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Understanding Macro and Asset Price Dynamics During the Climate Transition

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ABSTRACT

This paper analyzes the transition to a low-carbon economy and its effects on macroeconomic quantities and asset prices. Empirically, we document that the relative valuation of fossil fuel firms has significantly declined with the rise of climate change risk awareness. We develop a macro asset pricing model for the climate transition that matches this empirical fact and allows us to characterize the dynamics of macroeconomic aggregates and asset prices during and after the transition. In particular, we analyze (i) firm valuation dynamics, (ii) climate policy risk premia, (iii) capital reallocation between sectors, and (iv) the behavior of oil prices.

Keywords: Climate change, Policy risk, General equilibrium, Risk premia, Oil market.

JEL codes: E2, E3, G12, Q43.

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 precise implications of the climate transition for economic and financial market outcomes are not well understood. This paper aims to close this gap by analyzing the effects of the climate transition on macroeconomic quantities and asset prices.

As a starting point, we ask whether first 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, following the logic that this sector is the one that is first and most significantly affected prior to other industries. We analyze how the market valuation of fossil fuel firms has changed with the increasing awareness for climate change risks, 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, fossil fuel 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 suggest that today's financial markets have started reflecting the beginning of the climate transition. At the same time, the analysis of current and past price and quantity information can only provide limited insights into the future dynamics of macroeconomic quantities and asset prices 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*: Firms' output is negatively affected by permanent changes in temperature, and the global temperature level is influenced by the greenhouse emissions of the economy, with "dirty" (fossil-fuel consuming) firms having a higher emissions intensity than "clean" firms. As dirty firms do not internalize the negative effect of their emissions on the rest of the economy, the climate change externality arises. To bring the economy closer to the social optimum, the regulator introduces a tax on greenhouse gas emissions. 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 over the first 20 years of the transition period in the calibrated model. The valuation of clean firms, on the other hand, increases in the medium 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. If the prevailing carbon tax is lower than socially optimal, a positive climate policy shock speeds up the climate transition by an unexpected increase towards the optimal tax level. The model reveals that climate policy risk premia arising from such shocks do not amplify, but rather counteract the cash flow effects of the climate transition — i.e., climate policy risk premia are *negative*. To understand this result, recall that a tax-increasing climate policy shock negatively affects the valuation of fossil fuel producers and other dirty firms, and positively affects clean firms. Such a tax-increasing shock is a "good" shock for the overall economy if the prevailing carbon tax is below its social optimum, leading to a decline of the stochastic discount factor. Therefore, fossil fuel firms and dirty firms respond negatively to "good" climate policy shocks (and positively to "bad", tax-reducing climate policy shocks), such that their climate policy risk premia are negative. This result is in line with the intuition provided by Baker, Hollifield, and Osambela (2019) and Roth Tran (2019) that dirty firms paradoxically provide a hedge against the consequences of climate change.

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 can also become positive, as it is then possible that the carbon tax is set to a too high level for the economy, which does not happen during our simulated transition period. If the carbon tax is higher than optimal, a further carbon tax increase is a “bad” shock for the overall economy, to which especially the dirty sector reacts negatively, such that dirty firms command overall positive climate positive risk premia. On the other hand, the situation for lower-than optimal carbon taxes is similar to the transition period, resulting in negative risk premia on climate policy risk.

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 as 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 (2018) 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 (2018) 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 (2018) show that real estate prices are affected only in regions where people believe in climate change. Bernstein, Gustafson, and Lewis (2018) and Murfin and Spiegel (2018) 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 (2016) 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 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 (2018), 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 Firm Valuations

This section lays important foundations for the paper and presents our main empirical result: that market valuations of fossil fuel firms have declined relative to other sectors over the same time period that the awareness for climate change risks has increased. We first show that the awareness for climate change risks has increased in the past two decades. Second, we argue that the fossil fuel sector is the sector that is most directly and immediately affected by climate transition risks, and therefore a perfect laboratory to test whether this trend is represented by firm valuations. Finally, we show that valuations in the oil sector have declined relative to other sectors, within a time period that coincides with the increased awareness for climate change risks.

2.1 Awareness of Climate Change Risks

The awareness of climate change and related risks has notably increased over the last 10 to 20 years and 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 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.

The increasing awareness for climate change risks does obviously not exclude financial

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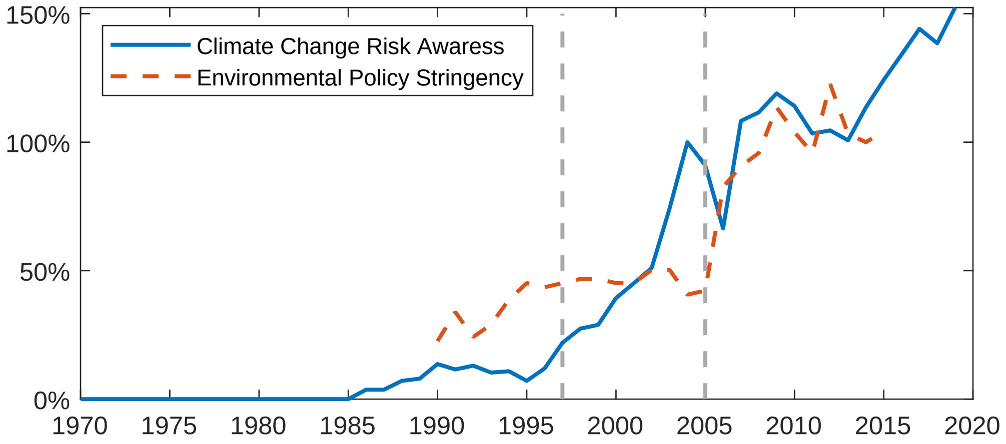
[1] This includes fixed carbon taxes as well as price-flexible emission trading systems, see World Bank (2019).

[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.

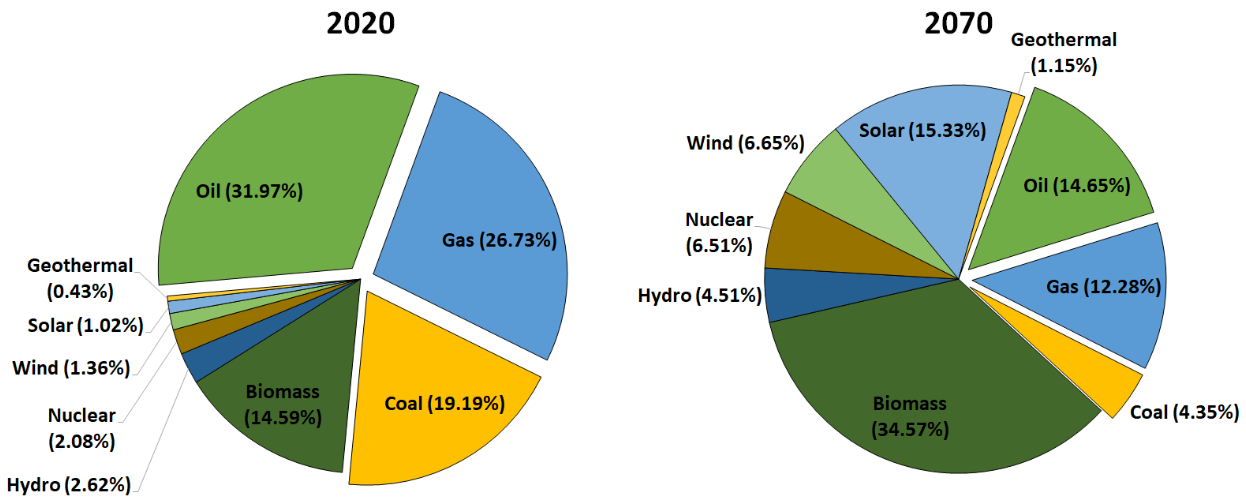


investors, for whom climate-related risks have become an important factor for investment and risk management decisions. While climate-related physical disasters risks are clearly on their long-term radar, an at least as prominent role is attributed to climate transition risks (political and technological), which have implications as of now. To this end, most financial data providers provide tools to evaluate firm-specific climate transition risks, such as the Carbon Risk Valuation Tool introduced by Bloomberg in 2013. Similar information is provided by initiatives like *2 degrees of separation*, which publishes data on the potential amount of stranded assets for a number of fossil fuel firms under different scenarios. In general, low carbon investing has become a big trend, and most asset management firms offer a variety of low-carbon funds by now.

