FEDERAL RESERVE BANK OF SAN FRANCISCO

WORKING PAPER SERIES

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June 2022

Working Paper 2021-06

https://www.frbsf.org/economic-research/publications/working-papers/2021/06/

Suggested citation:

Fried, Stephie, Kevin Novan, William B. Peterman. 2022 "Climate Policy Transition Risk and the Macroeconomy," Federal Reserve Bank of San Francisco Working Paper 2021-06. https://doi.org/10.24148/wp2021-06

This paper was previously circulated under the title "The Macro Effects of Climate Policy Uncertainty."

Climate Policy Transition Risk and the Macroeconomy

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June 20, 2022

Abstract

Uncertainty surrounding if the U.S. will implement a federal climate policy introduces risk into the decision to invest in long-lived capital assets, particularly those designed to use, or to replace fossil fuel. We develop a dynamic, general equilibrium model to quantify the macroeconomic impacts of this climate policy transition risk. The model incorporates beliefs over the likelihood that the government adopts a climate policy causing the economy to dynamically transition to a lower carbon steady state. We find that climate policy transition risk decreases carbon emissions today by causing investment to become relatively cleaner and output to fall. This result counters the Green Paradox, which argues that climate policy risk raises emissions today by increasing incentives to extract fossil fuel, expanding its supply. Even allowing for the supply-side response, we find the demand-side response dominates, and the net effect of climate policy transition risk is still to reduce emissions today.

Email: stephie.fried@sf.frb.gov, knovan@ucdavis.edu, william.b.peterman@frb.gov. The views expressed in this paper are our own and do not reflect the views of the Federal Reserve System or its staff. This paper was previously circulated under the title "The Macro Effects of Climate Policy Uncertainty." For helpful comments we thank Sylvain Leduc and Derek Lemoine, as well as seminar and conference participants at SED, the San Francisco Fed Conference on Climate Change, the Federal Reserve Energy System Meeting, Midwest Macro, ASSAs, Berkeley Climate Economics Workshop, UCSB, Harvard, and Universidad del Rosario, and four anonymous referees. All potential errors are our own.

1. Introduction

The economic effects of climate change include both the physical risk from rising temperatures and the transition risk from governments considering adopting policies to reduce emissions (Rudebusch, 2021). Understanding both of these risks has become an important issue for central banks (Carney, 2015; Daly, 2021) and government agencies (CBO, 2021). While some researchers and policymakers have focused on how the realization of the climate policy transition risk will affect macroeconomic outcomes in the future (Brainard, 2021; Carattini et al., 2021; Diluiso et al., 2020), we instead focus on the impacts for the economy today, before the climate policy is implemented. Ample anecdotal evidence suggests that the possibility of future climate policy alters firms' investment in long-lived capital assets before any actual policy goes into place. To quantitatively analyze these impacts, we develop a dynamic, general equilibrium model of the U.S. economy that incorporates beliefs about the likelihood of a future policy establishing a carbon price.[1] We show that climate policy transition risk meaningfully distorts the composition of capital and reduces the level of output, leading to a reduction in carbon emissions even though the climate policy is not actually in place. This reduction in emissions, however, represents only a small fraction of the reduction that would be achieved by adopting the carbon price, and it comes at a much higher cost.

To understand the effects of climate policy transition risk, we first develop an analytic, dynamic and multi-sector model in which entrepreneurs internalize transition risk. We focus on a steady state in which there is no carbon tax, but there is a positive probability that a carbon tax will be imposed in the next period. If the carbon tax is imposed, then all uncertainty is resolved and the economy endogenously transitions to a new steady state with the tax in place. Prior to learning whether the tax will be imposed, entrepreneurs choose the level of investment in fossil capital that is specialized to use fossil fuel (e.g., a coal boiler or an internal combustion engine), and clean capital that is not specialized to use fossil fuel (e.g., a solar panel).

The key feature of the steady state with transition risk is that entrepreneurs make their investment decisions knowing there is some chance the carbon tax will be imposed next period and that this would cause the economy to dynamically transition to a new steady state with a carbon tax in place. Thus, entrepreneurs' expectations of the likelihood of the carbon tax and the resulting dynamics if the tax is adopted affect the equilibrium composition of capital and

[1] While, we use a carbon price as an example of a future climate policy, the paper's intuition and mechanisms hold for any climate policy that increases the return to investment in clean capital or reduces the return to investment in fossil capital. For example, U.S. policymakers recently considered implementing the Clean Electricity Performance Program, which creates incentives for utilities to produce more electricity from renewable sources and less from fossil sources (www.reuters.com/world/us/us-democrats-unveil-details-150-bln-clean-electricity-plan-budget-bill-2021-09-09/).

level of output in the steady state with transition risk. We measure the impacts of climate policy transition risk by comparing the pre-tax steady state with transition risk to a counterfactual pre-tax steady state without transition risk – i.e. a steady state in which there is no tax and entrepreneurs assume there is zero probability of a future carbon tax.

We use the analytic model to highlight two key channels through which climate policy transition risk reduces the demand for fossil fuels, and consequently emissions. First, climate policy transition risk reduces the expected return to fossil capital relative to clean capital, shifting the economy towards cleaner production. Second, climate policy risk reduces output because it shifts the composition of capital away from the allocation entrepreneurs optimally choose without climate policy risk. In essence, climate policy risk decreases emissions because the economy produces less and the remaining production is cleaner.

To quantify the macroeconomic impacts of climate policy transition risk, we move beyond the simple, analytic setting and develop a richer general equilibrium neoclassical growth model that adds risk-averse households, partially-irreversible investment, and separates a non-energy capital from the rest of clean capital. Importantly, including risk-aversion could amplify the impacts of climate policy transition risk because it causes entrepreneurs to hedge against the potential future carbon price by further directing investments towards clean assets. Moreover, partially-irreversible investment captures the potential losses from selling capital after the introduction of the carbon tax.[2] Finally, separately modeling a non-energy capital accounts for the fact that capital that is not specialized to use or replace fossil fuel (e.g. non-energy capital) may respond differently to climate policy transition risk than capital that is specialized to use or replace fossil fuel (e.g., fossil and clean capital).

We assume that, if adopted, a carbon tax would be set at \$51 (in 2020 dollars) per ton of CO_2, the interim value of the social cost of carbon from the Biden administration (IWG, 2021). In our main specification, we assume that firms believe there is a 75 percent chance the government will introduce this tax within the next ten years. While we show these beliefs are consistent with the internal carbon fees used by many firms to voluntarily reduce their emissions (CDP, 2021), we also explore how our results change over a range of carbon tax probabilities, from a 5 percent chance the government introduces the tax within 10 years to a 99 percent chance.

Calibrating the model to reflect the U.S. economy, we quantify the impacts of climate policy transition risk on the macroeconomy today. As a point of reference, we find that the steady state CO_2 emissions would be 20 percent lower with a \$51 per ton tax on CO_2 compared to a baseline world without a tax and without climate policy transition risk. We find that the

[2] Baldwin et al. (2019) examine how irreversibility in “dirty” and “clean” capital affects the optimal trajectory of a carbon price and environmental subsidies, focusing on a setting where future policy is known.

economy's response to climate policy transition risk implies that the U.S. has already attained one tenth of the total drop in emissions, even though no actual climate policy is in place. This reduction in emissions from climate policy transition risk is equivalent to the reduction that would be achieved in a steady state with no transition risk and a carbon tax of $4.91 per ton.

The emissions reductions caused by climate policy transition risk stem from the two channels highlighted in the analytic model. First, climate policy transition risk decreases the expected return to investments in fossil capital relative to clean capital, leading to an 8.86 percent decrease in the ratio of fossil to clean capital. This composition effect is responsible for 84 percent of the decline in emissions caused by climate policy transition risk. Intuitively, the composition effect arises because the introduction of the carbon tax leads to a large decline in the value of fossil capital, a phenomenon the earlier literature has called "stranding" (see e.g., van der Ploeg and Rezai, 2020). The possibility of stranded capital causes entrepreneurs to shift from fossil to clean capital in the pre-tax steady state with risk.

Second, climate policy transition risk reduces output by 0.34 percent. The decline in output occurs because climate policy risk distorts the composition of capital away from the allocation entrepreneurs optimally choose without risk, and because this distortion, combined with the possibility of a future carbon tax, reduces the expected marginal product of capital, leading to lower aggregate capital. The output effect is responsible for the remaining 16 percent of the emissions reductions from climate policy risk.

The results from our analysis provide new insights surrounding the cost of delayed action with regards to climate policy. One interpretation of the results is that, since transition risk leads to reductions in emissions, the environmental costs of delaying policy action are smaller than previously thought. However, we find that the emissions reductions caused by the response to transition risk fall far short of the emissions reductions that would be achieved by adopting the climate policy. Moreover, our analysis reveals that the non-environmental welfare cost of the emissions reductions from climate policy transition risk are almost double the welfare costs incurred by achieving the same emissions reductions using a $4.91/ton tax. This higher cost stems from the fact that, with risk-averse agents, output falls by much more in response to transition risk than in response to a small, certain carbon tax.

Counterintuitively, our results also demonstrate that delaying policy action and allowing agents to respond to climate policy transition risk does not reduce the non-environmental welfare costs of adopting a carbon price today. At first glance, it might seem that climate policy transition risk will reduce the non-environmental welfare cost because it moves the economy part of the way to a world with the carbon tax in place. However, because climate policy transition risk reduces the aggregate capital stock, there is less scope for agents to consume savings if and when a carbon tax is adopted. The resulting increase in the transitional welfare costs from having less savings to consume almost exactly offsets any decrease in costs from the fact that the economy has already moved part of the way to the ultimate steady state with a carbon tax.

Our result that climate policy transition risk reduces emissions runs counter to the predictions from the green paradox literature (e.g., Sinn (2008)). This literature argues that the risk of future climate policy would drive up current emissions by increasing incentives to extract fossil fuel, expanding its supply. In contrast, we find that the risk of future climate policy decreases emissions by shifting investment towards cleaner capital and reducing output, both of which reduce demand for fossil fuel. To evaluate these competing predictions, we extend our model to include a reduced-form increase in fossil fuel supply in response to climate policy transition risk. We find that even when we incorporate the green paradox by allowing for this supply-side response, the demand-side response dominates, and the net effect of climate policy transition risk is still to reduce emissions today.

