climate policy shock.

Figure 6: Impact of carbon tax shocks on main macroeconomic aggregates and clean and dirty sectors for three values of the carbon tax level: 50%, 100%, and 110% of the optimal carbon tax. These three values correspond to three cases: a "Low Tax" case, the "Baseline Model" case, and a "High Tax" case (in which the tax is set higher than optimal). The figure shows conditional impulse response functions of quantities and prices to a positive one-standard-deviation policy shock materializing at $t = 1$. Lowercase letters refer to log variables.

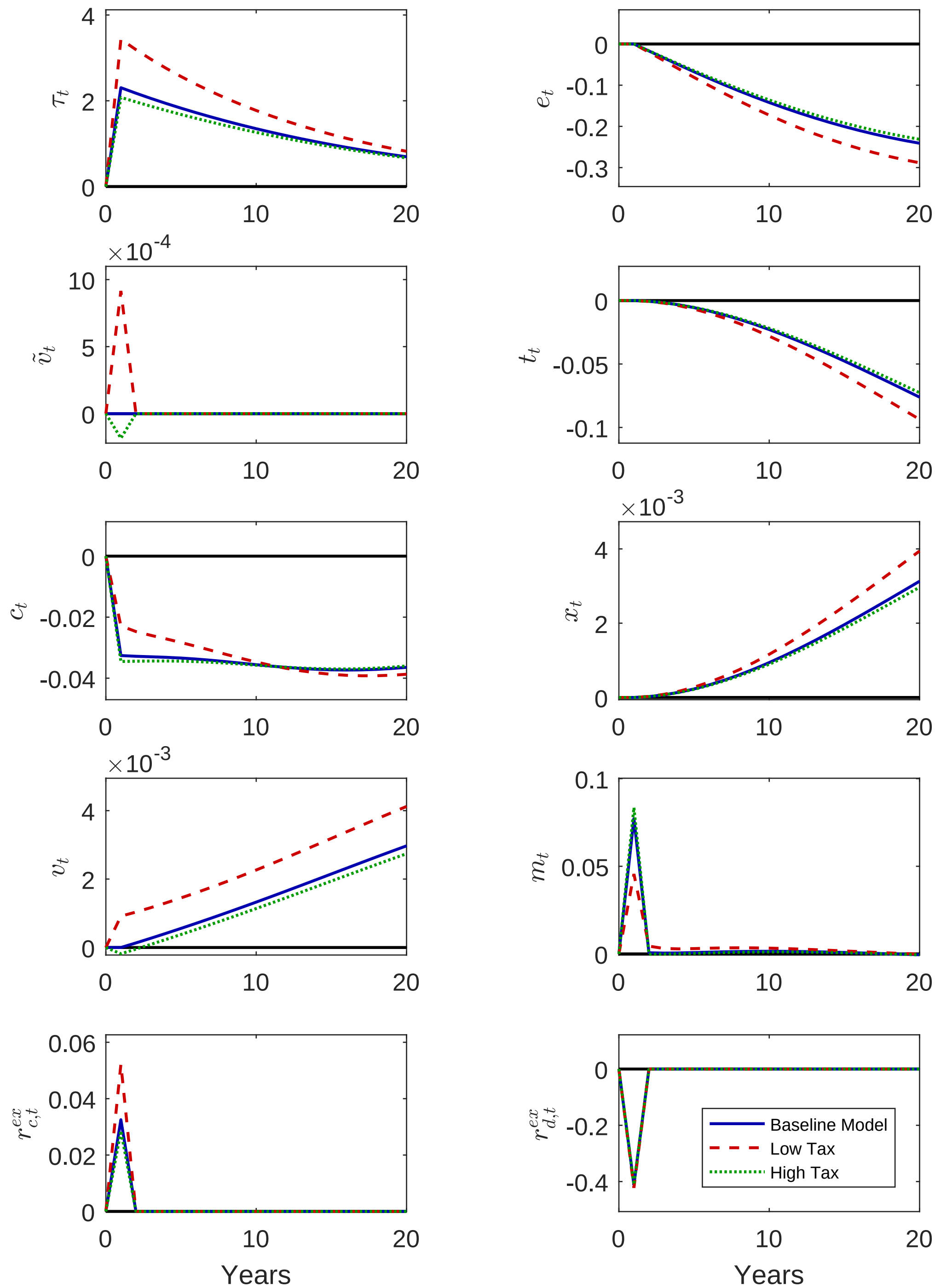
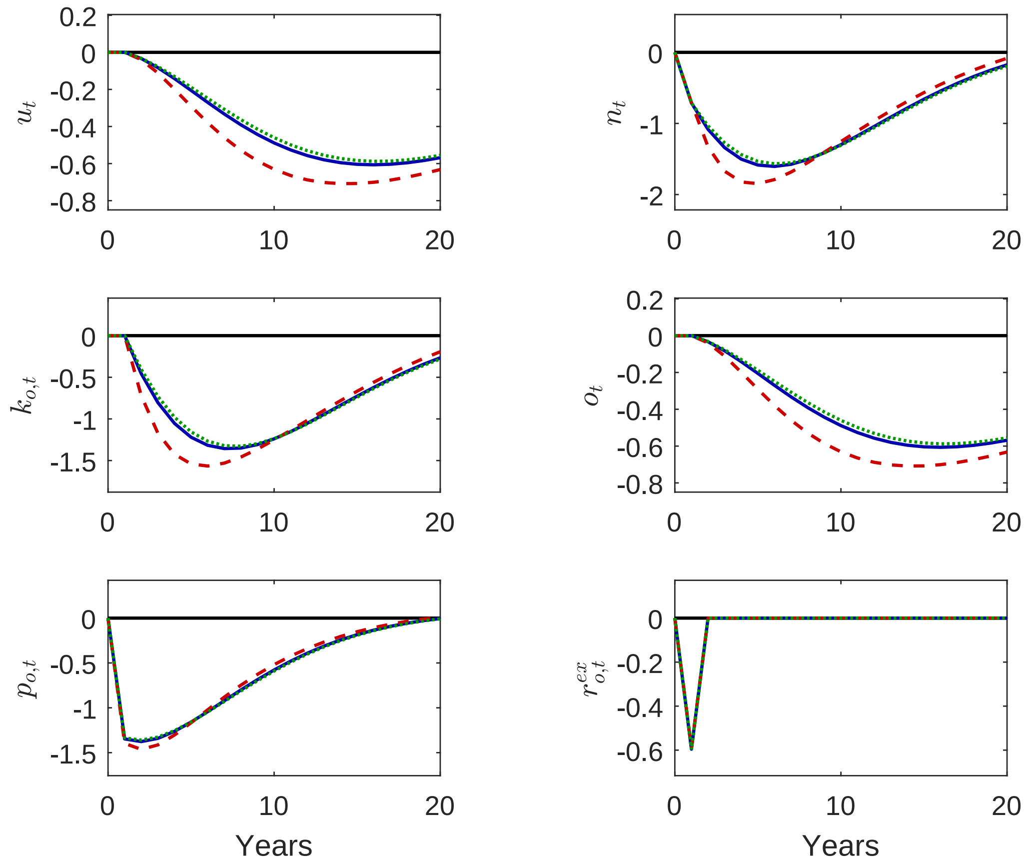