2.2 Transition Dynamics in the Energy Sector

It is immediately clear 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. 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]

Figure 2: Primary energy consumption sources based on the TIAM-WORLD model.



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. Figure 2 depicts how the composition of worldwide energy consumption (including electricity generation, transportation, industrial use, as well as for residential and commercial buildings) is predicted to change in the next 50 years if the 2 degrees limit is maintained, based on simulations of the popular TIAM-WORLD model. It is eye-catching that 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

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

through their combustion.

Figure 3: Worldwide fossil fuel consumption and CO_2 emission the scenarios based on the TIAM-WORLD model.

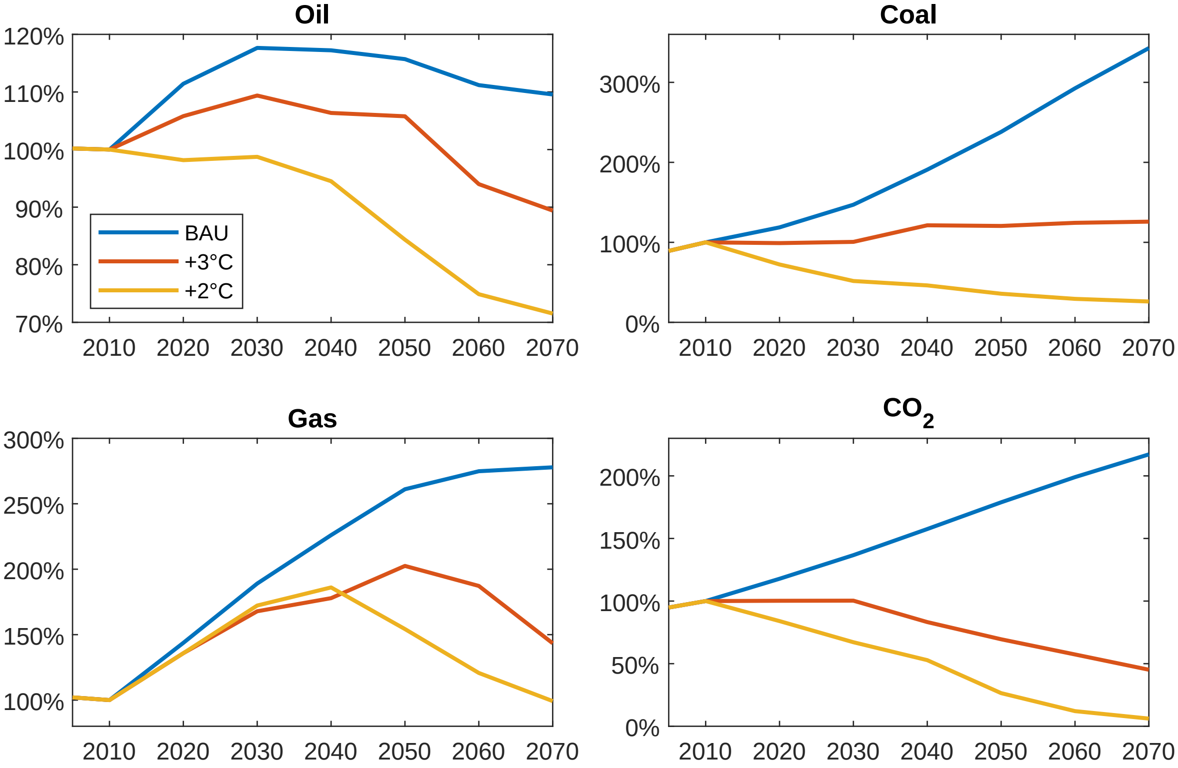

Figure 3 illustrates the transition of the energy sector in more detail. It becomes directly apparent that the fossil fuel sector is strongly affected by the climate transitions over the next 5 to 10 years already. While the worldwide consumption of oil is predicted to increase by 20% until 2030 under the business-as-usual (BAU) scenario with no additional climate policies, oil consumption will decline if policies are implemented 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.

2.3 Exposure of Fossil Fuel Firms

In order to demonstrate the strong exposure of fossil fuel firms with respect to changes in climate policy or announcements about changes in climate policy, we perform an event study. 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 the value-weighted returns data for the 17 industry portfolios, supplied by Ken French on his website[4], for the sectoral returns data. For the event dates, we use the events compiled by Barnett (2018) that are associated with stricter climate policy and thus are labeled with a "+" in the "Shock Sign" column of Figure 17 in Appendix B of the aforementioned paper. Moreover, we expand this list by using the dates in the United Nations Framework Convention on Climate Change (UNFCCC) that are supplied on `https://unfccc.int/timeline`, which correspond to key milestones in the evolution of international climate policy. Table A.2 in Appendix A contains the date and short description of all the events we use in our event study.

To compute the 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 days with respect to the day of the event). Therefore, we use only past information to

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

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

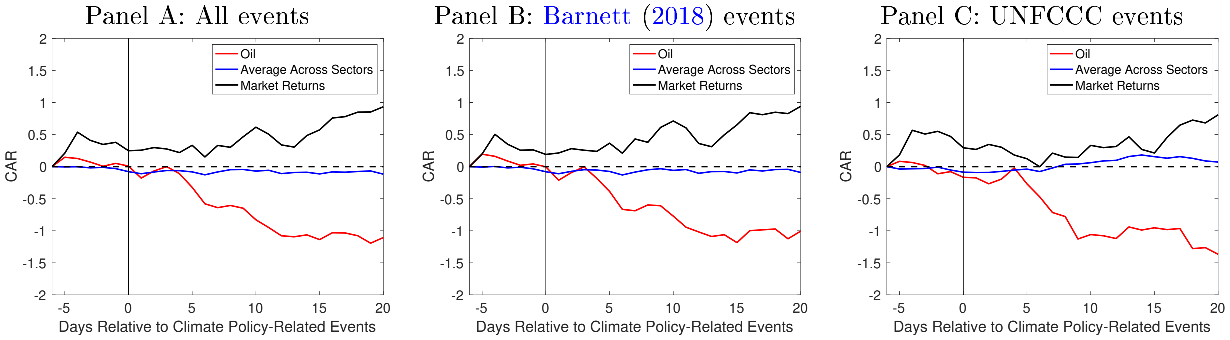
$$R^A_{i,t} = R_{i,t} - \hat{R}_{i,t}. \tag{2}$$

The cumulative abnormal returns for each sector are then computed by summing up abnormal returns around the event (from -5 to $+20$ trading days). 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 4 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 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.[5]

Figure 4: Oil sector's exposure to climate policy events.



Panel A: All events

Panel B: Barnett (2018) events

Panel C: UNFCCC events

2.4 Valuation of Fossil Fuel Firms

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

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[5] The results are very similar when we use equal-weighted returns instead of value-weighted returns. The figures are not shown in order to conserve space, but are available upon request from the authors.

changed together with the increased awareness for 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.

	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.[6] This implies that the valuation of fossil fuel firms has decreased by

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[6] 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. Fossil-fuel firms.