The scope for a supply-side response to climate policy transition risk, particularly for energy sources like coal, has been the subject of debate (e.g., Hoel (2010), van der Ploeg and Withagen (2012)). Moreover, previous work highlights that the Hotelling Model of resource extraction, which is at the heart of the green paradox argument, poorly predicts fuel market dynamics (Kronenberg (2008), Slade and Thille (2009), Livernois (2009)). The literature has instead begun to focus on other channels, beyond simply shifting fossil fuel supply over time, through which the threat of a future climate policy can affect emissions. For example, van der Ploeg and Rezai (2020) highlight that the threat of a climate policy could reduce investment in capital used to extract fossil fuel. Most closely related to our analysis, Lemoine (2017) demonstrates how expectations of a future climate policy can alter the demand for fossil fuels by affecting investment in fossil capital more broadly (e.g., coal boilers). Our paper contributes to this line of work by highlighting that climate policy transition risk can affect the demand for fossil fuels by not only altering investment in fossil capital, but also in clean capital and, through the economy's general equilibrium channels, in the much larger stock of non-energy capital.

It is important to note that our main analysis abstracts from two additional avenues through which climate policy risk can potentially affect current investment. First, we do not capture interactions between climate policy risk and climate damage. Directly incorporating climate damage into our framework is challenging because climate damage grows at a non-constant rate, implying that the model would not have pre-tax steady states with and without transition risk for us to study. Instead, we consider a reduced-form extension of our model which links emissions with climate damage and productivity. We find that the impact of climate policy transition risk is effectively unchanged when we include these climate-damage effects. This is because a carbon tax, once adopted, will have an immediate impact on the returns to different investments. In contrast, it takes far longer for the productivity impacts from the resulting emissions reductions to be large enough to meaningfully impact investment.

Second, our model abstracts from endogenous innovation. Intuitively, the possibility of a future carbon tax could increase the expected returns to innovating in clean technologies relative to fossil. This innovation response to climate policy risk could further reduce the ratio of fossil to clean capital, magnifying the composition effect and the resulting reduction in emissions. Thus, our results should be viewed as a lower bound on the impact of climate policy transition risk on the macroeconomy.

Our analysis builds on a burgeoning climate finance literature examining the effects of climate policy transition risk on equity markets.[3] Consistent with investors demanding a premium for investing in firms most exposed to transition risk, Hsu et al. (2020) and Bolton and Kacperczyk (2021) find higher expected returns for firms with relatively higher carbon emissions. Our quantitative results point to the same finding. Driven by risk-averse entrepreneurs requiring a higher expected return for investments in fossil capital, the pre-tax steady state expected return to fossil capital equals 4.08 percent, which exceeds the expected return to clean capital of 3.9 percent. Our analysis also echoes the findings from Barnett (2020), Choi et al. (2020), and Engle et al. (2020) which show that stock prices for firms most exposed to transition risk perform relatively worse during periods when attention to regulatory risk is plausibly higher (e.g., when there is negative news about climate change) or following events that likely increase the perceived likelihood of a future climate regulation. While these empirical analyses uncover evidence that investors indeed respond to climate policy transition risk, our analysis seeks to understand the general equilibrium impacts of these responses on emissions and the macroeconomy.

More generally, our paper contributes to the literature studying the impacts of policy uncertainty. Baker et al. (2016) measure general economic policy uncertainty arising from an array of sources (e.g., budget debates, wars) and find that aggregate investment falls in response to this general uncertainty. Related work by Rodrik (1991), Hassett and Metcalf (1999), Born and Pfeifer (2014), and Fernández-Villaverde et al. (2015) also highlight negative economic impacts of uncertainty arising from fiscal, monetary, and regulatory policy shocks. Similarly, this paper examines uncertainty surrounding future policies, however it focuses on environmental policies that target the fossil fuel sector. Thus far, the literature exploring the impacts of environmental policy uncertainty largely has focused on partial equilibrium impacts or on the effects within specific sectors.[4] For example, Xepapadeas (2001) and Pommeret and Schubert

[3] For a review of the literature examining the impacts of climate change and transition risks on financial markets, see Giglio et al. (2021).

[4] In contrast to policy driven uncertainty, a much larger literature focuses on how optimal environmental policies are affected by uncertainty stemming from, often irreversible, environmental shocks (e.g., Lemoine and

(2017) consider the partial equilibrium impacts of environmental policy uncertainty on the investment and location decisions of affected firms.

Similar to our analysis, Bretschger and Soretz (2018) also study the general equilibrium impacts of climate policy uncertainty. However, they focus on a different type of uncertainty in which an existing carbon tax follows a stochastic process.[5] Their model of aggregate uncertainty follows the standard approach in the macro literature in which economy-wide, stochastic shocks (e.g., TFP shocks) generate uncertainty that is never resolved. For example, Kydland and Prescott (1982) and King and Rebelo (1999) explore the impact of stochastic TFP shocks in real-business cycle models. Similarly, Krusell and Smith (1998) focus on stochastic TFP shocks in a model with heterogeneity. In contrast, our model focuses on a pre-climate-policy world in which there is uncertainty surrounding a one-time, permanent introduction of a carbon tax, instead of a world with a continually evolving policy or TFP shock.[6] As a result, we are able to quantify the impacts of climate policy transition risk on the current U.S. economy in which there is no existing federal climate policy, but rather the possibility that one could be introduced in the future.

The remainder of the paper proceeds as follows. Section 2 summarizes the anecdotal evidence surrounding how firms respond to climate policy transition risk. Section 3 analytically demonstrates the channels through which climate policy transition risk reduces carbon emissions. Section 4 introduces a richer, general equilibrium model to quantify the impacts of climate policy transition risk on the U.S. economy. Section 5 discusses the calibration of the key parameters. Section 6 summarizes the impacts of climate policy transition risk on the current U.S. economy. Section 7 examines the sensitivity of the results as we alter the structure of the carbon tax and the likelihood it is adopted. Section 8 concludes.

2. Evidence of climate policy transition risk

Our objective is to quantify the macroeconomic impacts of climate policy transition risk on the economy today. This section summarizes the anecdotal evidence suggesting that many

Traeger (2014)).

[5]Related work by Kelly (2005) also examines the general equilibrium impacts of uncertainty generated by an environmental regulation in the presence of risk averse households. However, rather than focusing on the risk stemming from uncertainty surrounding if and when a policy will be adopted, Kelly (2005) examines how households are differentially affected by the adoption of a price mechanism (i.e a pollution tax) versus a quantity mechanism (i.e. a cap-and-trade program). The theoretical analysis highlights that, under a quantity mechanism, pollution permit prices will be positively correlated with shocks to productivity, leading to less variability in overall consumption. Consequently, if households are sufficiently risk averse, a quantity mechanism would achieve higher expected welfare than a price mechanism.

[6]A similar form of uncertainty is also considered in Caliendo et al. (2019) and Kitao (2018) which both use dynamic, general equilibrium models to examine the uncertainty surrounding the timing and structure of future changes to social security.

firms believe the government will implement a climate policy at some unknown point in the future and that this belief meaningfully alters their investments today.

Intuitively, for the risk of a future climate policy to meaningfully affect investment, two conditions must be met. First, the likelihood of a federal climate policy being adopted in the near future – i.e. in a period of time that is shorter than the lifespan of the capital investments – cannot be trivially small. While there is no direct measure of the economy-wide probability of a U.S. climate policy, there is certainly anecdotal evidence suggesting that the probability is not fleetingly small. For one, recent surveys demonstrate that a majority of U.S. adults now support increasing energy prices to combat climate change.[7] Additionally, several federal climate policy proposals were nearly adopted over the past decade (e.g., Waxman-Markey, the Clean Power Plan). This broad base of public support suggests that there is widespread awareness that a federal climate policy could be adopted in the near future.[8]

The second condition that must be met for climate policy transition risk to meaningfully affect present investment decisions is that firms must believe the climate policy, if implemented, will be stringent enough to alter the returns to investments. Again, there is no comprehensive measure of this subjective belief. However, all signs suggest that, if implemented, a climate policy would indeed have significant consequences for the returns to different types of capital. Consistent with this view, there is growing empirical evidence that variation in the exposure to a potential future climate policy across firms is responsible for some of the cross-sectional and temporal variation in asset prices.[9]

Moreover, looking towards other regions of the world, the EU's Emissions Trading Scheme has established a price on carbon emissions that, as of 2019, has hovered around 25 Euros (27 USD) per ton of CO_2. At this price, there is already clear evidence that fossil-fuel intensive capital, such as a coal-fired electricity generator, is experiencing a dramatic reduction in profitability (IEEFA, 2019). Policy proposals that are garnering the greatest support in the U.S. call for even stronger actions to reduce emissions. For example, the proposal put forth by the Climate Leadership Council (CLC) calls for a $40/ton tax on CO_2 (Baker III et al., 2017). The Biden Administration's interim estimate for the social cost of carbon is $51/ton (IWG, 2021). The Green New Deal supports U.S. carbon neutrality by 2050, which would require far more dramatic reductions in emissions than what would be achieved with a $40 or $51 per ton tax.

[7] A 2016 survey completed by the Energy Policy Institute at the University of Chicago and The AP-NORC Center for Public Affairs Research found that 65 percent of Americans believe climate change is a problem the federal government should address and 57 percent would support paying higher energy bills to do so.

[8] Indeed, this understanding has been directly expressed by firms. For example, the Director of Sustainability at The Dow Chemical Company noted, "It's very difficult to predict the future, obviously, but we need to look at the probabilities. With external carbon prices, it's only a matter of time. (WBCSD, 2015)"

[9] See, for example, Barnett (2020), Choi et al. (2020), Engle et al. (2020), Hsu et al. (2020), and Bolton and Kacperczyk (2021).

The combination of growing public support combined with the current policy proposals suggest that both the likelihood and expected stringency of a future U.S. climate policy are large enough to impact firms' investment decisions.

There is also ample anecdotal evidence across a wide range of industries that firms adjust investment at least partly in response to climate policy transition risk. For example, some firms have begun to set their own science-based internal emissions targets.[10] In a recent survey of 138 of the largest firms in the highest emitting sectors, Dietz et al. (2018) note that 85 percent have established internal policies committing them to reduce carbon emissions using a range of alternative approaches (e.g., energy efficiency targets). Similarly, many firms have voluntarily adopted stricter regulations than those imposed by the federal government. For example, automakers Ford, Honda, Volkswagen, and BMW chose to adopt California's proposed, stricter fuel economy standards, which would have required an average fuel economy for new cars and trucks equal to 54.5 miles per gallon, instead of the relatively lax standards proposed by the Trump administration (Holden, 2019). Reportedly, "the companies are worried about years of regulatory uncertainty that could end with judges deciding against Trump" and implementing the stricter standards.[11] Transportation is responsible for 29 percent of U.S. carbon emissions, and thus the fuel economy standards represent an important form of climate policy.

Additionally, a growing set of firms are voluntarily using internal carbon prices to reduce their emissions. In a survey of nearly 6,000 firms performed by CDP (Carbon Disclosure Project), 853 reported using internal carbon prices and another 1,159 had plans to adopt internal prices within two years (CDP, 2021).[12] Over half of the surveyed firms in the energy sector, which is the most exposed to climate policy transition risk, use internal carbon prices. Similarly, 39 percent and 29 percent of firms in the transportation and manufacturing sectors, respectively, reported using internal carbon prices. Surveys of firms using internal carbon prices find that the "single largest motivation for adopting a shadow [carbon] price is to better understand and anticipate the business risks from existing or expected carbon regulations and shift investments toward projects that would be competitive in a carbon-constrained future" (Ahluwalia, 2017). That is, firms are at least in part responding to the threat of future climate policy when they distort their capital portfolios in favor of cleaner investments.