Figure 7: Impact of carbon tax shocks on the oil sector for three values of the carbon tax level: 50%, 100%, and 110% of the optimal carbon tax. These three values correspond to three cases: a "Low Tax" case, the "Baseline Model" case, and a "High Tax" case (in which the tax is set higher than optimal). This figure shows conditional impulse response functions of quantities and prices to a positive one-standard-deviation policy shock materializing at $t = 1$. Lowercase letters refer to log variables.



In our benchmark calibration, this decline outweighs the positive effect of getting closer to the social planner equilibrium. With a lower speed of convergence to the optimal carbon tax, a lower emission intensity of the dirty sector, and a slightly higher elasticity of substitution between the consumption good and environmental quality, i.e., by setting $\rho_\theta = 0.98$, $\xi_d = 0.15$, and $\rho = 0.4$ in contrast to the values in our benchmark calibration, the model produces a decline in the stochastic discount factor in the "Low Tax" case.

Oil sector dynamics The oil price, depicted in the lower-left panel of Figure 5, exhibits a pronounced decrease in the beginning of the transition period due to the negative impact on the dirty and oil firms that leads to a much lower demand of oil. The oil price starts to rebound slightly after that due to the then high scarcity of oil and demand from the dirty firms starting to stabilize, as the decline in dirty firm's capital slows down over time.

The impulse response analysis in Figure 7 provides additional insights into the response of the oil sector to carbon tax shocks. It becomes clear that the oil sector is clearly negatively affected on all dimensions. This is due to the just explained and observed negative effect on the dirty firms that need to decrease their demand of oil subsequently. Therefore, the number of oil wells, the production of new oil wells, the oil sector's capital, and the amount of extracted oil all decrease in response to a positive carbon tax shock. The effects are again stronger if the carbon tax is lower initially.

These negative effects on the oil sector's fundamentals translate to a strong and persistent decrease of the oil price, as well as a negative effect on the oil firm's excess returns. The decrease in the oil firm's excess return is about 50% stronger than the decrease in the dirty firm's excess return in Figure 6. Therefore, from an asset pricing point of view, the oil firm has in absolute value a higher positive climate policy risk premium than the dirty firm.

4.5 Climate Policy Risk Premia in the Post-Transition Time

In addition to our detailed analysis of the climate transition period, the model also allows us to make predictions for the time when the economy has successfully moved to a low-carbon state. While most effects should naturally level off once the transition is accomplished, it is clear that climate policy risk premia will still exist in the post-transition time due to the partly unpredictable policy actions of the regulator.

Our analysis in Figure 6 reveals that in those times, as can be seen by looking at the conditional impulse response functions for the 100% tax case, climate policy risk premia tend to remain positive, regardless of whether the regulator over- or undershoots the optimal carbon tax level. Therefore, the climate policy risk premia retain sign in the post-transition time. Intuitively, a carbon tax increase drives the tax to a higher-than-optimal level in these cases, such that it becomes even a worse shock for the economy than in the transition period. Therefore, setting the tax above the optimal level leads to an unambiguous decrease in welfare and the climate risk premia become larger.

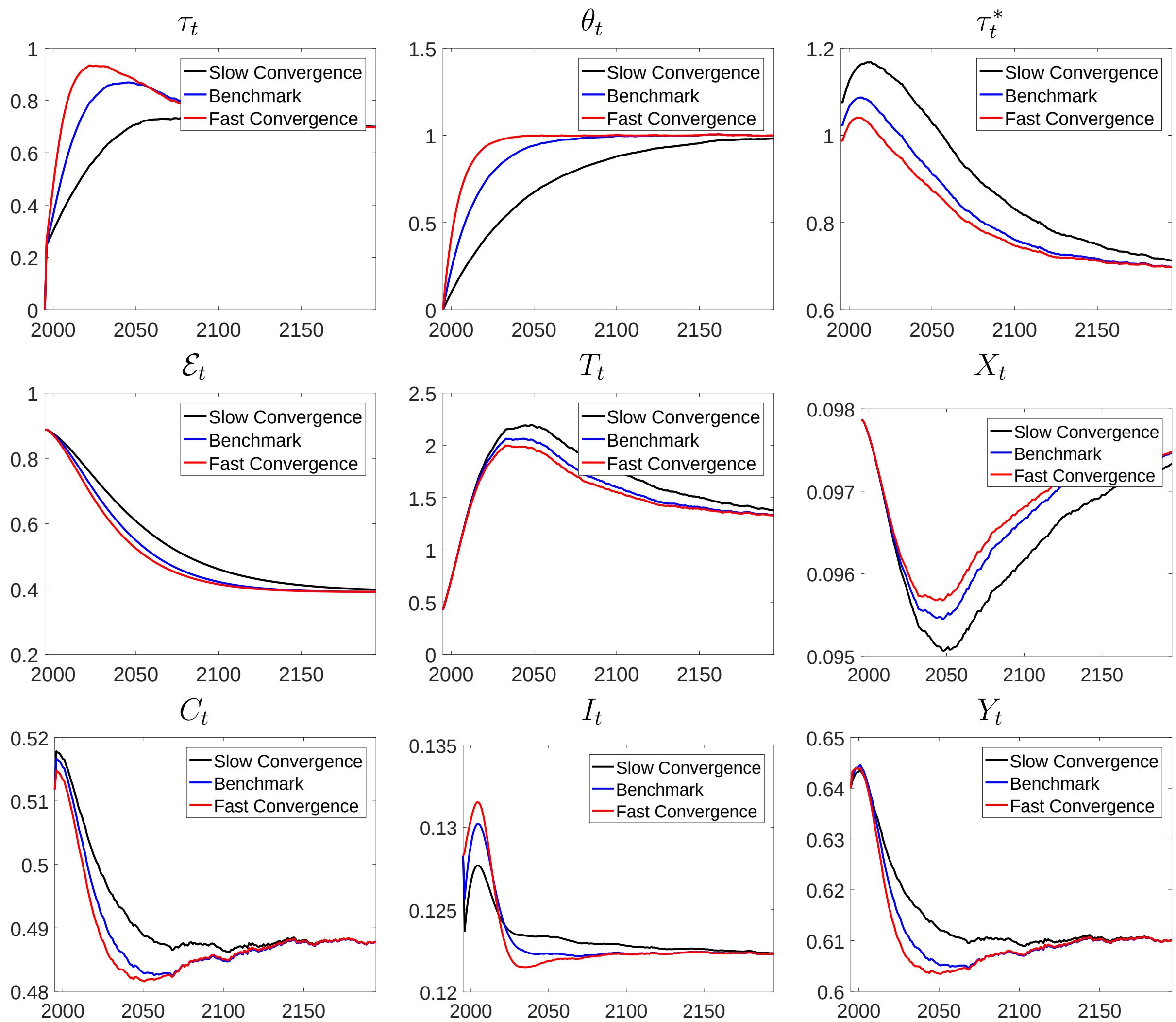
If the regulator accidentally sets the carbon tax to a higher than optimal level, an additional carbon tax increase is even a worse shock for the overall economy than in the 100% tax case, as the larger increase of the stochastic discount factor in the 110% case reveals, and economic welfare decreases. The negative response of the dirty sector makes dirty firms command more positive climate policy risk premia in that case.