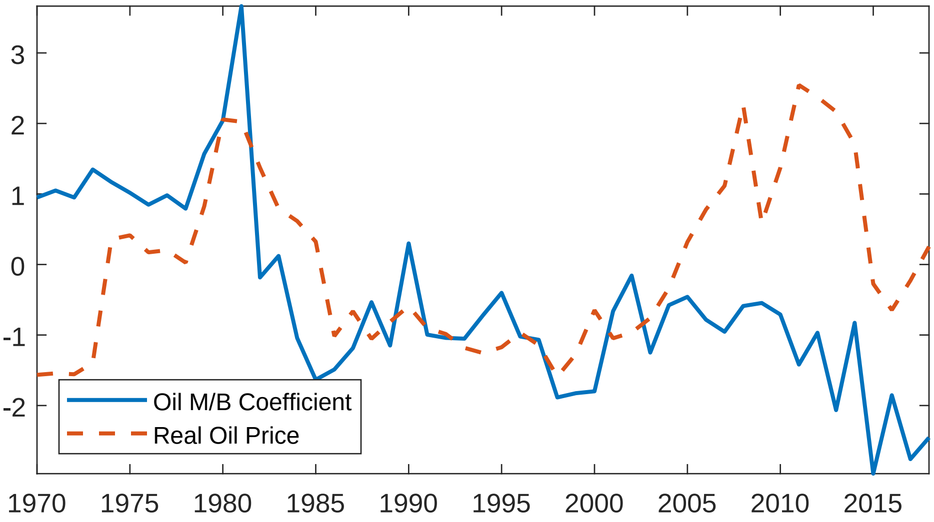
	(1)	(2)	(3)	(4)	(5)	(6)
	mtob	mtob	mtob	mtob	mtob	mtob
fossil_dummy	-0.326	-0.298	-0.226	-0.326	-0.298	-0.226
	(-1.21)	(-1.08)	(-0.79)	(-1.21)	(-1.08)	(-0.79)
ccrai	0.0132***	0.0143***	0.0246***	0.0132***	0.0143***	0.0246***
	(5.19)	(5.68)	(9.33)	(5.18)	(5.67)	(9.32)
fossil_ia_ccrai	-0.0131***	-0.0153***	-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

Notes: This table reports estimations results from panel regressions of firms' valuation on *fossil_dummy*,*ccrai*, *fossil_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.

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 5 plots the related coefficients of the yearly dummies' interaction terms with the oil sector. The plot depicts that the yearly 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.

Figure 5: Coefficients of the year-oil sector interaction dummies based on the panel regression setup, compared to the real oil price.



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 economy's future output. 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. The clean sector is labeled with the letter c and the dirty one with the letter d. The final goods producers compose the output from the clean firms and the dirty firms to a final good

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

which is 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 clean and dirty sectors differ in the amount of carbon emissions they generate as part of their production process, and also with respect to their temperature sensitivity of output. In particular, firms in the dirty sector emit ξ_d tons of greenhouse gas for each unit of produced output, and we assume for simplicity that $\xi_c = 0$. In the clean sector, goods are produced according to the following production function

$$Y_{c,t} = \frac{(A_t L_{c,t})^{1-\alpha} K_{c,t}^{\alpha}}{1 + \kappa_{c,1} T_t^{\kappa_{c,2}}}, \tag{5}$$

such that the clean sector's output depends on the temperature level T_t in addition to physical capital $K_{c,t}$ and labor $L_{c,t}$. The sensitivity of the output function to temperature is modeled similarly to the damage function of Nordhaus (1992), with temperature sensitivity parameters $\kappa_{c,1}$ and $\kappa_{c,2}$. Therefore, positive temperature anomalies $T_t > 0$ harm the output of the clean sector. The labor productivity A_t of the economy follows the process

$$\ln(A_{t+1}) = \ln(A_t) + \mu_A + \sigma_A \varepsilon_{t+1}^{A} \tag{6}$$

with productivity shocks ε_{t+1}^{A}. The dirty sector's production function is given by

$$Y_{d,t} = (A_t L_{d,t})^{1-\alpha} Z_t^{\alpha}, \tag{7}$$

where Z_t is a constant-elasticity-of-substitution (CES) aggregate of physical capital $K_{d,t}$ and oil O_t,

$$Z_t = \left((1-\iota) K_{d,t}^{1-\frac{1}{o}} + \iota O_t^{1-\frac{1}{o}} \right)^{\frac{1}{1-\frac{1}{o}}}. \tag{8}$$

The quantity of oil O_t is produced by the oil sector, which will be described in detail further below. As only the clean sector's production output is negatively affected by rising temperature levels,[7] a negative *emissions externality* arises through climate change. This externality

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[7] This somewhat stark assumption is made for two reasons: First, a negative climate externality only arises if the clean sector is more negatively affected by rising temperatures than the dirty sector. Second, we can only solve explicitly for the optimal carbon tax in the model if one of the sectors is unaffected by rising

is addressed by the regulator in form of a carbon tax of τ_t on each ton of greenhouse gas emissions, as specified below.

Overall, the perfectly competitive intermediate goods firms maximize

$$\mathbb{E}_t\left[\sum_{t=0}^{\infty}\mathbb{M}_t\left(p_{c,t}Y_{c,t}-R^K_{c,t}K_{c,t}-w_tL_{c,t}-\tau_t\xi_cY_{c,t}\right)\right], \tag{9}$$

$$\mathbb{E}_t\left[\sum_{t=0}^{\infty}\mathbb{M}_t\left(p_{d,t}Y_{d,t}-R^K_{d,t}K_{d,t}-w_tL_{d,t}-p_{o,t}O_t-\tau_t\xi_dY_{d,t}\right)\right], \tag{10}$$

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

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

$$\mathcal{E}_{t+1}=(1-\eta)\mathcal{E}_t+\frac{\xi_d}{A_t}\cdot Y_{d,t}, \tag{11}$$

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 $\xi_c=0$ for simplicity). 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

$$T_{t+1}=\nu T_t+\chi\mathcal{E}_{t+1}+\sigma_T T_{t+1}\varepsilon^T_{t+1}. \tag{12}$$

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_{t+1}, whose volatility

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temperatures. Our choice also provides a nice distinction between the polluting sector and the sector which is most negatively affected by the consequences of climate change. Note that the indirect general equilibrium effects of rising temperatures do affect also the firms in the dirty sector.

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. Data on the global temperature anomaly will be used to compare the model-implied values with the empirical evidence. Therefore, $T_t > 0$ implies that the temperature is above the pre-industrial long-run temperature value and only $T_t > 0$ induces output losses via the damage function in Equation (5).

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 fluctuates between zero and the optimal level. When we set $\mu_\theta > 0$ so that the implemented level right now (i.e., in the steady state) is below the optimal carbon tax, we can study an economy that does not fully take care of the climate externalities. The implemented carbon tax is subject to policy shocks ε_{t+1}^θ, and a positive policy shock brings the carbon tax closer to the socially optimal level.

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

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

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 final goods C_t. The households therefore maximize Epstein and Zin (1991) utility

$$V_t = \left[(1-\beta)C_t^{1-\frac{1}{\psi}} + \beta\left(\mathbb{E}_t[V_{t+1}^{1-\gamma}]\right)^{\frac{1-\frac{1}{\psi}}{1-\gamma}}\right]^{\frac{1}{1-\frac{1}{\psi}}} \tag{21}$$

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

$$1 - \ell = L_{c,t} + L_{d,t} + L_{o,t}, \tag{22}$$

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

$$Y_t = C_t + I_{c,t} + I_{d,t} + I_{o,t}. \tag{23}$$

3.2 Equilibrium

We derive the household's and the firms' first order conditions in order to solve for the model equilibrium. For the former, we define the pricing kernel as

$$\mathbb{M}_{t+1} = \beta\left(\frac{C_{t+1}}{C_t}\right)^{-\frac{1}{\psi}}\left(\frac{V_{t+1}}{\left(\mathbb{E}_t[V_{t+1}^{1-\gamma}]\right)^{\frac{1}{1-\gamma}}}\right)^{\frac{1}{\psi}-\gamma} \tag{24}$$

and obtain that the Euler equation

$$\mathbb{E}_t\left[\mathbb{M}_{t+1}R_{t+1}\right] = 1 \tag{25}$$

holds for the assets traded in the economy, with return R_{t+1}.