The above evidence suggests that many firms believe there is a non-trivial risk of future

[10] For example, Walmart launched Project Gigaton in 2017 to reduce emissions throughout its supply chain. The company plans to reduce its scope 1 and 2 emissions by 18 percent by 2025 and purchase 50 percent of its electricity from renewable sources (Walmart, 2017). See sciencebasedtargets.org for an extensive list of companies that have or are committed to setting emissions targets.

[11] Similarly, BP, Shell, and Exxon Mobil were among several major oil and gas companies to oppose the Trump administration's rollback of methane regulations. Shell even went so far as to pledge that "while the law may change in this instance, our environmental commitments will stand" (Krauss, 2019).

[12] Many of these firms are either located in the U.S. or do business in the U.S.

climate policy and that the realization of such a policy would meaningfully affect the relative returns to investment projects with different carbon intensities. Consequently, firms are responding to this transition risk by shifting their current investment towards clean capital. In the following sections, we develop a model to explore the general equilibrium implications of this climate policy transition risk for emissions and the macroeconomy.

3. Model

We build a simple dynamic model to analytically demonstrate the channels through which climate policy transition risk reduces emissions. The economy has two sectors: a carbon-emitting "fossil" sector and a non-emitting "clean" sector. We focus on the production side of the economy, taking the interest rate and labor supply as exogenous, and we abstract from investment frictions. In Section 4, we add the household and solve for the general equilibrium.

3.1. Environment

The economy is comprised of unit masses of infinitely-lived fossil entrepreneurs and clean entrepreneurs, a unit mass of final-good aggregators, and a unit mass of infinitely-lived workers. The workers are each endowed with one unit of labor, which they supply exogenously.

3.2. Production

There is a unique final good, y, that is produced competitively from a clean intermediate input, x^c, a carbon-intensive fossil intermediate input, x^f, and labor, l. The production for the final good is:

$$y = (x^e)^{\gamma} l^{1-\gamma} \quad \text{where} \quad x^e = \left((x^c)^{\frac{\varepsilon-1}{\varepsilon}} + (x^f)^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}}.$$

The final good is the numeraire.

The clean intermediate is produced competitively from clean capital, k^c, according to the linear production function, $x^c = A^c k^c$, where A^c denotes total factor productivity in the production of the clean intermediate. The fossil intermediate is produced competitively from fossil capital, k^f, and fossil fuel, f, according to the Leontief production function, $x^f = A^f \min[k^f, f]$, where A^f denotes total factor productivity in the production of the fossil intermediate. Fossil capital refers to any capital that is specialized to use fossil fuel. Examples include capital used to produce electricity from fossil fuels, such as a coal boiler, capital that requires fossil fuel to operate, such as an internal combustion engine, and capital used in fossil fuel extraction, such as an oil rig. Clean capital refers to all other capital. This includes capital that preforms the same function as the fossil capital, but does not use fossil fuel (such as a wind turbine or a nuclear reactor), capital that increases energy efficiency, (such as regenerative brakes in hybrid vehicles) and capital that is not directly related to energy (such as a sewing machine).

The Leontief production function for the fossil intermediate implies that there is no substitutability between fossil capital and fossil fuel. For example, a given internal combustion engine or coal boiler each require specific quantities of fossil fuel to operate. In practice, firms can reduce fossil fuel consumption by switching to non-carbon emitting (clean) energy sources or by improving energy efficiency. We model both of these channels as part of clean capital. Thus, holding labor supply constant, any reduction in the carbon intensity of the final good, must be achieved by substituting the clean intermediate for the fossil intermediate, and not by substituting fossil capital for fossil fuel.[13]

Fossil fuel is produced from units of final good at constant marginal cost, ζ. In our quantitative analysis, we also consider a case consistent with the Green Paradox literature in which the cost of fossil fuel endogenously responds to the probability of future climate policy.

3.3. Climate policy transition risk

To study climate policy transition risk, we focus on a state of the world in which there is no carbon tax in place, but each entrepreneur expects that the government will introduce a carbon tax, τ, with probability, ρ, next period. If the government introduces the tax, then we assume that all uncertainty is resolved and the economy dynamically transitions to a long-run steady state with the tax in place. Under this model of transition risk, the entrepreneurs internalize that the introduction of the tax will affect the economy next period, and for all future periods along the dynamic transition and in the eventual steady state with the tax in place. As discussed in Section 2, such an environment is well-suited to describe the U.S economy; while there currently is no federal carbon price, firms' actions indicate that they internalize the possibility the government could introduce a climate policy in the future.[14]

The timing of decisions is as follows. Entrepreneurs learn if the government introduced the tax at the start of the period. After learning about the current period's tax, the representative fossil entrepreneur chooses her fossil fuel input and produces the fossil intermediate. The representative clean entrepreneur produces the clean intermediate. The fossil and clean entrepreneurs sell their intermediates to the final-good aggregator, at prices p^f and p^c, re-

[13]As an alternative, one could separately model energy-efficiency capital instead of including it as part of clean capital. In online appendix A, we show for a special case that such an approach is isomorphic to our baseline model with a single type of clean capital. More generally, separately modeling energy-efficiency capital affects the ease with which the economy can substitute away from the fossil intermediate. To this end, we consider a sensitivity exercise for the elasticity of substitution between the clean and fossil intermediates in our quantitative analysis.

[14]Of course, it is always possible that the carbon tax, once introduced, could be repealed, in which case all uncertainty would not be resolved after the introduction of the tax. In our subsequent quantitative analysis, we relax this assumption and show that climate policy risk still has substantial effects on the macroeconomy even if the carbon tax is known to be temporary (i.e. the probability of repeal is one).

spectively. The representative final-good aggregator hires labor and produces the final good. Finally, the fossil and clean entrepreneurs choose next period's levels of fossil and clean capital, respectively. Importantly, the entrepreneurs make these investment decisions before they learn whether the government will introduce the tax next period, implying that their expectations of future climate policy affect their current investment.

We describe the optimization problem for the representative final-good aggregator, and for the representative fossil and clean entrepreneurs under climate policy transition risk. The final-good aggregator chooses the clean and fossil intermediates and labor to maximize profits, taking prices as given. The first order conditions imply the following expressions for the prices of the clean and fossil intermediates:

$$\begin{aligned} p^c &= \gamma\left[\left((x^c)^{\frac{\varepsilon-1}{\varepsilon}}+(x^f)^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}}\right]^{\gamma-1}\left((x^c)^{\frac{\varepsilon-1}{\varepsilon}}+(x^f)^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{1}{\varepsilon-1}}(x^c)^{\frac{-1}{\varepsilon}}, \\ p^f &= \gamma\left[\left((x^c)^{\frac{\varepsilon-1}{\varepsilon}}+(x^f)^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}}\right]^{\gamma-1}\left((x^c)^{\frac{\varepsilon-1}{\varepsilon}}+(x^f)^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{1}{\varepsilon-1}}(x^f)^{\frac{-1}{\varepsilon}}. \end{aligned} \tag{1}$$

The representative clean entrepreneur chooses next period's level of clean capital to maximize the expected present discounted value of future profits. Let $V^c(k^c)$ denote the clean entrepreneur's value function in the pre-tax economy with transition risk, and let $W_t^c(k^c)$ denote her value function t periods into the transition after the government introduces the carbon tax. The clean entrepreneur's value function in the pre-tax economy with transition risk equals:

$$V^c(k^c) = \max_{k^{c\prime}}\left\{p^c A^c k^c - (k^{c\prime}-(1-\delta)k^c) + \left(\frac{1}{1+r}\right)[\rho W_1^c(k^{c\prime}) + (1-\rho)V^c(k^{c\prime})]\right\}.$$

We use 'prime' throughout the paper to denote next period's value of a variable. Parameter r denotes the exogenous interest rate and parameter δ is the depreciation rate. The clean entrepreneur's flow profits equal the total revenue from production, $p^c A^c k^c$, minus investment expenses, $i^c \equiv k^{c\prime}-(1-\delta)k^c$. The continuation value is a weighted average of the continuation value if the government does introduce the carbon tax and the economy is in the first period of the transition, $W_1^c(k^{c\prime})$, and the continuation value if the government does not introduce the carbon tax and the economy remains in the state of the world with no carbon tax, but with risk of a future tax, $V^c(k^{c\prime})$. The weights, ρ and $1-\rho$, are equal to the probability that the government does, and does not, introduce the carbon tax in the next period.

If the tax is adopted, the clean entrepreneur's value function t periods into the transition following the adoption equals:

$$W_t^c(k^c) = \max_{k^{c\prime}}\left\{p^c A^c k^c - (k^{c\prime}-(1-\delta)k^c) + \left(\frac{1}{1+r}\right)W_{t+1}^c(k^{c\prime})\right\}.$$

Since all uncertainty is resolved after the introduction of the carbon tax, the continuation value in period t of the transition simply equals the value function in period $t+1$ of the transition.

The representative fossil entrepreneur chooses fossil fuel and next period's level of fossil capital to maximize the expected, present-discounted value of future profits. Using notation parallel to that for the clean entrepreneur, the fossil entrepreneur's value function in the pre-tax economy with transition risk equals:

$$V^f(k^f) = \max_{k^{f\prime}, f} \left\{ p^f A^f k^f - \zeta f - (k^{f\prime} - (1-\delta)k^f) + \left(\frac{1}{1+r}\right)[\rho W_1^f(k^{f\prime}) + (1-\rho)V^f((k^f)')] \right\},$$

subject to the Leontief constraint that the fossil entrepreneur purchases sufficient fossil fuel to operate the fossil capital, $f \geq k^f$. The fossil entrepreneur's flow profits, equal her total revenue, $p^f A^f k^f$, minus her expenses on fossil fuel, ζf, and minus her investment, $i^f \equiv k^{f\prime} - (1-\delta)k^f$. Since there is no carbon tax, the entrepreneur only pays the extraction cost, ζ, for each unit of fossil fuel.

If the tax is adopted, the fossil entrepreneur's value function t periods into the transition following the adoption equals:

$$W_t^f(k^f) = \max_{k^{f\prime}, f} \left\{ p^f A^f k^f - (\zeta + \tau) f - (k^{f\prime} - (1-\delta)k^f) + \left(\frac{1}{1+r}\right) W_{t+1}^f(k^{f\prime}) \right\},$$

subject to the Leontief constraint. With the carbon tax in place, the fossil entrepreneur must pay the extraction cost, ζ, plus the tax, τ, for each unit of fossil fuel.