5 Sensitivity Analysis: Speed of Transition

In the previous section, we have analyzed the transition from an economy without a carbon tax to an economy that sets the carbon tax optimally in our benchmark model. The transition to an almost 100% optimal carbon tax level takes about 80 years in these scenarios, and macroeconomic, environmental, and asset pricing dynamics stabilize at about 50–80 years after the start of the transition. The question of how long the transition to optimal climate policy will take in the real world is surrounded by large uncertainty. Political agendas and elections as well as technological progress and the extent of international cooperation will all influence the speed of the climate policy transition. This is why in this section we repeat our simulation with different assumed speeds of transition to the optimal carbon tax. Relative to the benchmark calibration, we simulate a model that allows for a faster convergence to the optimal carbon tax and a model that leads to a slower convergence to the optimal carbon tax.

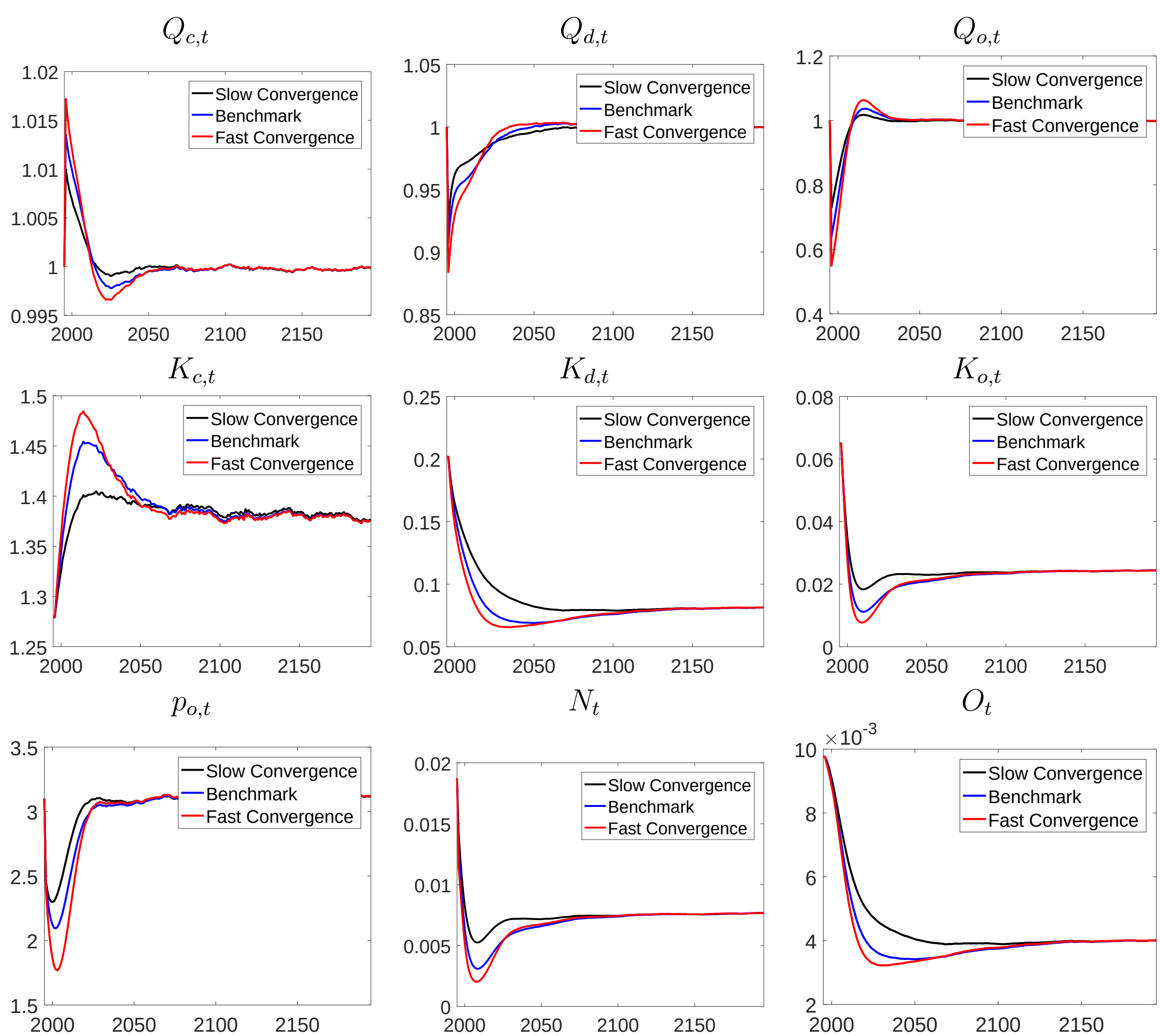
Figures 8 and 9 depict the results. Three model variants are considered in each graph. In addition to the "Benchmark" case, which uses a parameter for the mean reversion of climate policy of $\rho_\theta = 0.95$, two other calibrations are depicted: The "Fast Convergence" model assumes a mean reversion parameter of climate policy of $\rho_\theta = 0.90$ and the "Slow Convergence" model assumes a value of $\rho_\theta = 0.98$. The second graph in the first row of Figure 8 shows how the "Fast Convergence" model is significantly faster in achieving an optimal carbon tax. It takes only about 40 years (instead of around 80) to reach the optimal carbon tax. On the contrary, the "Slow Convergence" model reaches roughly the optimal carbon tax only after 200 years, i.e. at the end of our simulated transition period.