From the firms' side, we obtain that (25) holds for the investment returns in the three sectors ($i \in \{c, d, o\}$),

$$R_{i,t+1} = \frac{R^K_{i,t+1} + ((1-\delta) + G'_{i,t+1}\frac{I_{i,t+1}}{K_{i,t+1}} - G_{i,t+1})Q_{i,t+1}}{Q_{i,t}}, \tag{26}$$

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

$$R^K_{c,t} = \alpha p_{c,t}\frac{Y_{c,t}}{K_{c,t}}, \quad R^K_{d,t} = \alpha(1-\iota)(p_{d,t} - \tau_t)\frac{Y_{d,t}}{Z_t^{1-\frac{1}{o}} K_{d,t}^{\frac{1}{o}}}, \quad R^K_{o,t} = \tau\lambda_{o,t}\frac{N_t}{K_{o,t}}, \quad Q_{i,t} = \frac{1}{1-G'_{i,t}}, \tag{27}$$

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)

$$p_{o,t} = \lambda_{d,t}\alpha\iota\frac{Y_{d,t}}{Z_t^{1-\frac{1}{o}} O_t^{\frac{1}{o}}}. \tag{28}$$

We furthermore obtain the condition

$$Y_{i,t} = p_{i,t}^{-\varepsilon} Y_t. \tag{29}$$

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

$$\tau_t^* = \epsilon_{c,t}, \tag{30}$$

where $\epsilon_{c,t}$ is a Lagrange multiplier describing the negative externality of the dirty firms on the clean sector as defined in Appendix C.

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

$$R_t^f = \frac{1}{\mathbb{E}_t[\mathbb{M}_{t+1}]}, \tag{31}$$

$$R_{t+1}^M = \frac{K_{c,t}Q_{c,t}R_{c,t+1}^K + K_{d,t}Q_{d,t}R_{d,t+1}^K + K_{o,t}Q_{o,t}R_{o,t+1}^K}{K_{c,t}Q_{c,t} + K_{d,t}Q_{d,t} + K_{o,t}Q_{o,t}}, \tag{32}$$

$$R_{ex,t}^{LEV} = (1 + \overline{DE})(R_t^M - R_{t-1}^f). \tag{33}$$

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, 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 of 10 and an elasticity of intertemporal substitution of 2, yielding a preference for the early resolution of uncertainty. The time discount factor β is set to 0.96. 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 $\zeta = 5.5$ to let the model produce a 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
Labor market		
Leisure share	ℓ	2/3
Final goods production		
Depreciation rate of capital	δ	0.06
Capital adjustment costs	ζ	5.5
Capital share of intermediate goods production	α	0.31
Average productivity growth rate	μ	0.0227
Volatility of productivity growth	σ_A	0.0319
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 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, $\xi_d = 0.1$, while the clean sector's emissions intensity is $\xi_c = 0$. Third, we assume that the dirty sector is not affected by changes in temperature, while the clean sector is temperature-sensitive with parameters $\kappa_{c,1} = 0.0144$ and $\kappa_{c,2} = 2$. These two parameter choices are motivated by the results in Nordhaus (1992).

Further parameters driving the overall emissions in the atmosphere as well as the global

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 clean sector	ξ_c	0
Emissions intensity of dirty sector	ξ_d	0.1
Temperature-sensitivity of clean sector	$\kappa_{c,1}$	0.0144
Temperature-sensitivity of clean sector	$\kappa_{c,2}$	2
Carbon retention rate	ν	0.966
Atmosphere recovery rate	η	0.02
Climate sensitivity to emissions	χ	0.18
Volatility of temperature shocks	σ_T	0.0675
Carbon Tax		
Average distance of carbon tax to optimal tax	μ_θ	0
Persistence of carbon tax	ρ_θ	0.98
Volatility of policy shocks	σ_θ	0.025

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 $\chi = 0.18$. We set the volatility of temperature shocks σ_T to 0.0675. 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 macroeconomic U.S. 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, global temperatures as specified by the dynamics (12) are not endogenous to the model anymore, but perceived as an exogenous process by the agents.

Table 5 reports the simulated moments for this pre-transition economy and its empirical counterparts based on U.S. data from 1960 to 1995. The model is calibrated to match the average output growth rate and the volatility of output growth. 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.

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. data for the period 1960–1995. Details on the construction of the sectoral output data is given in Appendix B.

Moment	Data	Model
$\mathbb{E}[I/Y]$	12.80	20.22
$\mathbb{E}[p_d Y_d/(p_c Y_c + p_d Y_d + p_o O)]$	20.87	25.90
$\mathbb{E}[p_c Y_c/(p_c Y_c + p_d Y_d + p_o O)]$	74.74	69.54
$\mathbb{E}[p_o O/(p_c Y_c + p_d Y_d + p_o O)]$	4.39	4.56
$\mathbb{E}[\Delta y]$	2.27	2.27
$\sigma(\Delta y)$	2.20	2.20
$\sigma(\Delta c)$	1.21	1.61
$\sigma(\Delta i)$	8.62	4.72

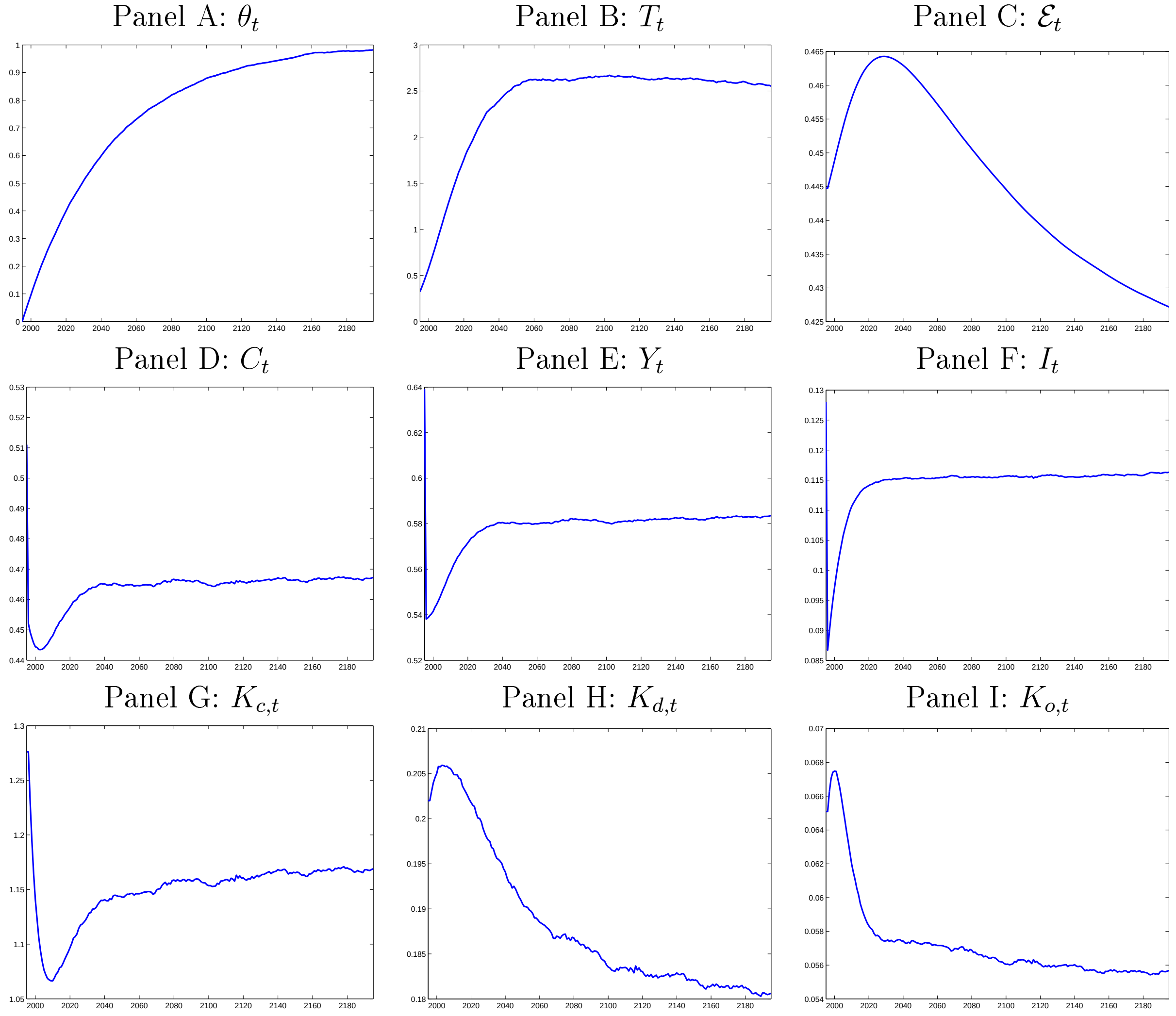
4.3 Simulating the Climate Transition

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 6 plots the average path of key macroeconomic quantities during the transition period. 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 about 2.5, which it reaches approximately in the year 2060 (see Panel B of Figure 6). Therefore, the economy is able to constrain the temperature increase to roughly 2.5 degrees Celsius over pre-industrial levels by setting the carbon tax optimally. The figure nicely demonstrates in Panel A, which depicts the fraction of the optimal carbon tax implemented, that the carbon tax actually takes longer than that under the given calibration to finally reach the socially optimal level. Emissions, as considered in Panel C, decrease relatively quickly in the transition period after an initial increase until the year 2030.