3.4. The pre-tax steady state with transition risk

We define a *recursive competitive equilibrium with transition risk* for this economy. The state variables are the levels of fossil and clean capital. A *recursive competitive equilibrium with transition risk* consists of policy functions for the final-good aggregator, $\{x^c, x^f, l\}$, value and policy functions for the clean entrepreneurs, $\{V^c, k^{c\prime}\}$, value and policy functions for the fossil entrepreneurs, $\{V^f, k^{f\prime}, f\}$, and prices for the clean and fossil intermediates and for labor $\{p^c, p^f, w\}$, such that given an interest rate r, and probability $\rho \in (0,1)$, of a carbon tax, τ, next period, the following conditions hold:

1. $\{x^c, x^f, l\}$ solves the final-good aggregator's profit maximization problem.
2. $\{V^c, k^{c\prime}\}$ solves the clean entrepreneur's expected profit-maximization problem.
3. $\{V^f, k^{f\prime}, f\}$ solves the fossil entrepreneur's expected profit-maximization problem.
4. The markets for labor and for the clean and fossil intermediate inputs clear.

A *pre-tax steady state with transition risk* is a recursive competitive equilibrium with transition risk in which all variables are constant from one period to the next (provided that the carbon tax is not introduced). Importantly, this steady state includes entrepreneurs' expectations of the dynamic transition to a lower carbon economy if the carbon tax is introduced, which are captured by the full sequence of value functions over the transition and in the new steady state.

Ultimately, we are interested in how the pre-tax steady state with transition risk differs from a pre-tax steady state without transition risk. The definition of the pre-tax steady state without transition risk is identical to the pre-tax steady state with transition risk except that the probability, ρ, of a carbon tax equals zero. The key difference between these steady states is that in the pre-tax steady state with transition risk, the possibility of a carbon tax and the ensuing dynamic transition affects entrepreneurs' decisions and the equilibrium values of the macroeconomic aggregates.

3.5. The aggregate effects of climate policy transition risk

Solving for the pre-tax steady state with transition risk, we find that climate policy transition risk operates through two key channels to reduce emissions today. First, transition risk shifts the composition of the capital stock towards cleaner capital, which lowers the emissions intensity of output. Second, transition risk reduces output. Thus, transition decreases emissions because the economy produces less and the remaining production is cleaner.

Focusing first on the composition channel, the ratio of fossil to clean capital in the pre-tax steady state with transition risk equals:

$$\frac{K^f}{K^c} = \left(\frac{A^f}{A^c}\right)^{\varepsilon-1} \left(\frac{r+\delta}{r+\delta+\zeta+\rho\tau}\right)^{\varepsilon} \equiv \Theta, \tag{2}$$

where uppercase letters denote aggregate quantities.[15] If the probability of the tax and the fossil fuel extraction cost both equal zero, $\rho = \zeta = 0$, then the ratio of fossil to clean capital equals the ratio of their respective technologies, raised to the $\varepsilon - 1$ power. A positive price of fossil fuel, $\zeta > 0$, raises the operating cost of fossil capital, reducing the ratio of fossil to clean capital. Similarly, the possibility of a future carbon tax, $\rho > 0$, raises the expected operating costs of fossil capital next period, further reducing the ratio of fossil to clean capital. Since equilibrium fossil fuel use equals the level of fossil capital, the decrease in the ratio of fossil to clean capital from transition risk reduces the carbon intensity of current production and the associated emissions.

Turning next to the output channel, the derivative of output with respect to the probability

[15] See online appendix A for the derivation. We assume that $\tau < (A^f(r+\delta+\zeta)-\zeta)/(1-A^f\rho)$ to ensure an equilibrium exists.

of a carbon tax, ρ, equals

$$\frac{\partial Y}{\partial \rho} = \gamma \left[(A^c K^c)^{\frac{\varepsilon-1}{\varepsilon}} + (A^f K^f)^{\frac{\varepsilon-1}{\varepsilon}} \right]^{\frac{\gamma\varepsilon}{\varepsilon-1}-1} l^{1-\gamma} \left[(A^c)^{\frac{\varepsilon-1}{\varepsilon}} (K^c)^{\frac{-1}{\varepsilon}} \frac{\partial K^c}{\partial \rho} + (A^f)^{\frac{\varepsilon-1}{\varepsilon}} (K^f)^{\frac{-1}{\varepsilon}} \frac{\partial K^f}{\partial \rho} \right].$$

This derivative is less than zero for all $\varepsilon > 0$, implying that transition risk reduces output. (Online appendix A provides a formal proof.) Intuitively, diminishing returns to the clean and fossil intermediates imply that output is maximized when the ratio of fossil to clean capital equals the ratio of the respective technologies, raised to the $\varepsilon - 1$ power. Referring to equation (2), entrepreneurs optimally choose this output-maximizing allocation when fossil fuel production costs are zero, $\zeta = 0$, and there is no climate policy risk, $\rho = 0$. Adding climate policy risk increases ρ from zero, and thus pushes the entrepreneur's optimal choices of clean and fossil capital away from the output-maximizing ratio, reducing total output.

To better understand the effects of climate policy risk on capital and output, we solve for the levels of clean and fossil capital in the pre-tax steady state with transition risk:

$$K^c = \left[\left(\frac{\gamma}{r+\delta} \right) (A^c)^{\gamma} \left(1 + \left(\frac{A^f}{A^c} \Theta \right)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{1-\varepsilon(1-\gamma)}{\varepsilon-1}} \right]^{\frac{1}{1-\gamma}} \tag{3}$$

$$K^f = \left[\left(\frac{\gamma}{r+\delta+\zeta+\rho\tau} \right) (A^f)^{\gamma} \left(1 + \left(\frac{A^f}{A^c} \Theta \right)^{\frac{-(\varepsilon-1)}{\varepsilon}} \right)^{\frac{1-\varepsilon(1-\gamma)}{\varepsilon-1}} \right]^{\frac{1}{1-\gamma}}. \tag{4}$$

For all values of $\varepsilon > 0$, the level of fossil capital is decreasing in the probability, ρ, of the carbon tax. Increases in the probability of a carbon tax raise the expected marginal cost of operating fossil capital, causing the fossil entrepreneurs to demand less fossil capital. The impact of climate policy risk on the level of clean capital depends on the elasticity of substitution. Climate policy risk reduces clean capital when clean and fossil capital are less substitutable, $\varepsilon < 1/(1-\gamma)$, and increases clean capital when clean and fossil capital are more substitutable, $\varepsilon > 1/(1-\gamma)$. Intuitively, if fossil and clean capital are very substitutable, a decrease in fossil capital, all else constant, raises the price of the clean intermediate, causing the clean entrepreneurs to rent additional capital.

Regardless of the direction of the change in clean capital, climate policy risk always reduces the ratio of fossil to clean capital (the composition effect). Mechanically, this is because when climate policy risk leads to a decrease in clean capital, it leads to an even larger decrease in fossil capital. On net, climate policy risk reduces total capital (e.g., fossil plus clean) when the elasticity of substitution is low, $\varepsilon < 1/(1-\gamma)$, amplifying the output effect. However, climate policy risk has ambiguous effects on total capital when the elasticity of substitution is high, $\varepsilon > 1/(1-\gamma)$, because fossil capital falls but clean capital rises.

While we abstract from endogenous innovation, the same mechanisms through which climate policy transition risk affects the relative levels of clean and fossil capital could also apply to relative levels of clean and fossil technology. Previous literature has found that the introduction of a carbon tax or similar climate policy could shift innovation towards cleaner technologies (see e.g., Acemoglu et al., 2012). Likewise, the possibility of a future carbon tax could also shift innovation towards cleaner technologies, raising A^c relative to A^f. Referring to equation (2), this innovation response to climate policy risk could further reduce the ratio of fossil to clean capital, magnifying the composition effect and the resulting reduction in emissions.

Ultimately, our analysis reveals that climate policy transition risk reduces emissions by shifting the economy towards cleaner capital and reducing output. Like climate policy risk, a carbon tax would also operate through these two channels to reduce emissions. In particular, in a steady state with carbon tax $\tilde{\tau}$ and no climate policy transition risk, the composition and levels of capital would still be defined by equations (2)-(4), but the climate policy transition risk term, $\rho\tau$, would be replaced with the actual carbon tax, $\tilde{\tau}$. Indeed, in this simple model, the effects of transition risk on the composition of capital and the level of output, and hence on emissions, are identical to the effects of an actual tax, $\tilde{\tau}$, where $\tilde{\tau}$ equals the expected tax, $\rho\tau$, from the pre-tax steady state with climate policy transition risk.

While the above results suggest that climate policy transition risk induces the same cost-effective emissions reductions that would be achieved using a carbon tax, the equivalence is due to the analytic model's simplifying assumptions. In particular, the simple framework focuses solely on the partial-equilibrium investment decisions risk neutral entrepreneurs would make when faced with a positive probability of a future carbon tax. In the subsequent quantitative general equilibrium model, the macro implications of climate policy transition risk are no longer equivalent to a less stringent version of the policy itself. We highlight that while transition risk will distort the composition of capital and reduce output, and consequently decrease emissions, these emissions reductions could be achieved at a lower overall welfare cost by instead using an actual carbon tax.

4. Quantitative model

To quantify the effects of climate policy transition risk on the U.S. economy, we extend the analytic model in several ways, but the fundamental intuition for the output and composition effects is unchanged. First, we model the household-side of the economy in which risk-averse entrepreneurs and workers make decisions to maximize the expected lifetime welfare for the household. Second, we allow for the allocation of labor across the different intermediate input sectors, providing entrepreneurs with a mechanism to immediately adjust production after learning whether the government introduced the carbon tax. Third, we separately model non-energy capital to allow capital that is not directly related to energy likely to respond differently to climate policy risk than capital that is specialized to use or to replace fossil fuel. And fourth, we model investment as partially irreversible to capture the potential losses from selling fossil capital after the introduction of the carbon tax. We assume that when the carbon tax is introduced, all revenue is returned back to the households through equal, lump-sum transfers.

4.1. Production

We model the allocation of labor across the different intermediate sectors. Unlike capital, each entrepreneur hires labor after she learns whether or not the government will introduce the carbon tax in that period. This additional flexibility allows the entrepreneur to adjust her production in response to the tax (or absence of a tax). The labor market is perfectly competitive; all entrepreneurs pay the market wage, w.