Figure 8: Transition dynamics of macroeconomic quantities for different speeds of transition. We assume $\rho_\theta = 0.90$ for the "Fast Convergence" case and $\rho_\theta = 0.98$ for the "Slow Convergence" case. The "Benchmark" case is computed using $\rho_\theta = 0.95$, as given in Table 4. The transition dynamics are computed for 200 years and 1000 sample economies. The initial point of the simulation is the steady state of the pre-transition economy. The mean paths across the 1000 economies are depicted for key macroeconomic quantities and the three calibrations.



The effects on macroeconomic quantities of faster convergence to the optimal carbon tax are in line with our intuition. Faster convergence implies a faster reduction of total emissions and higher levels of implemented carbon taxes across the whole transition period. Interestingly, the *optimal* carbon tax level is lower in the case of fast convergence, compared to the benchmark scenario. Therefore, the fast implementation of effective climate change policy prevents very high optimal tax rates, highlighting the positive effect of acting quickly. Environmental quality does not decrease as much compared to a slower convergence to the optimal carbon tax and the temperature increase is slightly less pronounced as well. These positive effects come at a cost of a larger reduction of output and consumption in the first half of the transition period. In the long run, all models converge to the same level of output and consumption. Fast convergence requires investment to

Figure 9: Transition dynamics of asset prices for different speeds of transition. We assume $\rho_\theta = 0.90$ for the "Fast Convergence" case and $\rho_\theta = 0.98$ for the "Slow Convergence" case. The "Benchmark" case is computed using $\rho_\theta = 0.95$, as given in Table 4. The transition dynamics are computed for 200 years and 1000 sample economies. The initial point of the simulation is the steady state of the pre-transition economy. The mean path across the 1000 economies are depicted for key asset pricing variables and the three calibrations.



be slightly higher than in the benchmark model in the first twenty years of the transition period. This is needed as clean capital needs to be build up more quickly to achieve the transition to a greener economy faster, as is visible in the second row of Figure 9. The decreases of capital in the dirty and oil sectors are also more pronounced for the "Fast Convergence" model. The production of new oil wells and the decrease in the number of oil wells behave similarly to oil sector's capital.

These dynamics are reflected by the asset prices in our economy. The clean firms benefit more in the first twenty years of the transition period if the convergence is fast, whereas the dirty and oil firms lose more valuation, as measured by their Tobin's Qs. Specifically, the oil sector's valuation decreases by more than 40% initially, compared to around 33% using the benchmark speed of convergence. In the empirical analysis, we found a valuation loss of about one third. Therefore, through the lens of our model investors in the real world might expect a transition to the optimal carbon tax in line with our assumed benchmark speed of convergence and thus in about 80 years. Last but not least, the oil price decreases more and more persistently when there is faster convergence to the optimal carbon tax due to a faster decline in demand for oil in this case.

For the "Slow Convergence" model, all the results are going into the opposite direction, relative to the "Benchmark" model. Environmental quality decreases more and temperature increases slightly more. Total emissions decrease more slowly and the levels of implemented (optimal) carbon taxes are lower (higher) than in the other two model versions. On the contrary, consumption and output decrease less and there is not such a large short-run investment boom, as in the "Fast Convergence" model. The reallocation of capital from the dirty and oil sectors to the clean sector works more slowly as well which implies less pronounced positive asset pricing effects for the clean firms and less pronounced negative asset pricing effects for the dirty and oil firms. Finally, the oil price decreases less and recovers faster with slower convergence to the optimal carbon tax and the decline in the production of new oil wells and the stock of oil wells is less pronounced.

6 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.

Empirically, we show that the market valuation of fossil fuel firms has already declined significantly as of now when compared to other firms, indicating that first effects of the climate transition are materializing. Theoretically, we develop a quantitative model that makes predictions on how macroeconomic quantities and asset prices behave as the transition proceeds. We particularly use the model to analyze its implications for firm valuations across sectors, the reallocation of capital, the features of climate policy risk premia, and the behavior of oil prices.

We find climate policy risk premia to be positive even for sub-optimal levels of carbon taxation. This is in line with arguments that make the climate policy risk premia responsible for low fossil fuel firm valuations since they amplify the negative cash flow effects of transitioning to a lower-carbon economy. Our model therefore corroborates the findings of the empirical literature that supports positive climate policy risk premia. However, our results also show that some effects of the climate transition based on a rigorous economic analysis turn out to be different from what it sometimes purported informally. For example, the view that market valuations of fossil fuel firms fall continuously throughout the transition period is contrasted by our model results. Rather, fossil fuel firm valuations fall in the beginning of the climate transition, before divestment kicks in and valuation ratios revert back to normal levels again.

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A Additional Tables and Figures

Figure A.1: Primary energy consumption sources based on the TIAM-WORLD model.

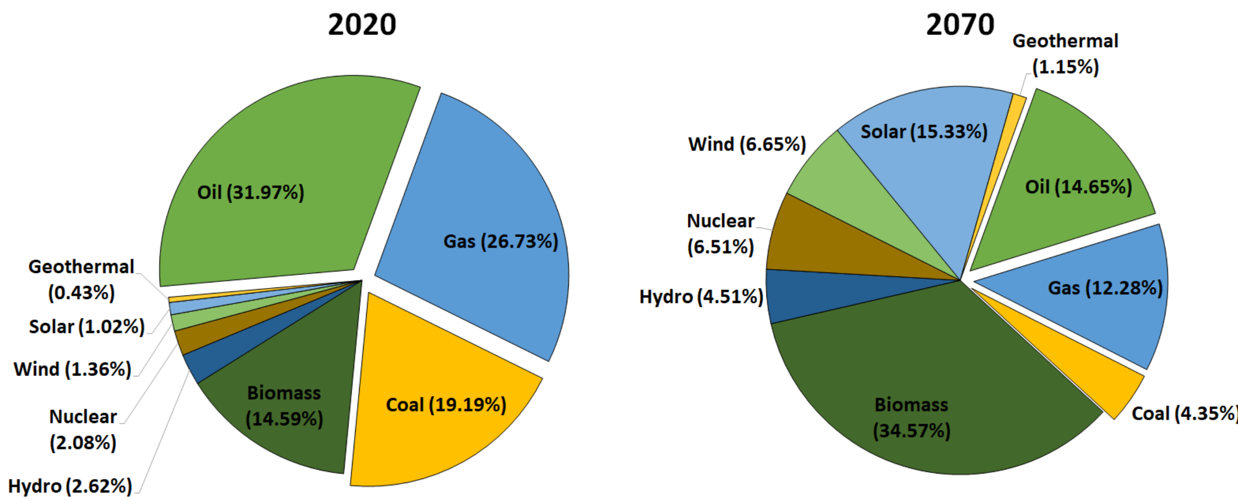

Figure A.2: Worldwide fossil fuel consumption and CO_2 emission the scenarios based on the TIAM-WORLD model.