Aggregate consumption, output, and investment (Panels D–F) all display a U-shaped behavior. First, the increase in the carbon tax depresses the economic aggregates, before starting to rebound. This rebound is coming from the clean sector that benefits in the long run from the steadily increasing carbon tax level, and capital in the clean sector shows a similar behavior in Panel G as does aggregate consumption, output, and investment. The dirty and the oil sector's capital levels decrease throughout the transition period after an initial short increase (Panels H and I). Therefore, over the transition period total aggregate capital decreases in the economy, but clean firms' capital starts to rebound strongly. These dynamics describe the reallocation of capital from dirty and oil firms to clean firms during the transition period.

Figure 6: 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.



Panel A: θ_t

Panel B: T_t

Panel C: $\mathcal{E}_t$

Panel D: C_t

Panel E: Y_t

Panel F: I_t

Panel G: $K_{c,t}$

Panel H: $K_{d,t}$

Panel I: $K_{o,t}$

4.4 Predictions for the Transition Period

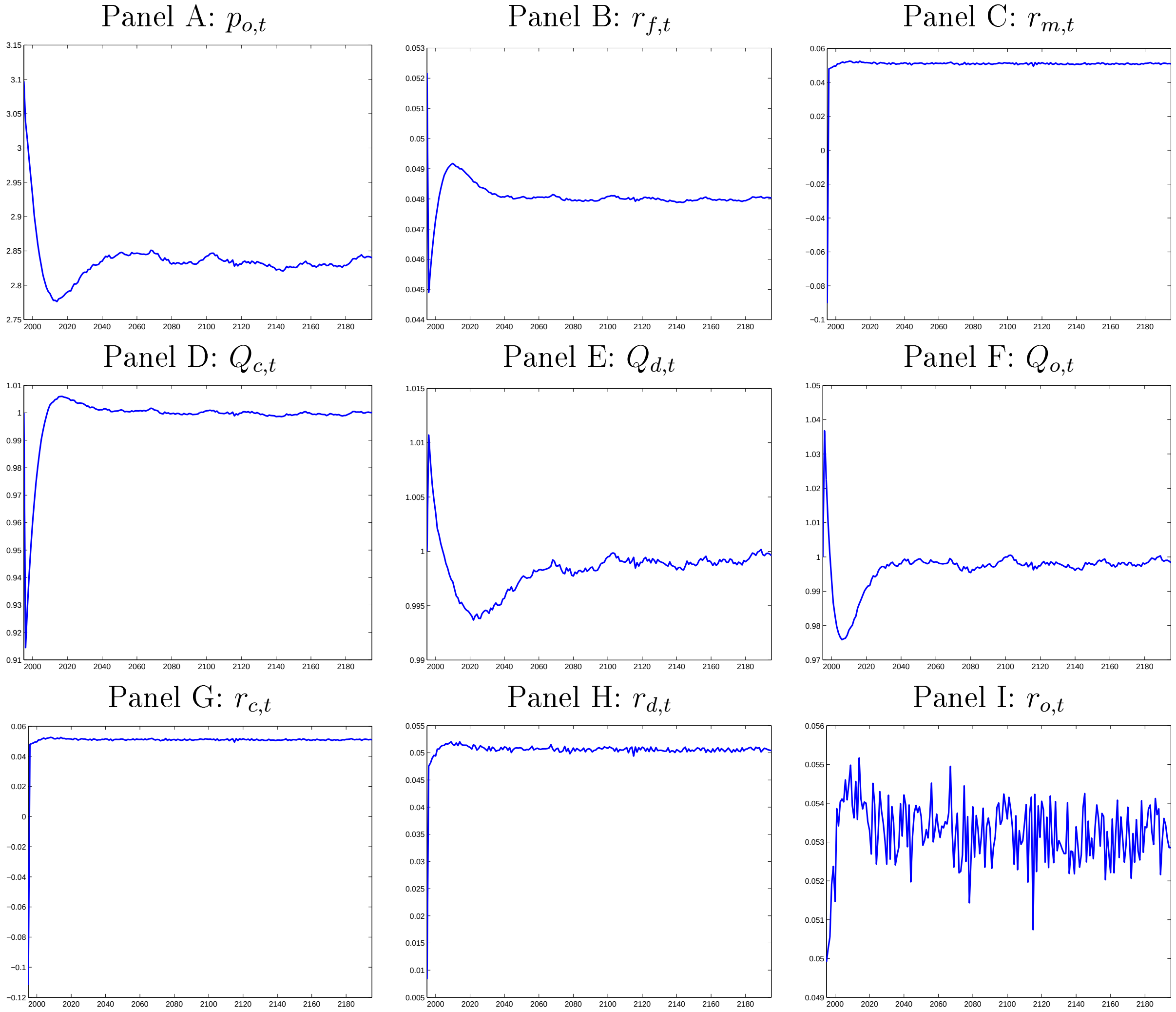
We pin down the model's main predictions for the climate transition period regarding the behavior of firm valuations and capital reallocation, climate policy risk premia, as well as the dynamics of the oil sector. We particularly analyze the mean transition paths of the respective variables as well as 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 7 depicts the average transition paths of key asset prices in the economy, showing the behavior of Tobin's Qs in the middle row. Our analysis reveals that the valuations of the dirty and the oil sector decline over the first twenty years, after a short initial increase. They stay below 1 during the entire transition period with the exception of the first 10 years (Panels E and F). Therefore, the model reproduces our empirical finding of Section 2 that fossil-fuel firms lost value relative to other firms in the economy, particularly from year 2005 onward. The Tobin's Q of the clean sector declines sharply initially but increases in the medium run (Panel D), 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 Panels H and I of Figure 6), and after an initial drop 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.

Climate policy risk premia An important question is whether the described decline in valuations for the dirty sector and 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 major macroeconomic aggregates as well as of clean and dirty sector quantities in response to shocks to the implemented carbon tax in Figure 8. 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

Figure 7: 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.


Panel A: $p_{o,t}$

Panel B: $r_{f,t}$

Panel C: $r_{m,t}$

Panel D: $Q_{c,t}$

Panel E: $Q_{d,t}$

Panel F: $Q_{o,t}$

Panel G: $r_{c,t}$

Panel H: $r_{d,t}$

Panel I: $r_{o,t}$

responses around a 110% carbon tax case, which could be attained after the transition if the regulator accidentally sets the tax too high.

The first observation to be made is that for carbon tax levels less or equal 100%, the stochastic discount factor declines in response to a higher carbon tax. Therefore, a higher carbon tax is seen as a good state of the economy by the households. This is completely in line with the intuition that there is negative climate externality, the stricter regulation of which improves economic welfare. After climate policy is tightened, emissions and temperatures

Figure 8: Impact of carbon tax shocks on major 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.