Building on the analytic model from the previous section, the production functions for the clean and fossil intermediate inputs now equal:

$$x^c = A^c (k^c)^\alpha (l^c)^{1-\alpha} \quad \text{and} \quad x^f = \min[A^f (k^f)^\alpha (l^f)^{1-\alpha}, \mu f].$$

Variables l^c and l^f denote labor hired by entrepreneurs in the clean and fossil sectors, respectively. Leontief parameter μ determines fossil energy's share of fossil-intermediate production.[16]

We introduce a third type of capital, which we call non-energy capital, that is not specialized to use or to replace fossil fuel. The majority of capital used in most production processes falls into this third, non-energy category. For example, tee-shirts are produced using factory buildings, sewing machines, lights, assembly lines, etc. While this capital all requires electricity to operate, it does not require that the electricity be made from fossil fuel, and thus we classify it as non-energy.[17] Investment in non-energy capital is given by: $i^n \equiv k^{n\prime} - (1-\delta)k^n$. The inclusion of non-energy capital allows us to reinterpret clean capital as capital that is specifically designed to replace fossil fuel through the production of clean energy or to replace fossil capital through improvements in energy efficiency.

To separately model non-energy capital, we introduce a non-energy intermediate input, x^n. The non-energy intermediate is produced competitively from non-energy capital, k^n, and

[16] One subtle difference from the analytic model is that the fossil technology term is inside the min function, allowing us to produce a model consistent with balanced growth.

[17] If the factory buildings and machines embody energy efficiency, then we would classify one portion of the buildings and machines as clean capital and the other portion as non-energy capital.

labor, l^n, according to the Cobb-Douglas production function:

$$x^n = A^n (k^n)^\alpha (l^n)^{1-\alpha}.$$

Parameter A^n denotes total factor productivity in non-energy production.

The final good is a CES aggregate of the non-energy, clean, and fossil intermediate inputs:

$$y = \left((x^e)^{\frac{\phi-1}{\phi}} + (x^n)^{\frac{\phi-1}{\phi}} \right)^{\frac{\phi}{\phi-1}} \quad \text{where} \quad x^e = \left((x^c)^{\frac{\varepsilon-1}{\varepsilon}} + (x^f)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}.$$

Parameter ε denotes the elasticity of substitution between the clean and fossil intermediates. Parameter ϕ denotes the elasticity of substitution between the composite of energy-related intermediates x^e, and the non-energy intermediate, x^n.

4.2. Partially irreversible investment

The analytical results in Section 3 demonstrate that the introduction of a carbon tax decreases demand for fossil capital. This could be especially costly for a fossil entrepreneur if she cannot recover the full value of any capital she re-sells. An entrepreneur might not recover the full value of re-sold capital because of the transactions and physical costs of re-sale, buyers' potential concerns that the used capital is a "lemon" (Bloom, 2009), and the possibility that capital designed for one particular firm might not be as useful in a different firm (Ramey and Shapiro (1998), Ramey and Shapiro (2001)). For example, suppose an entrepreneur in the fossil sector sells a coal boiler to a clean entrepreneur. The clean entrepreneur's valuation of the boiler's parts is likely less than the value of the boiler.

To incorporate resale losses, we model an asymmetric adjustment cost on investment:

$$G(i) = \frac{\lambda}{2}\left[-i + (i^2 + \eta)^{\frac{1}{2}} \right],$$

where variable i denotes the entrepreneur's level of investment. For small values of η, the adjustment cost function, $G(i)$, provides a twice-differentiable approximation to the piecewise adjustment-cost function, H:

$$H(i) = \begin{cases} 0 & : i \geq 0 \\ |\lambda i| & : i < 0. \end{cases}$$

Parameter $\lambda \in [0,1]$ equals the fraction of the capital stock the entrepreneur looses from re-sale. At the extremes, $\lambda = 1$ corresponds to perfectly irreversible investment and $\lambda = 0$ corresponds to perfectly reversible investment.

Unlike capital, labor is fully fungible across the different sectors. We do not model any type of adjustment costs on labor because of the broad nature of the different sectors. For example, the skills of a chemist or a construction worker could be combined with all three types of capital, and thus used in all three sectors.

4.3. Households

The economy is inhabited by a continuum of infinitely-lived, identical households, comprising entrepreneurs from each sector and workers. The worker in each household is endowed with one unit of time which she can divide between leisure and labor. The worker can supply labor to any entrepreneur in the economy, not just the ones in her household. Each period, the household receives utility from consumption, c, and dis-utility from hours worked, h. The per-period utility function is:

$$u(c,h) = \frac{c^{1-\sigma}}{1-\sigma} - \chi \frac{h^{1+\frac{1}{\theta}}}{1+\frac{1}{\theta}},$$

where parameter σ is the coefficient of relative risk aversion, parameter χ measures the dis-utility from hours worked, and parameter θ is the Frisch elasticity of labor supply.

4.4. Climate policy transition risk

As in the analytic model, to study climate policy transition risk, we focus on a state of the world in which there is no carbon tax in place, but the entrepreneurs and workers in each representative household expect that the government will introduce a carbon tax, τ, with probability, ρ, next period. If the government introduces the tax, then we assume that all uncertainty is resolved and the economy dynamically transitions to a long-run steady state with the tax in place. The entrepreneurs and workers make decisions to maximize the household's expected present discounted value of lifetime utility, and thus inherit the household's risk averse preferences. They take prices and the probability of the future carbon tax as given.

The timing of decisions parallels that of the analytic model. Agents learn whether or not the government introduced the tax at the start of the period. After learning about the current period's tax, the representative fossil entrepreneur chooses her fossil fuel input and labor demand and produces the fossil intermediate. The representative clean and non-energy entrepreneurs choose their respective labor demands and produce the clean and non-energy intermediates. The fossil, clean, and non-energy entrepreneurs sell their intermediates to the final-good aggregator, at prices p^f, p^c and p^n respectively. The representative final-good aggregator produces the final good. Finally, the fossil, clean and non-energy entrepreneurs choose next period's levels of fossil and clean capital, respectively. Again, we stress that even though there is no carbon tax in the current period, the entrepreneurs make these investment decisions understanding that there is the potential for the government to introduce the tax next period, implying that their expectations of future climate policy affect their current investment. The collective investment decisions by all three types of entrepreneurs determine the household's level of saving.

We describe the optimization problems for the final-good aggregator and for entrepreneurs and workers under climate policy transition risk. The representative final-good aggregator chooses the clean, fossil, and non-energy intermediates. The first order conditions yield the expressions for the equilibrium prices of the clean, fossil, and non-energy intermediate, analogous to equation (1) in the analytic model.

We write the optimization problem for the workers and for the clean, fossil, and non-energy entrepreneurs as a single household value function. Let $V(k^c, k^f, k^n)$ denote the household's value function in the pre-tax economy with transition risk, and let $W_t(k^c, k^f, k^n)$ denote her value function in period t of the transition after the government introduces the carbon tax. The household's value function in the pre-tax economy with transition risk equals:

$$V(k^c, k^f, k^n) = \max_{k^{c\prime}, k^{f\prime}, k^{n\prime}, h, l^c, l^f, l^n, f} u(c, h) + \beta \left[\rho W_1(k^{c\prime}, k^{f\prime}, k^{n\prime}) + (1-\rho) V(k^{c\prime}, k^{f\prime}, k^{n\prime}) \right], \quad (5)$$

subject to the budget constraint,

$$c = wh + \pi^n + \pi^f + \pi^c. \quad (6)$$

Household income includes labor income, wh, and the flow profits from the clean, fossil, and non-energy entrepreneurs, denoted by π^c, π^f, and π^n, respectively:

$$\pi^c = p^c x^c - w l^c - i^c - G(i^c), \quad \pi^f = p^f x^f - \zeta f - w l^f - i^f - G(i^f), \quad (7)$$
$$\text{and} \quad \pi^n = p^n x^n - w l^n - i^n - G(i^n).$$

Parameter β is the household's discount factor.

If the government introduces the carbon tax, then the household's value function in period t of the resulting transition equals:

$$W_t(k^c, k^f, k^n) = \max_{k^{c\prime}, k^{f\prime}, k^{n\prime}, h, l^c, l^f, l^n, f} u(c, h) + \beta W_{t+1}(k^{c\prime}, k^{f\prime}, k^{n\prime}), \quad (8)$$

subject to the budget constraint over the transition,

$$c = wh + \pi^n + \pi^f + \pi^c + T. \quad (9)$$

The household's budget constraint over the transition includes the transfers, T, from the carbon tax revenue. Additionally, the fossil entrepreneur's profits over the transition incorporate that she must pay the extraction cost, ζ, plus the carbon tax, τ, for each unit of fossil fuel:

$$\pi^f = p^f x^f - (\zeta + \tau) f - w l^f - i^f - G(i^f).$$

The expressions for the clean and non-energy entrepreneurs' profits over the transition are the same as in the pre-tax economy with transition risk (equation (7)).

4.5. The pre-tax steady state with transition risk

As in the analytic model, we define a *recursive competitive equilibrium with transition risk* for this economy. The state variables are the levels of fossil, clean, and non-energy capital. A *recursive competitive equilibrium with transition risk* consists of policy functions for the final-good aggregator, $\{x^c, x^f, x^n\}$, value and policy functions for the households, $\{V, k^{c\prime}, k^{f\prime}, k^{n\prime}, h, f, l^c, l^f, l^n\}$, and the prices for the clean, fossil, and non-energy intermediates and for labor and capital $\{p^c, p^f, p^n, w, r\}$, such that given probability $\rho \in (0,1)$, of a carbon tax, τ, next period, the following conditions hold:

1. $\{x^c, x^f, x^n\}$ solves the profit-maximization problem for the final-good aggregator.
2. $\{V, k^{c\prime}, k^{f\prime}, k^{n\prime}, h, f, l^c, l^f, l^n\}$ solves the household's expected utility-maximization problem.
3. The markets for labor, capital, and for the clean, fossil and non-energy intermediate inputs clear.

Again parallel to the analytic model, a *pre-tax steady state with transition risk* is a recursive competitive equilibrium with transition risk in which all variables are constant from one period to the next (provided that the carbon tax is not introduced). We compare the pre-tax steady state with transition risk to a pre-tax steady state without transition risk (i.e., $\rho = 0$) and to a post-tax steady state that is reached following the adoption of the carbon tax equal to τ. The definition of the pre-tax steady state without transition risk is analogous to the definition of the pre-tax steady state with transition risk except that $\rho = 0$. The definition of the post-tax steady state is in online appendix B.

To solve for the pre-tax steady state with transition risk, we must solve for both the model's steady state and the dynamic transition path following the introduction of the carbon tax at the same time. The steady state value function partially depends on the value function in the first period of the transition, which, in turn, partially depends on the value function in the second period of the transition, and so on (see equations (5) and (8)). Thus, the full transition path of the economy following the introduction of the carbon tax affects the equilibrium values in the steady state with transition risk. Similarly, the steady state equilibrium values also affect the behavior of the economy over this transition. To capture this interplay, we solve for the steady state and the transition simultaneously. Specifically, we solve a system of non-linear equations derived from the household's first order conditions and from the market-clearing conditions in both the pre-tax steady state with risk and in each period of the transition. See online appendix B for a full description.