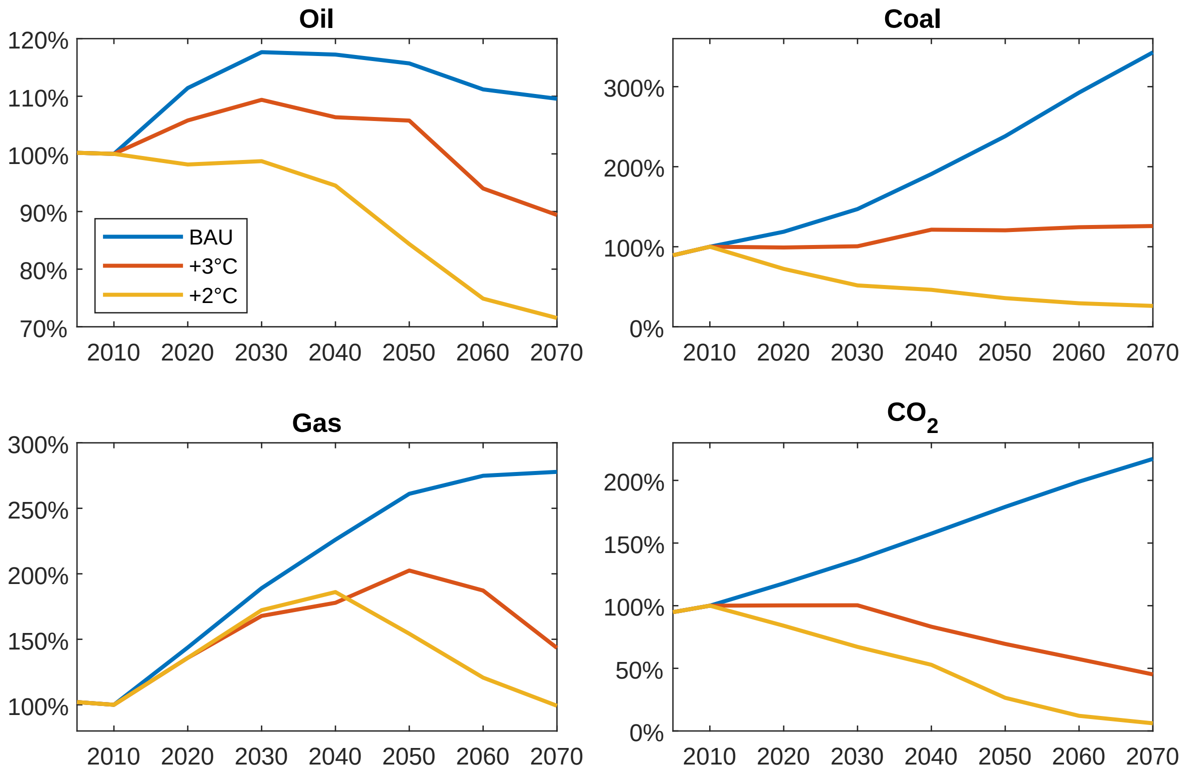

Figure A.3: Oil sector's exposure to climate policy events. For this figure and in contrast to Figure 2, the 3-factor Fama-French model has been used to derive abnormal returns instead of the CAPM.

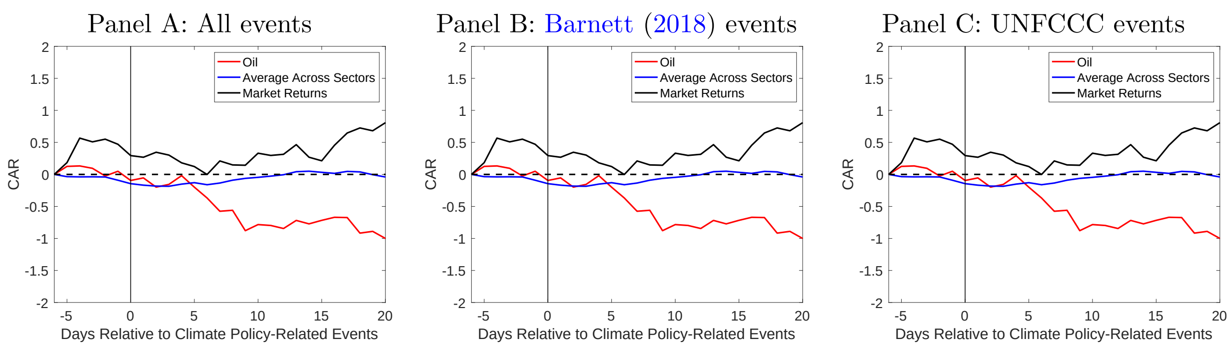

Figure A.4: Oil sector's exposure to climate policy events. For this figure and in contrast to Figure 2, an event window that lasts from -15 to +30 trading days around the event date has been used.

Panel A: All events | Panel B: Barnett (2018) events | Panel C: UNFCCC events

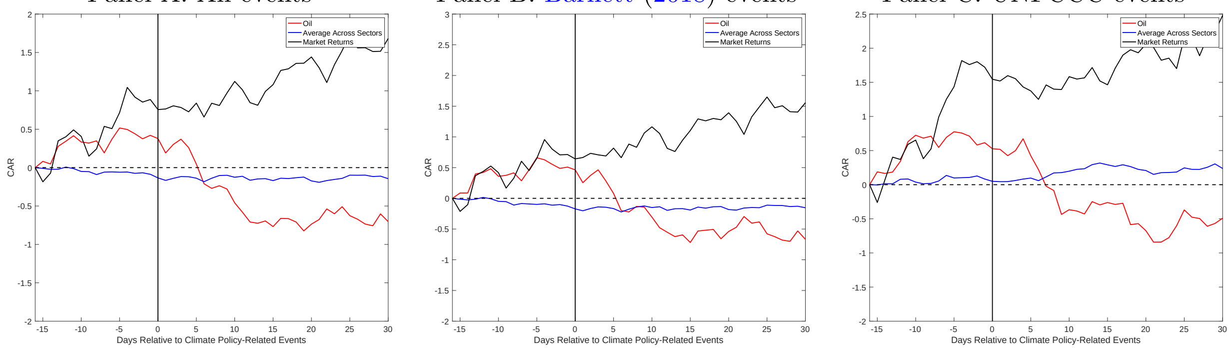

Figure A.5: Oil sector's exposure to climate policy events. For this figure and in contrast to Figure 2, an event window that lasts from -15 to +30 trading days around the event date has been used, as well as equal-weighted returns instead of value-weighted returns.