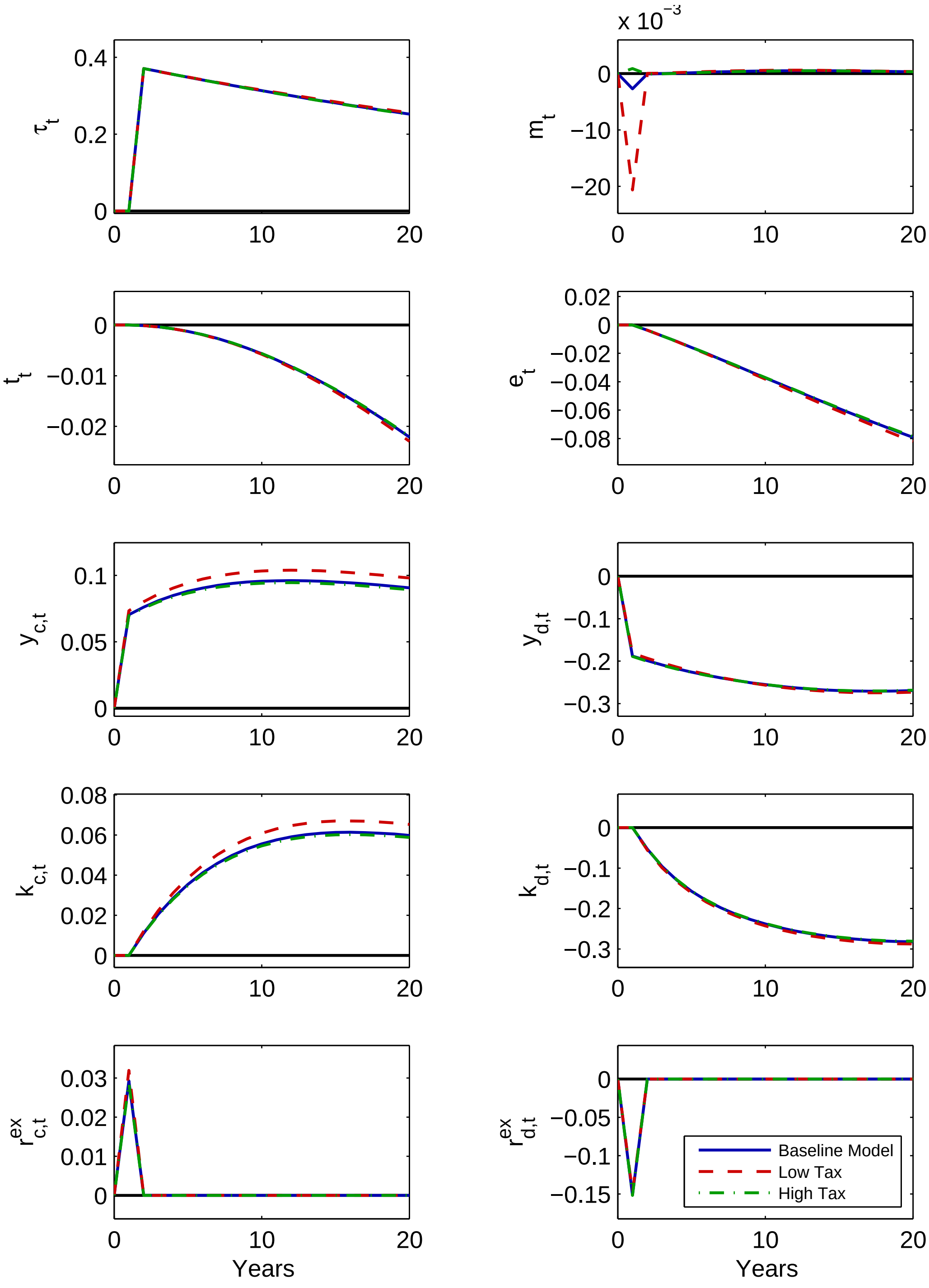
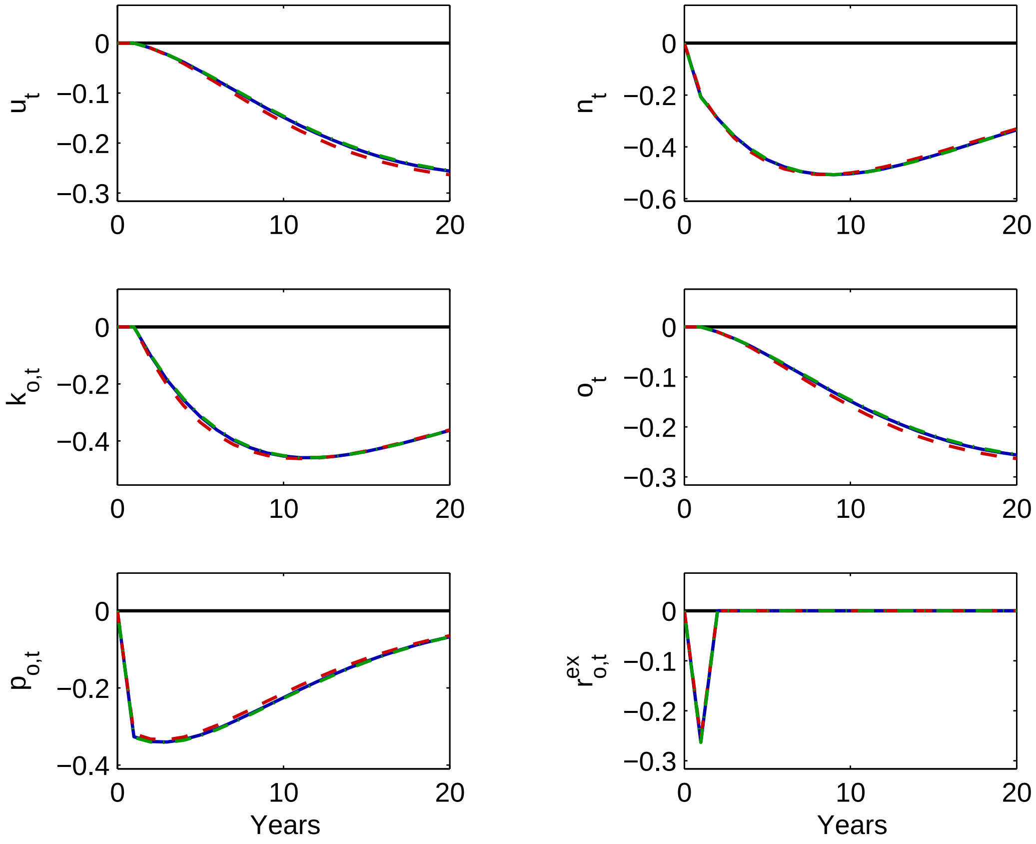


Figure 9: Impact of carbon tax shocks on the oil sector for three values of the carbon tax level: 50%, 100%, and 110% of the optimal carbon tax. These three values correspond to three cases: a "Low Tax" case, the "Baseline Model" case, and a "High Tax" case (in which the tax is set higher than optimal). 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.



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 positive climate policy risk premia for the clean sector and negative climate policy risk premia for the dirty sector. This result, which implies that climate policy risk premia dampen the devaluation of dirty and oil firms rather than amplifying it, is in line with the intuition provided by Baker, Hollifield, and Osambela (2019) and Roth Tran (2019) that dirty firms paradoxically provide a hedge against the consequences of climate change.

Climate policy risk premia are quantitatively larger if the implemented carbon tax is far below the optimal value (at 50%), as a positive carbon tax shock is a particularly good shock in that case. Therefore, the effects described are more pronounced than in the 100% case, in particular the fall of the stochastic discount factor.

Oil sector dynamics The oil price, depicted in Panel A of Figure 7, 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 9 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 8. Therefore, from an asset pricing point of view, the oil firm has a more negative 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 8 reveals that in those times, climate policy risk premia can become positive or negative, depending on whether the regulator over- or undershoots the optimal carbon tax level. If the regulator accidentally sets the carbon tax to a higher than optimal, an additional carbon tax increase is a “bad” shock for the overall economy, as the rise of the stochastic discount factor in the 110% case reveals. The negative response of the the dirty sector makes dirty firms command positive climate policy risk premia in that case. On the other hand, the situation for lower than optimal carbon taxes is similar to the transition period, resulting in negative risk premia on climate policy risk.