5. Calibration

Table 1: Parameter Values: External Calibration

Parameter	Value
Production	
Capital share: α	0.33
Clean and fossil substitution elasticity: ε	3
Energy and non-energy substitution elasticity: ϕ	0.10
Adjustment cost: λ	0.43
Perturbation parameter: η	1.0e-09
Fossil fuel extraction cost: ζ	1
Preferences	
Frisch labor supply elasticity: θ	0.5
Coefficient of relative risk aversion: σ	2
Policy risk	
Size of the carbon tax: τ	0.61
Probability of the carbon tax: ρ	0.13

Note: This table reports the parameter values that we take directly from existing estimates.

We calibrate our model's pre-tax steady state to match the current U.S. economy in which agents place a positive probability on a future carbon tax, in line with the evidence presented in Section 2. The model time period is one year. We calibrate nine parameters, $\{\alpha, \varepsilon, \phi, \lambda, \eta, \rho, \theta, \tau, \sigma\}$ directly from the data and existing literature. Given these externally calibrated parameters, we jointly calibrate the remaining six parameters $\{\mu, A^c, A^f, \delta, \beta, \chi\}$ internally so that six moments in the model match six empirical targets. Tables 1 and 2 report the parameter values that we calibrate externally and internally, respectively.

Table 2: Parameter Values: Internal Calibration

Parameter	Value
Production	
Leontief parameter: μ	15.53
Clean productivity: A^c	2.43
Fossil productivity: A^f	4.72
Depreciation rate: δ	0.06
Preferences	
Discount factor: β	0.96
Disutility of labor: χ	73.27

Note: This table reports the parameter values that we jointly calibrate so that a set of moments in the model match their corresponding empirical targets.

5.1. Climate transition risk

We assume that, if adopted, the future carbon tax will be set at \$51/ton of CO_2 (in 2020 dollars), in line with the interim estimates of the social cost used by the Biden administration (IWG, 2021). While the evidence discussed in Section 2 suggests that firms anticipate a carbon price could be introduced in the future, we do not know what probability they place on that future price. In our baseline specification, we assume that there is a 75 percent chance that the carbon tax will be implemented within the next 10 years, implying a baseline value of $\rho = 0.13$. We show this value is broadly consistent with firms' behavior by comparing the emissions reduction implied by our model with $\rho = 0.13$ to the voluntary emissions reduction effort we observe among firms. Additionally, we explore the effects of alternative probabilities on our main results in Section 7 and in online appendix D.3.

5.2. Production and preferences

We set capital's income share, α, equal to one third. We choose Leontief parameter μ so that the fossil energy share of GDP equals 0.04 (Golosov et al., 2014). We normalize the fossil fuel extraction cost, ζ, to unity. This amounts to an implicit choice of units. We calculate that the \$51/ton carbon tax is approximately 61 percent of the 2019 composite price of coal, oil, and natural gas, so we set the value of the future carbon tax in our model, τ, equal to 0.61. We set the depreciation rate on capital equal to 0.065, the average depreciation rate for fixed assets (NIPA Tables 1.1 and 1.3) over the most recent five years of data, 2015-2019.

We set the elasticity of substitution between clean and fossil intermediates, ε, equal to 3 (Papageorgiou et al., 2017). Taking a macroeconomic approach consistent with our study, Papageorgiou et al. (2017) estimate the elasticity of substitution between clean and fossil inputs directly from an aggregate production function with neutral technical change. Their results provide strong empirical evidence that the elasticity of substitution exceeds unity in this setting, with estimates ranging from 1.3 to 3 (see Table 8 of Papageorgiou et al., 2017). We use the estimate of 3 from their preferred specification for our main analysis.

Following Fried (2018), we design the model so that the elasticity of substitution between the non-energy and energy intermediates, ϕ, is close to zero. Empirically, entrepreneurs can substitute away from fossil fuel by switching to renewable energy or by increasing energy efficiency. However, both of these channels correspond to increases in the clean intermediate, not the non-energy intermediate. Therefore, we set the elasticity of substitution between the non-energy and energy intermediates to be close to zero; $\phi = 0.1$.

Parameter λ determines the cost firms incur from selling capital. Based on the estimates in Bloom (2009), we set $\lambda = 0.43$, implying that capital looses almost half of its value when it is resold. We choose the perturbation parameter in the adjustment cost function to be very small, $\eta = 1.0e-9$, to provide as close of an approximation as possible to the piecewise function in which firms only pay the adjustment cost on negative investment.

We normalize TFP in non-energy intermediate production to unity, $A^n = 1$. We choose TFP in clean, A^c, and fossil, A^f, intermediate production to match the ratio of fossil capital to total capital, K^f/K, and the ratio of fossil to clean intermediate production, X^f/X^c, in the U.S. data. We construct the ratio of K^f/K from the detailed data for fixed assets and consumer durable goods, described in online appendix C. The data provides information on capital stocks dis-aggregated by type of capital (e.g., mainframes) and sector (e.g., farms). We define fossil capital as all capital that is specialized to use fossil fuel. For example, we count internal combustion engines in every sector as fossil capital and we count "special industrial machinery" as fossil capital in sectors that directly relate to fossil energy (e.g., oil and gas extraction). Our calculated ratio of K^f/K equals 0.1.

To determine X^f/X^c, we focus on two sectors for which we directly observe clean and fossil production, electricity and transportation. Combined, electricity and transportation account for 70 percent of all U.S. carbon emissions (EIA, 2021). We define fossil electricity as any electricity that is produced from fossil fuels (e.g. coal, oil, natural gas), and clean electricity as any electricity that is produced without using fossil fuels (e.g. solar, wind, hydro, nuclear). The ratio of fossil to clean electricity generation equals 1.67.

We define fossil and clean transportation as vehicle miles traveled in fossil and clean capital, respectively. The average vehicle contains both fossil and clean capital. Vehicles are specialized to use fossil fuel, implying that they must contain at least some fossil capital. However, many vehicles have special capital, such as regenerative brakes, that is specifically designed to reduce fossil fuel use through improvements in fuel economy. We classify this type of capital as clean. We use data on the fuel economy of different vehicle models and the average fuel economy of the U.S. vehicle fleet to construct the average fractions of fossil capital embodied in autos and light-trucks, including sport utility vehicles (see online appendix C). We find that 70 percent of autos and 85 percent of light trucks are fossil capital. Thus, we classify 70 percent of vehicle miles traveled by autos and 85 percent traveled by light trucks as fossil. We classify all vehicle miles traveled by motorcycles, buses, single-unit trucks and combination trucks as fossil. The resulting ratio of fossil to clean miles traveled equals 3.26. The ratio of fossil to clean intermediate production targeted in our calibration equals $X^f/X^c = 2.53$, which is the average of the ratios of fossil to clean electricity generation and fossil to clean vehicle miles traveled, weighted by the levels of emissions in each sector.[18]

We set the discount factor, β, equal to 0.96 to match the average U.S. capital-output ratio (NIPA Tables 1.1 and 1.1.5) over the most recent five years of data (2015-2019), equal to 3.04. Following Conesa et al. (2009), we set the coefficient of relative risk aversion, θ_1, equal to 2 and, consistent with Peterman (2016), we set the Frisch elasticity of labor supply, θ_2, equal to 0.5. We choose the dis-utility of hours so that workers spend one third of their time endowment working. We use a Nelder-Meade algorithm to jointly minimize the distance between the empirical and model values of the targets. The model matches the calibration targets quite closely (see online appendix C).

5.3. Evaluating the assumed beliefs

The key parameter of interest to quantify the impacts of climate policy transition risk is the subjective probability of a carbon price being adopted, ρ. In the absence of direct measures of these subjective beliefs, we assume $\rho = 0.13$ in our baseline specification. This assumption implies that firms believe there is a 75 percent chance that the carbon tax will be implemented within the next 10 years. We highlight that this assumed probability is in line with the firm-level beliefs that can be inferred from the anecdotal evidence discussed in Section 2.

Recall from Section 2, firms are responding to the risk of future climate policy in a variety of ways. However, inferring firms' beliefs about the likelihood of future climate policy from these various responses is challenging. For example, many firms have set their own carbon reduction goals. Intuitively, if the costs incurred by making the investments required to achieve these reductions are large, that would imply the firms believe a climate policy may be imminent. However, without knowing the private costs incurred by firms to achieve these reductions, we cannot used the observed emissions reduction targets to infer the firms' beliefs surrounding the likelihood of a future climate policy.

As an alternative to setting targets for the quantity of emissions, a large number of firms are

[18] Combined, electricity and transportation produced 3,537 million metric tons of carbon dioxide in 2019; 46 percent of these emissions were from the electricity sector and the remaining 54 percent were from the transportation sector (EIA, 2021).

using internal carbon prices.[19] The most common internal carbon price is a "carbon shadow price". Firms use these shadow prices primarily to evaluate the net-present value of long-lived investments under different scenarios with future carbon taxes in place (Ahluwalia, 2017).[20] However, the shadow price only contains information surrounding a firm's expected level of the tax, not the firm's beliefs over the likelihood of the tax being adopted. For example, suppose a firm evaluates the profitability of an investment opportunity under two scenarios, one with a shadow carbon price of zero and one with a shadow price of \$51/ton of CO_2. Whether or not the firm chooses to undertake that investment depends on the probabilities the firm places on each scenario, which we do not observe.

Importantly, there is a second type of internal carbon price, an internal "carbon fee", which does provide information about firms' beliefs surrounding the likelihood of a future climate policy. The internal carbon fee is a carbon price that a firm levies on its direct emissions, or on the emissions embodied in its energy use. The revenue raised by this internal fee can be transfered within the organization or, in some cases, used to pay for emission offsets or renewable energy credits. For example, Microsoft imposes an internal carbon fee of \$10/ton of CO_2 on the emissions resulting from its energy use – with the revenue being used to purchase carbon offsets and renewable energy credits. Likewise, Walt Disney, Alphabet, Ben and Jerry's and Phillip Morris all impose internal carbon fees ranging from \$10 - \$20 per ton. More generally, 15 percent of companies that report using internal carbon pricing use internal carbon fees, with a median fee of \$18 per ton (CDP, 2021). Importantly, if a firm uses an internal carbon fee, there is no additional probability analysis. Firms simply make investments as though there was a carbon tax equal the internal carbon fee. Therefore, the level that firms choose for the fee implicitly reveals information on both the probability and level of the expected carbon price.

To examine whether our assumed values for ρ align with firms' observed behavior, we solve for the internal carbon fee that firms would optimally choose within our calibrated model and then compare this implied carbon fee to the internal carbon fees that firms adopt in practice. Mechanically, we solve for an additional steady state with no transition risk, but with an internal carbon fee. We choose the size of fee so that the ratio of fossil to clean capital in this steady state is the same as it is in the pre-tax steady state with transition risk. Thus, the internal fee equals the tax that attains the same ratio of fossil to clean capital as the firm optimally chooses in response to climate policy transition risk. Table 3 reports the model value of the internal carbon fee in response to transition risk over a range of 10-year carbon tax probabilities. We

[19] Over half of the world's largest companies by market capitalization incorporate internal carbon prices into their decision making processes (CDP, 2021). Many of these firms are either located in the U.S. or do business in the U.S.