Panel A: All events | Panel B: Barnett (2018) events | Panel C: UNFCCC events

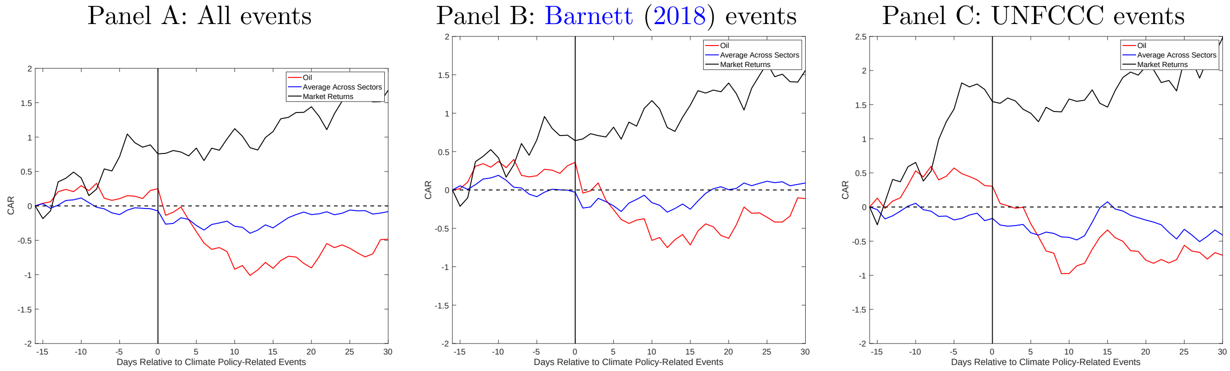

Figure A.6: Oil sector's exposure to climate policy events. For this figure and in contrast to Figure 2, equal-weighted returns instead of value-weighted returns have been used.

Panel A: All events | Panel B: Barnett (2018) events | Panel C: UNFCCC events

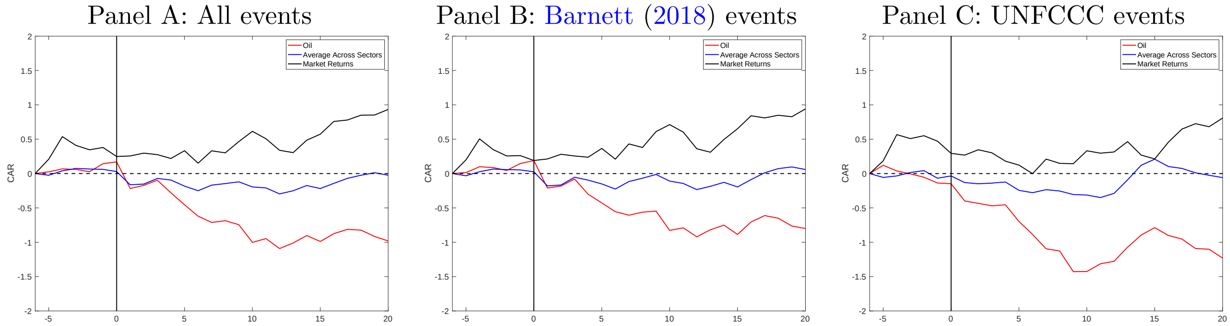

Table A.1: Panel regression. Only oil firms.

	(1) mtob	(2) mtob	(3) mtob	(4) mtob	(5) mtob	(6) mtob
oil_dummy	-0.312	-0.261	-0.200	-0.312	-0.261	-0.200
	(-1.13)	(-0.92)	(-0.68)	(-1.13)	(-0.92)	(-0.68)
ccrai	0.0131***	0.0143***	0.0245***	0.0131***	0.0142***	0.0245***
	(5.19)	(5.67)	(9.34)	(5.19)	(5.66)	(9.33)
oil_ia_ccrai	-0.0134***	-0.0153***	-0.0115***	-0.0133***	-0.0153***	-0.0115***
	(-3.73)	(-4.28)	(-3.12)	(-3.72)	(-4.28)	(-3.12)
cash_ratio		0.0258**	0.0217**		0.0257**	0.0217**
		(2.29)	(2.25)		(2.29)	(2.25)
debt_assets		5.157***	6.990***		5.160***	6.992***
		(8.55)	(9.91)		(8.56)	(9.91)
logat			-0.616***			-0.616***
			(-14.42)			(-14.42)
rd_sale_1000				0.244	0.391	0.314
				(1.32)	(1.61)	(1.56)
N	163972	163972	163784	163972	163972	163784

Notes: This table reports estimations results from panel regressions of firms' valuation on *oil_dummy*,*ccrai*, *oil_ia_ccrai* and controls (*cash_ratio*, *debt_assets*, *logat*, *rd_sale*_1000). Firm-fixed effects are included. Standard errors are clustered at the firm level. The sample spans the period 1970–2018. *** and ** denote significance at the 1% and the 5% level, respectively.

Table A.2: Barnett (2018) and UNFCCC Events for event study. The UNFCCC events are the ones in *italic* font.