5 Conclusion

This paper provides an analysis of the climate-related transition towards a low-carbon and less fossil-fuel intense economy and its implications for macroeconomic and financial market outcomes. 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.

Our results 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. Another example are climate policy risk premia, which are sometimes made responsible for low fossil fuel firm valuations. However, it turns out that from a general equilibrium point of view, climate policy risk premia are negative and therefore counteract the described cash flow effects instead of amplifying them, as dirty firms react negatively to “good” climate policy shocks.

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A Additional Tables

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 standard 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 (29).

Intermediate goods firms The clean and dirty intermediate goods producers, $i \in \{c, d\}$, optimize (9) and (10), respectively, subject to the laws of motion (5) and (7), respectively, as well as (11) and (12), leading to the problem

$$\begin{aligned}\max_{\{Y_{i,t};L_{i,t};K_{i,t};O_t;T_{t+1};\mathcal{E}_{t+1}\}} \mathbb{E}_t\Bigg[\sum_{t=0}^{\infty}\mathbb{M}_t\Bigg(& p_{i,t}Y_{i,t} - R^K_{i,t}K_{i,t} - w_t L_{i,t} - \mathbb{1}_{\{i=d\}}p_{o,t}O_t - \tau_t\xi_i Y_{i,t} \\ & - \mathbb{1}_{\{i=c\}}\lambda_{c,t}\left(Y_{c,t} - \frac{(A_t L_{c,t})^{1-\alpha}K_{c,t}^{\alpha}}{1+\kappa_{c,1}T_t^{\kappa_{c,2}}}\right) \\ & - \mathbb{1}_{\{i=d\}}\lambda_{d,t}\left(Y_{d,t} - (A_t L_{d,t})^{1-\alpha}\left((1-\iota)K_{d,t}^{1-\frac{1}{o}} + \iota O_t^{1-\frac{1}{o}}\right)^{\frac{\alpha}{1-\frac{1}{o}}}\right) \\ & - \phi_{i,t}A_t(\nu T_t + \chi\mathcal{E}_{t+1} + \sigma_T T_{t+1}\varepsilon^T_{t+1} - T_{t+1}) \\ & - \epsilon_{i,t}A_t(\xi_d/A_t Y_{d,t} + \xi_c/A_t Y_{c,t} + (1-\eta)\mathcal{E}_t - \mathcal{E}_{t+1})\Bigg)\Bigg]\end{aligned} \tag{C.3}$$

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

$$p_{i,t} - \tau_t\xi_i - \lambda_{i,t} - \epsilon_{i,t}\xi_i = 0. \tag{C.4}$$

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

$$0 = -\mathbb{E}_t\left[\mathbb{M}_{t+1}\lambda_{c,t+1}Y_{c,t+1}\frac{\kappa_{c,1}\kappa_{c,2}T_{t+1}^{\kappa_{c,2}-1}}{1+\kappa_{c,1}T_{t+1}^{\kappa_{c,2}}}\right] - \nu\mathbb{E}_t[\mathbb{M}_{t+1}\phi_{c,t+1}A_{t+1}] + \phi_{c,t}A_t, \tag{C.5}$$

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

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

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

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 laws of motion (16), (15), and (17), leading to the problem

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

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

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

C.2 Social Planner Solution

The social planner considers the production sector as a whole and optimizes

$$\begin{aligned}\max_{\{Y_t;Y_{i,t};L_{i,t};K_{i,t};T_{t+1};\mathcal{E}_{t+1};O_t;U_{t+1};N_t\}} \mathbb{E}_t\Bigg[\sum_{t=0}^{\infty}\mathbb{M}_t\Bigg(& Y_t - \sum_{i\in\{c,d\}}(R^K_{i,t}K_{i,t} - w_tL_{i,t}) \\ &- \mu_t(Y_t - p_{c,t}Y_{c,t} - p_{d,t}Y_{d,t}) - \lambda_{c,t}\left(Y_{c,t} - \frac{(A_tL_{c,t})^{1-\alpha}K^{\alpha}_{c,t}}{1+\kappa_{c,1}T_t^{\kappa_{c,2}}}\right) \\ &- \lambda_{d,t}\left(Y_{d,t} - (A_tL_{d,t})^{1-\alpha}\left((1-\iota)K_{d,t}^{1-\frac{1}{o}} + \iota O_t^{1-\frac{1}{o}}\right)^{\frac{\alpha}{1-\frac{1}{o}}}\right) \\ &+ p_{o,t}\kappa_oU_t - R^K_{o,t}K_{o,t} - w_tL_{o,t} - \lambda_{o,t}(N_t - (A_tL_{o,t})^{1-\tau}K^{\tau}_{o,t}) - \phi_{o,t}(U_{t+1} - (1-\kappa_o)U_t - N_t) \\ &- \phi_tA_t(\nu T_t + \chi\mathcal{E}_{t+1} + \sigma_TT_{t+1}\varepsilon^T_{t+1} - T_{t+1}) \\ &- \epsilon_tA_t\Big(\xi_d/A_tY_{d,t} + \xi_c/A_tY_{c,t} + (1-\eta)\mathcal{E}_t - \mathcal{E}_{t+1}\Big)\Bigg)\Bigg].\end{aligned} \tag{C.17}$$

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

$$p_{i,t} - \lambda_{i,t} - \epsilon_t\xi_i = 0, \tag{C.18}$$

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

$$-\chi\phi_tA_t - (1-\eta)\mathbb{E}_t[\mathbb{M}_{t+1}\epsilon_{t+1}A_{t+1}] + \epsilon_tA_t = 0, \tag{C.19}$$

and T_{t+1}, which yields

$$-\mathbb{E}_t\left[\mathbb{M}_{t+1}\left(\lambda_{c,t+1}Y_{c,t+1}\frac{\kappa_{c,1}\kappa_{c,2}T_{t+1}^{\kappa_{c,2}-1}}{1+\kappa_{c,1}T_{t+1}^{\kappa_{c,2}}}\right)\right]-\nu\mathbb{E}_t[\mathbb{M}_{t+1}\phi_{t+1}A_{t+1}]+\phi_t A_t=0. \tag{C.20}$$

The main difference to the first order conditions for the competitive equilibrium is that there are joint Lagrange multipliers $\epsilon_t A_t$ and $\phi_t A_t$ instead of individual ones, such that the effects of emissions and temperatures are internalized, in line with intuition.

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 $\kappa_d = 0$ and $\xi_c = 0$, which leads to $\epsilon_{d,t} = 0$ and $\epsilon_{c,t} = \epsilon_t$, and we have

$$p_{c,t} = \lambda_{c,t} \qquad \text{and} \qquad p_{d,t} = \lambda_{d,t} + \tau_t\xi_d \tag{C.21}$$

in the competitive equilibrium and

$$p_{c,t} = \lambda_{c,t} \qquad \text{and} \qquad p_{d,t} = \lambda_{d,t} + \epsilon_t\xi_d \tag{C.22}$$

in the social planner solution. Therefore, for a carbon tax of $\tau_t^* = \epsilon_t = \epsilon_{c,t}$, 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:

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

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

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:

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

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

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

$$\hat{Y}_{c,t} = \frac{L_{c,t}^{1-\alpha} \hat{K}_{c,t}^{\alpha}}{1+\kappa_{c,1} T_t^{\kappa_{c,2}}}, \tag{D.11}$$

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

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

$$0 = p_{i,t} - \tau_t \xi_i - \lambda_{i,t} - \epsilon_{i,t}\xi_i, \tag{D.14}$$

$$0 = -\mathbb{E}_t \left[\mathbb{M}_{t+1} \lambda_{c,t+1} \hat{Y}_{c,t+1} \frac{\kappa_{c,1}\kappa_{c,2} T_{t+1}^{\kappa_{c,2}-1}}{1+\kappa_{c,1} T_{t+1}^{\kappa_{c,2}}} \right] - \nu \mathbb{E}_t[\mathbb{M}_{t+1} \phi_{c,t+1} e^{\Delta a_{t+1}}] + \phi_{c,t}, \tag{D.15}$$