[20] For example, to guide long-term capital investment decisions, Shell uses a shadow price of \$40/ton of CO_2 – which has reportedly resulted in the decision to pass on many potential CO_2-intensive investment opportunities.

find that the firm's optimal internal fee in response to transition risk increases from 41 cents when there is only a 5 percent chance of a carbon tax being introduced in the next 10 years to $21.13 when there is a 99 percent chance of a carbon tax. The internal fee for our baseline calibration equals $8.84 per ton, approximately half of the median internal fee reported in CDP (2021).

Table 3: Internal Carbon Fee Consistent With
10-Year Carbon-Tax Probability

10-yr probability (percent)	5	25	50	75	95	99
Internal fee ($/ton)	0.41	2.19	4.89	8.84	15.84	21.13

Note: This table reports the internal carbon fees that result in the same ratio of fossil to clean capital as we find in the pre-tax steady state with transition risk. The implied internal carbon fees are displayed for a range of probabilities of a future climate policy being adopted within the next 10 years.

Generally, we would expect the internal fee implied by transition risk in the model to be less than the internal fees that we observe among firms. While firm surveys suggest that internal fees are used primarily to address climate policy transition risk (Ahluwalia, 2017), firms may also be motivated by a desire to differentiate their products as being "green" or to mitigate reputation risks. The use of an internal carbon fee to raise revenues for environmental objectives may also be partially driven by a belief in corporate social responsibility. Our model allows us to isolate the internal fee that firms would choose in response to only transition risk. The additional, non-transition-risk motives for reducing emissions could cause firms to choose a larger internal fee, leading to greater emissions reduction, then what they would choose if transition risk were the only factor.

A second reason why we would expect the internal fee in our model to be smaller than the internal fees we observe among firms is that firms vary in terms of how much they voluntarily reduce their carbon emissions, and even whether they choose to reduce emissions at all. This heterogeneity could result from many different factors outside of our model, including different beliefs over the likelihood of future climate policy and different environmental objectives. Our model is designed to capture the average firm's response to climate policy transition risk, including the firms that are voluntarily reducing their emissions and also the firms that are not reducing emissions at all. We would expect the internal fee for the average firm in our model to be less than the internal carbon fees that we observe among a selected sample of firms that voluntarily choose to reduce their emissions.

Ultimately, we don't know how much smaller the internal fee implied by our model should be, compared to the fees reported in the data. This difference depends on the fraction of U.S. output that is produced by firms that are engaged in emissions abatement and on the strength of the non-transition-risk motives, neither of which we observe. Our choice of a 75 percent chance of a carbon tax within 10 years, which implies an internal fee approximately half of median value in CDP (2021), is consistent with the view that one half of U.S. output is produced by firms engaged in abatement, or with the view that half of the observed level of the internal fee is due to non-transition-risk motives. While both of these views, or a combination of the two, seem reasonable, we recognize that there could be other reasonable views which would lead to different 10-year carbon-tax probabilities. To account for this, we report our main results across a range of 10-year carbon tax probabilities in Section 7 and in online Appendix D.3.

6. Results

We use our calibrated model to quantify the impacts climate policy transition risk has on the current U.S. economy, and to explore the implications of climate policy transition risk for delaying action on climate change and the Green Paradox.

6.1. The effects of climate policy transition risk on the macroeconomy

We solve the model for four steady states. First, we solve for a pre-tax steady state without climate policy transition risk (i.e. $\tau = 0$ and $\rho = 0$). Second, we solve for a pre-tax steady state with climate policy transition risk. Specifically, we assume that there is a 13 percent probability that the government will introduce a \$51/ton tax in the next period. Third, we solve for an "emissions-equivalent" steady state in which we remove transition risk and impose a carbon tax that results in the same level of emissions as the pre-tax steady state with transition risk. Finally, we solve for a policy steady state with a \$51/ton tax in place and no climate policy transition risk.

Table 4 reports the percentage changes in various outcomes in (1) the pre-tax steady state with climate policy transition risk, (2) the emissions-equivalent steady state, and (3) the policy steady state, all relative to the pre-tax steady state without climate policy transition risk. Focusing on Column (1), we see that climate policy transition risk reduces emissions by 2.12 percent. For comparison, emissions fall by 20.34 percent in the policy steady state. Hence, transition risk by itself is responsible for approximately one tenth of the total drop in emissions going from a world with no risk of a future carbon tax to a world with a carbon tax in place.[21]

[21] Our baseline model assumes that it is costly to sell used capital; firms must pay an adjustment cost if they want to reduce their capital by more than the amount of depreciation. Online appendix Table D1 shows how the pre-tax steady state outcomes change in response to climate policy transition risk when we re-calibrate the model under the assumption that there are no adjustment costs ($\lambda = 0$). We find that removing the adjustment cost has only a small impact on the quantitative results. Intuitively, regardless of the whether there are adjustment costs, in the first period after the government introduces the tax, firms are stuck with the level of capital they chose in the steady state with transition risk and no tax. After the first period, fossil entrepreneurs decrease their capital. Yet the size of this decrease is only slightly larger than depreciation, making the impact of the adjustment cost small.

Table 4: Effects of Climate Policy Transition Risk on Macro-Aggregates
(Percent change from pre-tax, no-risk steady state)

	Pre-tax risk SS	Emissions-equivalent SS	Policy SS
Aggregates			
Fossil fuel: F	-2.12	-2.12	-20.34
Output: Y	-0.34	-0.26	-2.58
Consumption: C	-0.13	-0.12	-1.30
Total capital: K	-0.79	-0.43	-3.88
Total labor: L	-0.00	-0.06	-0.45
Composition			
Fossil to clean capital: K^f/K^c	-8.86	-5.05	-39.74
Fossil to clean labor: L^f/L^c	-3.08	-5.05	-39.75
Fossil to clean intermediates: X^f/X^c	-5.03	-5.05	-39.75

Note: This table reports the percentage changes in outcomes in (1) the pre-tax steady state with climate policy transition risk, (2) the emissions-equivalent steady state, and (3) the policy steady state, all relative to the pre-tax steady state without climate policy transition risk.

Climate policy transition risk reduces emissions through the two key channels highlighted in the analytic model: the composition of the capital stock becomes relatively cleaner and total output falls. Focusing first on the composition effect, Table 4 highlights that the ratio of fossil to clean capital falls by 8.86 percent in response to climate policy transition risk. The introduction of the carbon tax leads to a large decline in the value of fossil capital, a phenomenon the earlier literature has called "stranding" (see e.g., van der Ploeg and Rezai, 2020).[22] Intuitively, the composition effect arises because the possibility of stranded capital causes entrepreneurs to shift from fossil to clean capital in the pre-tax steady state with risk.[23] This response, in turn, reduces the amount of stranded capital if the carbon tax realizes.

The reduction in emissions from the change in the composition of capital is partly undone by the entrepreneur's ability to adjust labor after she learns whether the government has introduced the tax. In particular, if the government does not introduce the tax, fossil entrepreneurs have too little capital relative to what they would have chosen had they known there would not be a carbon tax. To compensate for the sub-optimally low fossil capital, the fossil entrepreneurs hire additional labor, which increases the production of the fossil intermediate and emissions. Due to this labor-demand response, the composition of labor is less responsive to climate pol-

[22] In particular, the introduction of the carbon tax leads to an immediate 37 percent decrease in the return to fossil capital, relative to the pre-tax steady state with risk.

[23] The expected return to fossil capital in the pre-tax steady state equals 4.08 percent, which is larger than the expected return to clean capital, equal to 3.9 percent. In equilibrium, this differential is necessary to compensate households for the large decline in the return to fossil capital following the introduction of the carbon tax.

icy transition risk; the drop in the ratio of fossil to clean labor is approximately one third of the drop in the ratio of fossil to clean capital. Combined, the changes in the composition of labor and capital cause the ratio of fossil to clean intermediates to decrease by 5.03 percent. These compositional changes are responsible for 84 percent of the drop in emissions caused by climate policy transition risk.[24]

Turning next to the output effect, climate policy transition risk reduces output by 0.34 percent. The output effect is responsible for the remaining 16 percent of the reduction in emissions caused by climate policy transition risk.[25] Output falls both because climate policy risk moves the economy away from the output maximizing allocation of clean and fossil capital, as highlighted in the analytic model, and also because quantitatively, climate policy risk reduces the total level of capital. The level of capital depends on the household's expected return to saving. The expected return to saving, in turn, depends on the expectation of the marginal product of capital and the marginal utility of consumption (i.e., the right-hand-side of the household's consumption-Euler equation). Climate policy transition risk reduces the marginal product of capital, which, all else constant, decreases the expected return to saving. Working in the other direction, the introduction of a carbon tax in the future reduces future consumption. Lower future consumption raises future marginal utility which, all else constant, increases the expected return to current saving. Ultimately, the decrease in the marginal product of capital dominates, and climate policy transition risk results in a 0.79 percent decrease in the total stock of capital.

The emissions reductions caused by the response to transition risk are equal to the emissions reductions that would be achieved in a steady state with no transition risk and a carbon tax of $4.91/ton. Recall, that in the simple analytic model, the emissions-equivalent tax exactly equals the expected tax in the pre-tax steady state with transition risk. However, in our richer quantitative model, the allocation of labor after entrepreneurs learn if there is a carbon tax undoes some of the emissions reductions implied by allocation of capital. Consequently, the size of the emissions-equivalent tax in the quantitative model is less than the expected tax in the pre-tax steady state. The expected tax in the pre-tax steady state equals $\rho \times \tau = 0.13 \times \$51 = \$6.60$ which is greater than the $4.91 carbon tax required to achieve the emissions reduction from climate policy transition risk.

Referring to the second column of Table 4, the emissions-equivalent tax operates through

[24] To quantify the impact of the compositional changes, we hold aggregate output constant in the pre-tax steady state without transition risk and impose fossil fuel intensity from the pre-tax steady state with climate policy transition risk.

[25] To quantify the impact of the output effect alone, we hold the fossil fuel intensity of output constant in the pre-tax steady state without transition risk and reduce total output to the level in the pre-tax steady state with transition risk.

the same and composition and output channels as climate policy transition risk to reduce emissions. The tax decreases the ratio of fossil to clean capital by 5.05 percent and reduces output by 0.26 percent. However, the magnitudes of the channels differ between the pre-tax steady state with climate policy transition risk and the emissions-equivalent steady state; the emissions reductions from the \$4.91 tax are achieved with a smaller reduction in output and a larger reduction in the ratio of fossil to clean intermediates. While the output effect alone was responsible for 16 percent of the emissions reductions stemming from climate policy transition risk, the output effect only accounts for only 12 percent of the emissions reductions achieved with the emissions-equivalent tax.