09-11-1988	*IPCC estabilished*
07-11-1990	*IPCC and Second World Climate Conference*
11-12-1990	*UN General Assembly Negotiations on a Framework Convention* Begin
11-05-1992	*The text of the United Nations Framework Convention on Climate Change is adopted at the United Nations Headquarters in New York.*
04-06-1992	*UNFCCC Opens for Signature at Rio Earth Summit*
21-03-1994	*UNFCCC Enters into Force*
07-04-1995	*COP 1, Berlin, Germany*
05-06-1996	Solar Two Plant Demonstates Low Cost Method of Storing Solar Energy
18-07-1996	COP 2, Givevra, Switzerland
29-10-1996	European Union adopts target of maximum 2°C rise in average global temperature
05-11-1996	Bill Clinton Elected POTUS
05-12-1996	EVI Eletric Car is made available to the public for lease. Lease program and EV1 Later Dismantled by GM
11-12-1997	COP 3, The Kyoto Protocoll on Climate Change
14-11-1998	COP 4, Buenos Aires, Argentina
05-11-1999	COP 5, Bonn, Germany
27-11-2000	COP 6, The Hague, Netherlands
27-07-2001	COP 6, Bonn, Germany
01-10-2001	The seventh Conference of the Parties results in the Marrakesh Accords, setting the stage for ratification of the Kyoto Protocol.
12-11-2001	COP 7, Marrakech, Morocco
13-05-2002	Farm Security and Rural Investments Act
01-11-2002	COP 8, New Delhi, India
06-02-2003	President Bush Unveils the Hydrogen Fuel Initiative
27-02-2003	Plans announced to build Worlds First Zero Emission Coal Power Plant
12-12-2003	COP 9, Milan Italy
17-12-2004	COP 10, Buenos Aires, Argentina
03-01-2005	EU Emission Trading Scheme is launched
16-02-2005	*Kyoto Protocol comes into force (excluding US and Australia)*
08-07-2005	31st G8 summit discusses climate change
08-08-2005	Energy Policy Act
09-11-2005	US House prevents drilling for Oil in the Artic National Wildlife Refuge
09-12-2005	COP 11/CMP 1, Montral, Canada
30-10-2006	The Stem Review is published
17-11-2006	*COP 12/CMP 2, Nairobi, Kenya*
16-02-2007	February 2007 Washington Declaration
07-06-2007	33rd G8 Summit
31-07-2007	2007 UN General Assembly plenary debate
03-08-2007	September 2007 Washington conference
31-08-2007	2007 Vienna Climate Change Talks and Agreement
24-09-2007	September 2007 United Nations High-Level-Event
19-11-2007	IPCC Fourth assessment report
14-12-2007	The thirteenth Conference of the Parties adopts the Bali Road Map
17-12-2007	COP 13, CMP 3, Bali, Indonesia
19-12-2007	Energy Independence and Security Act
30-01-2008	First commercial cellulosic Ethanol plant goes into production
22-05-2008	Food, Conservation, and Energy Act
07-10-2008	National Biofuel Action Plan Unveiled
04-11-2008	Barack Obama elected POTUS
12-12-2008	COP 14, CMP 4, Poznan, Poland
22-12-2008	*Worst coal ash spliss in US History in Kingston, Tennessee*
17-02-2009	ARRA (2009) contains funding forrenewable energy
22-04-2009	First framework for Wind Energy Development on the US outer continental shelf announced
05-05-2009	President Obama issues Presidential Directive to USDA to expand access to biofuel
27-05-2009	US announces funding in Recovery Act Funding for Solar and Geothermal Energy Development
26-06-2009	US House of Representatives passes the American Clean Energy and Security Act
22-09-2009	September 2009 United Nations Secretary General's Summit on Climate Change
27-10-2009	US inverst \$3.4 bilion to modernize energy grid
18-12-2009	COP 15/CMP 5, Copenhagen, Denmark
20-04-2010	BP Oil rig explodes and causes largest oil spill in US history
10-12-2010	COP 16/CMP 6, Cancún, Mexico
11-03-2011	Earthquake off coast to Japan damages six powerplants at Fukushima
06-12-2011	17th Conference of the Parties
09-12-2011	COP 17/ CMP 7, Durban, South Africa
09-02-2012	US Nuclear Regulatory Commission (NRC) approves new nuclear power plants
27-03-2012	EPA announces first clean air act stantard for carbon pollution from new power plants
17-04-2012	EPA issues first ever clean air rules for natural gas produced by fracking
06-11-2012	Barack Obama elected POTUS
07-12-2012	COP 18/CMP 8, Doha, Qatar
10-12-2012	18th Conference of the Parties
25-06-2013	President Obama releases his Climate Change Action Plan
20-09-2013	EPA issues new proposed rule to cut Greenhouse gas emissions from power plans
27-09-2013	IPCC Releases 2nd Part of Fifth Assessment Report
25-11-2013	COP 19/CMP 9, Warsaw, Poland
13-02-2014	Ivanpah, the world's lagest concentrated solar power generation plan, goes online
09-05-2014	President Obama announces solar power commitments and executive act
02-06-2014	EPA proposes first ever rules to reduce carbon emissions from eisting power plants
22-09-2014	Rockfellers and over 800 global investors announce fossil fuel disinvestment
23-09-2014	Climate Summit 2014
03-11-2014	IPCC Fifth assessment report
12-12-2014	COP 20/ CMP 10, Lima, Peru
03-08-2015	President Obama announces clean power plan
14-12-2015	*COP 21/CMP 11, Paris, France*
18-11-2016	*COP 22/CMP 12/CMA 1, Marrakech, Morocco*
09-05-2018	*Solar Power to be required on all New California homes by 2020*

B Sectoral Output Construction in U.S. Data

To construct a measure for the output of the dirty, clean, and oil sectors, we use U.S. data from the Bureau of Economic Analysis. Specifically, we use the gross output by industry data between 1960 and 1995. We let output by all private industries (Line 2) be aggregate output. From these private industries, the gross output of the following industries is summed up to obtain the gross output of the dirty 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 clean sector's output is then the residual or private industries output (Line 2) minus our measure of dirty sector's output and minus our measure of oil sector's output.

C Model Equilibrium Conditions

C.1 Competitive Equilibrium with Carbon Tax

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

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

which leads to the equilibrium condition

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

in line with Equation (31).

Intermediate goods firms The clean and dirty intermediate goods producers, $i \in \{c, d\}$, optimize (8) and (9), respectively, subject to the production functions in Equation (5), as well as the laws of motion (10) and (11), leading to the problem

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Oil firm The oil producer optimizes (18), subject to the production function (16), as well as the laws of motion (15) and (17), leading to the problem

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

The first derivative with respect to N_t implies

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

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

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

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

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

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

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

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

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

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

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

and

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

C.2 Social Planner Solution

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

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

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

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

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

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

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

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

and T_{t+1}, which yields

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

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

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

C.3 Optimal Carbon Tax

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

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

in the competitive equilibrium and

$$p_{c,t} = \lambda_{c,t} \qquad \text{and} \qquad p_{d,t} = \lambda_{d,t} + \epsilon_t^S \xi_d \tag{C.27}$$

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

D Normalized Equilibrium Conditions

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

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

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

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

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

The following variables do not need to be normalized:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The asset pricing equations in normalized form look as follows:

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

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

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

The other equations in normalized form look as follows:

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

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

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

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

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

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

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

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

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

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

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

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

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

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

E Temperature Shocks

In the main text, we have analyzed the effects of carbon tax shocks. In this section, we analyze the macroeconomic and asset pricing effects of temperature shocks using conditional impulse response functions. Figures E.1 and E.2 illustrate impulse responses to a positive temperature shock ε^T_{t+1}. The former figure depicts the dynamics of main macroeconomic aggregates and dirty and clean sectors, while the latter figure depicts the dynamics of the oil sector. The figures depict the impulse response functions for the baseline model, in which the carbon tax level is at its optimal level, for a "Low Tax" model, in which the carbon tax level is only 50% of the optimal value, and for a "High Tax" model, in which the carbon tax level is set to 110% of the optimal value.