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

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

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

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

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

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

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:

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

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

$$R^K_{c,t} = \alpha p_{c,t}\frac{\hat{Y}_{c,t}}{\hat{K}_{c,t}}, \tag{D.34}$$

$$R^K_{d,t} = \alpha(1-\iota)(p_{d,t} - \tau_t)\frac{\hat{Y}_{d,t}}{\hat{Z}_t^{1-\frac{1}{o}}\hat{K}_{d,t}^{-\frac{1}{o}}}, \tag{D.35}$$

$$R^K_{o,t} = \tau\lambda_{o,t}\frac{\hat{N}_t}{\hat{K}_{o,t}}, \tag{D.36}$$

$$Q_{i,t} = \frac{1}{1-G'_{i,t}}. \tag{D.37}$$

The other equations in normalized form look as follows:

$$\hat{V}_t = \left[(1-\beta)\hat{C}_t^{1-\frac{1}{\psi}} + \beta\left(\hat{\mathbb{E}}_t[V_{t+1}^{1-\gamma}]\right)^{\frac{1-\frac{1}{\psi}}{1-\gamma}}\right]^{\frac{1}{1-\frac{1}{\psi}}}, \tag{D.38}$$

$$\hat{\mathbb{E}}_t[V_{t+1}^{1-\gamma}] = \mathbb{E}_t[(\hat{V}_{t+1}e^{\Delta a_{t+1}})^{1-\gamma}], \tag{D.39}$$

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

$$1-\ell = L_{c,t} + L_{d,t} + L_{o,t}, \tag{D.41}$$

$$\hat{Y}_t = \hat{C}_t + \hat{I}_{c,t} + \hat{I}_{d,t} + \hat{I}_{o,t}, \tag{D.42}$$

$$\mathcal{E}_{t+1} = (1-\eta)\mathcal{E}_t + \xi_d\hat{Y}_{d,t}, \tag{D.43}$$

$$T_{t+1} = \nu T_t + \chi\mathcal{E}_{t+1} + \sigma_T T_{t+1}\varepsilon^T_{t+1}, \tag{D.44}$$

$$\tau_t = \theta_t\tau^*_t, \tag{D.45}$$

$$\tau^*_t = \epsilon_{c,t}, \tag{D.46}$$

$$\theta_{t+1} = (1-\rho_\theta)(1-\mu_\theta) + \rho_\theta\theta_t + \sigma_\theta\varepsilon^\theta_{t+1}. \tag{D.47}$$

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 major 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. The output of the clean, temperature-sensitive sector is strongly negatively affected due to the direct negative impact through the production function. The effect on the dirty, temperature-robust sector is even positive, as agents reallocate both capital and labor to this sector. As a result, the equity return of temperature-sensitive firms responds strongly negatively due to a decline in the price of related sector-specific capital. The return is positive for temperature-robust firms.

The related climate productivity risk premium follows from the covariance of sector-specific equity returns with the stochastic discount factor in response to the temperature shock. Therefore, there is a positive climate productivity risk premium in general equilibrium, as a portfolio that goes long temperature-sensitive firms and short temperature-robust firms generates positive excess returns.

In the "Low Tax" model, the dirty firm's excess return is increasing more in response to the temperature shock, which implies that the climate productivity risk premium is larger as well. This is intuitive, as this economy does not take full care of the climate externality. Thus, there must be a larger premium for climate productivity risk, as the effects of temperature shocks are more harmful in the "Low Tax" economy relative to the baseline 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 increasing in response to a positive temperature shock. The effects are a bit larger in the "Low Tax" model. The oil price declines due to the larger supply of oil in the economy that is not fully compensated for by the larger demand of the dirty firm.

The oil firm's excess return responds strongly positively to the innovation in temperature. Therefore, a strategy going long in the clean sector and short in the oil sector earns a higher risk premium than the aforementioned strategy going short in the dirty sector.

Figure E.1: Impact of temperature shocks on major 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.

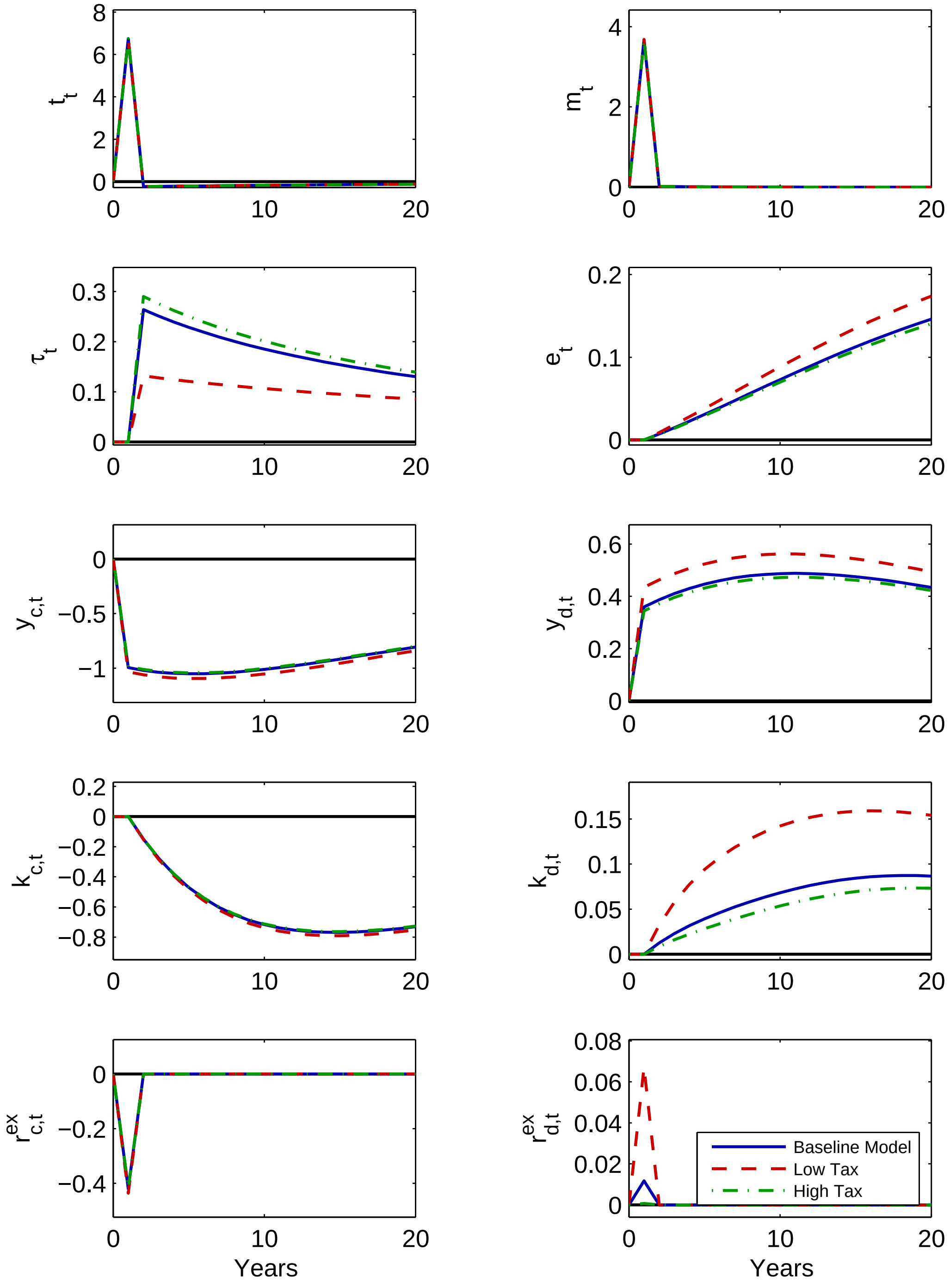

Figure E.2: Impact of temperature shocks on the oil sector for three values of the carbon tax level: 50%, 100%, and 110% of the optimal carbon tax. These three values correspond to three cases: a “Low Tax” case, the “Baseline Model” case, and a “High Tax” case (in which the tax is set higher than optimal). 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.