In line with intuition, the plots reveal that the temperature increase is a negative shock to the overall economy, as reflected by an increase of the stochastic discount factor. Since the higher temperature reduces environmental quality, the carbon tax rate increases. This leads to a negative effect on the dirty sector and a positive effect on the clean sector, as agents reallocate both capital and labor to the clean sector. Therefore, the output and capital of the clean sector increase, whereas the output and capital of the dirty sector decrease. As a result, the equity return of clean firms responds strongly positively. The return is negative for dirty firms.

The related climate productivity risk premium follows from minus one times the covariance of sector-specific equity returns with the stochastic discount factor in response to the temperature shock. Therefore, clean firms provide a hedge against climate productivity risk and thus carry a negative climate productivity risk premium and dirty firms carry a positive climate productivity risk premium.

In the "Low Tax" model, the dirty firm's excess return is decreasing less in response to the temperature shock, which implies that the climate productivity risk premium is smaller as well. This is intuitive, as the output and capital of the dirty sector decrease less in this economy due to the fact that the tax burden increases less than in the benchmark economy.

Moreover, the oil sector's dynamics are similar to the dirty sector. The number of oil wells, the production of new oil wells, physical capital of the oil sector, and the quantity of oil extracted and consumed are decreasing in response to a positive temperature shock. The effects are again smaller in the "Low Tax" model. The oil price declines due to the lower demand for oil and the supply is only adjusting downwards with a lag.

The oil firm's excess return responds strongly negatively to the innovation in temperature, similarly as for the dirty firms. The decrease is larger for oil firms than dirty firms.

Figure E.1: Impact of temperature shocks on main macroeconomic aggregates and clean and dirty sectors for three values of the carbon tax level: 50%, 100%, and 110% of the optimal carbon tax. These three values correspond to three cases: a “Low Tax” case, the “Baseline Model” case, and a “High Tax” case (in which the tax is set higher than optimal). This figure shows conditional impulse response functions of quantities and prices to a positive one-standard-deviation temperature shock materializing at $t = 1$. Lowercase letters refer to log variables.

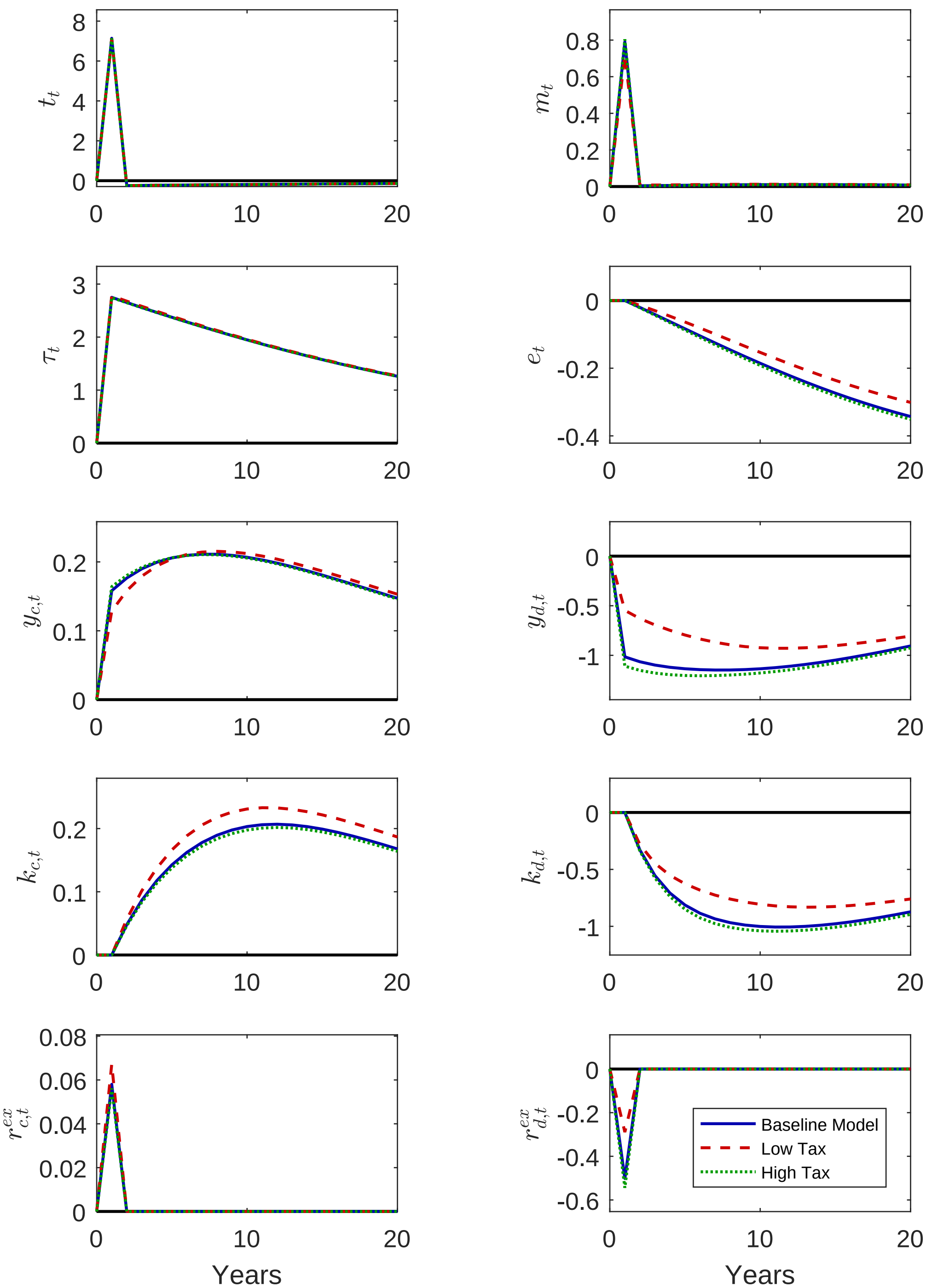

Figure E.2: Impact of temperature shocks on the oil sector for three values of the carbon tax level: 50%, 100%, and 110% of the optimal carbon tax. These three values correspond to three cases: a "Low Tax" case, the "Baseline Model" case, and a "High Tax" case (in which the tax is set higher than optimal). This figure shows conditional impulse response functions of quantities and prices to a positive one-standard-deviation temperature shock materializing at $t = 1$. Lowercase letters refer to log variables.