Climate policy transition risk relies more heavily on a decrease in output to reduce emissions for two reasons. First, since entrepreneurs choose capital before they learn if the government introduces the carbon tax and labor after they learn, climate policy transition risk distorts the capital-labor ratio. In contrast, the emissions-equivalent tax does not distort the capital-labor ratio because entrepreneurs know that the tax is in place when they make both their capital and labor decisions. The distorted capital-labor ratio under climate policy transition risk directly reduces output and also reduces the expected marginal product of capital, leading to a larger decrease in capital, and consequently, an even larger fall in output.

Second, risk-aversion amplifies the effects of climate policy transition risk, resulting in an even larger decrease in output in the pre-tax steady state with climate policy transition risk. When entrepreneurs make investment decisions in the presence of transition risk, they must weigh their optimal action if the carbon tax is not implemented next period (i.e. relatively less clean capital) versus their optimal action if the tax is implemented the next period (i.e. relatively more clean capital). Risk aversion causes entrepreneurs to hedge against the outcome with the lowest utility, which corresponds to the government introducing the tax. Consequently, risk aversion pushes the economy even closer to the policy steady state, magnifying the compositional change in fossil-to-clean capital. This larger composition effect further distorts the mix of capital away from the allocation entrepreneurs would have chosen in the absence of risk, leading to an even more pronounced decrease in output from climate policy transition risk. Combined, the different timing of the labor and capital decisions and the risk-averse households imply that climate policy transition risk relies more heavily on the decrease in output to reduce emissions.

The above results highlight that climate policy risk reduces current and expected future emissions, implying that it could impact current and expected future climate damage. Adopting the view that climate damage reduces productivity implies that any change in climate damage as a result of climate policy transition risk could impact the investment response to that transition risk. In online appendix D.5, we augment our model with a reduced-form representation of the links between changes in emissions, damage, and productivity. We find that the impact of climate policy transition risk is effectively unchanged when we include these emissions-productivity effects. This is because a carbon tax, once adopted, will have an immediate impact on the returns to different investments. In contrast, it takes a longer time for the productivity impacts from the resulting emissions reductions to be large enough to meaningfully impact investment.

6.2. Implications for the costs delaying action on climate change

Our quantitative findings provide new insights surrounding the costs of delaying action on climate change. One interpretation of the results is that since climate policy transition risk reduces emissions, the environmental costs of delaying action on climate change are smaller than previously thought. However, that is only one side of the story. It is important to also consider the non-environmental welfare costs incurred by achieving the reductions in emissions from climate policy transition risk.

We measure the non-environmental welfare cost of climate policy transition risk as the negative of the consumption-equivalent variation (CEV) for the pre-tax steady state with transition risk.[26] The CEV for the pre-tax steady state with transition risk equals the percent change in consumption an agent would need in the pre-tax steady state without transition risk so that she is indifferent between living in either steady state. For comparison, we also calculate the CEV for the emissions-equivalent steady state. We find that the non-environmental welfare cost of the emissions reductions from climate policy transition risk is almost twice as large as the non-environmental welfare cost of the emissions reductions from an actual carbon tax. The CEV for the pre-tax steady state with transition risk is -0.13 while the CEV for the emissions-equivalent steady state is -0.07. This higher cost results from two factors. First, households are risk averse, implying that the uncertainty caused by the climate policy transition risk reduces welfare. Second, unlike the emissions-equivalent tax, climate policy transition risk does not induce the output and composition effects that achieve the most efficient emissions reductions. Rather, climate policy transition risk operates more heavily through reductions in output. Thus, while climate policy transition risk reduces emissions, it is a very costly way to achieve the emissions reduction.

It is also important to consider how climate policy risk affects the non-environmental welfare costs incurred by adopting a carbon tax. We measure the non-environmental welfare costs from adopting a carbon tax as the negative of the CEV over the transition. Specifically, we compare an economy in one of the pre-tax steady states (with or without climate policy transition risk) to an economy that undergoes the dynamic transition towards the eventual policy steady

[26]These CEV measures do not capture any welfare changes from the environmental benefits of lower emissions.

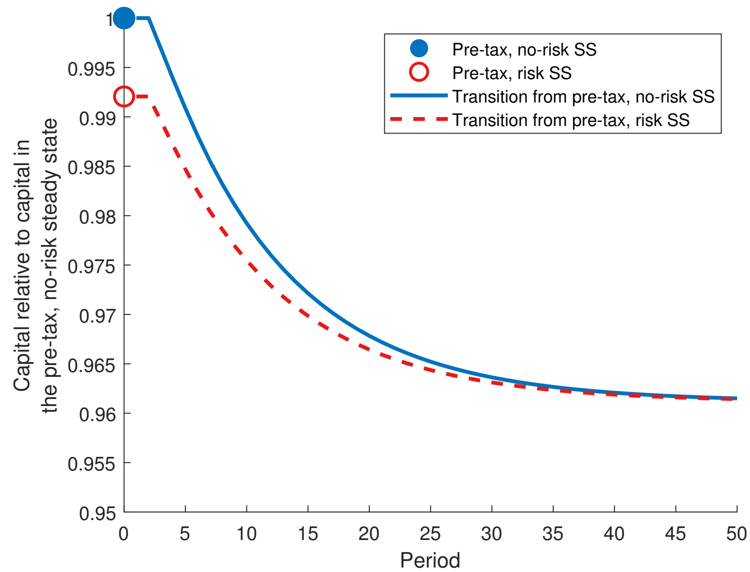
state. We find that climate policy transition risk has almost no effect on the non-environmental welfare cost incurred by adopting the carbon tax; the transitional CEV if the economy begins in the pre-tax steady state with climate policy transition risk equals −0.30 while the transitional CEV if the economy begins in the pre-tax steady state without transition risk equals −0.31.

This near equivalence in the transitional CEVs stems from three counteracting forces. First, climate policy transition risk implies that the economy is already part way to the policy steady state. Consequently, less adjustment is required over the transition when the economy begins in the pre-tax steady state with transition risk, reducing the non-environmental welfare cost of adopting the tax. Second, introducing the tax from the pre-tax steady state with transition risk eliminates the uncertainty caused by climate policy transition risk, further reducing the non-environmental welfare cost. However, the third factor works in the opposite direction. Figure 1 plots the time paths of the total capital stock over the transition from the pre-tax steady state without transition risk (solid blue line) and over the transition from the pre-tax steady state with transition risk (dashed red line). Climate policy transition risk reduces the pre-tax steady state level of the capital stock (the hollow red circle is below the solid blue circle). The lower initial level of capital implies that agents are less able to dis-save over the transition (the dashed red line falls less than the solid blue line), raising the non-environmental welfare cost when the economy begins in the steady state with transition risk. Ultimately, the benefits from being part-way to the policy steady state and eliminating the uncertainty almost perfectly offset the costs from the lower capital stock. This finding suggests that continuing to delay policy action and allowing agents to respond to climate policy transition risk will not reduce the non-environmental welfare cost after a carbon price is imposed.

The above discussion focuses on how climate policy risk affects the non-environmental welfare cost of introducing the policy today. In online appendix D.2, we explore how climate policy risk affects the non-environmental welfare cost when agents are in the pre-tax steady state with risk for up to ten years before the carbon tax is introduced. The welfare measure in this new experiment thus includes a period of time before the carbon tax is introduced when the economy is in the pre-tax steady state with risk, as well as the dynamic transition following the introduction of the tax. We find that a period of delay reduces the non-environmental welfare cost because the actual introduction of the carbon tax is costly. However, even when accounting for a period of delay, climate policy transition risk has almost no effect on the non-environmental welfare cost of adopting the carbon tax.[27]

[27] While our analysis abstracts from endogenous innovation, it is interesting to consider the interplay between climate policy risk, innovation, and the non-environmental welfare cost from adopting the carbon price. As discussed in Section 3, climate policy risk likely increases incentives for clean innovation relative to fossil. Consequently, when the carbon tax is eventually adopted, clean technology relative to fossil will be higher if agents anticipated the future tax than if they did not. The impact of this innovation response to climate policy risk on

Figure 1: Total Capital Stock Over the Transition



Note: We normalize the value of the capital stock in the pre-tax steady state with no climate policy transition risk to unity. Conditional on this normalization, the open and solid circles show the value of the capital stock in the pre-tax steady states with and without transition risk, respectively. The dashed and solid lines plot the time path of the capital stock over the transition to the policy steady state when the tax is introduced from the steady states with, and without transition risk, respectively.

6.3. Implications for the Green Paradox

Our analysis highlights that climate policy transition risk not only alters investment in capital that extracts or uses fossil fuels, but also in clean capital that substitutes for fossil fuels as well as in the much larger stock of non-energy capital. We find that these investment responses decrease the demand for fossil fuels, reducing carbon emissions today. While our analysis isolates the impacts of climate policy transition risk on the current demand for fossil fuels, the Green Paradox literature (e.g., Sinn (2008)) focuses instead on the potential impacts of transition risk on the current supply of fossil fuels. This literature argues that owners of fossil resources respond to the threat of a future climate policy by increasing the supply of fossil fuels today, leading to an increase in emissions today. To evaluate these competing predictions for the effects of climate policy transition risk on emissions, we extend our model to include a reduced-form supply-side response to climate policy transition risk. We find that even when we allow for a supply-side response that is consistent with recent evidence, the demand-side response dominates, and the net effect of climate policy transition risk is still to reduce emissions

the non-environmental welfare cost from adopting the carbon price depends on how it affects both the composition of capital and the level of output in the pre-tax steady state with risk. A higher ratio of clean to fossil technology increases the ratio of clean to fossil capital (see Section 3) but its implications for output are unclear. Consequently, it is not obvious how endogenous innovation would impact the effect of climate policy risk on the non-environmental welfare cost of adopting a carbon tax.

today.

To incorporate such a supply-side response in our quantitative model, we allow the fossil fuel price to vary inversely with the level of climate policy transition risk.[28] If climate policy transition risk is reduced to zero (i.e. there is no longer a threat of a future carbon tax), then our analysis demonstrates that the steady state demand for fossil fuels would increase. Moreover, as the Green Paradox literature argues, with no threat of a future carbon tax, the expected profitability of supplying fossil fuels in the future would no longer be depressed. Consequently, owners of fossil resources may reduce the supply of fossil fuels today, shifting supply into the future. Both the increase in the current demand for fossil fuels, and the potential decrease in the current supply of fossil fuels, could lead to a higher fossil fuel price in the pre-tax steady state once climate policy transition risk is removed. Therefore, to understand how climate policy transition risk affects investment in clean, fossil, and non-energy capital, we need to quantify how much higher current fossil fuel prices would be in the absence of climate policy transition risk.

To do so, we use two pieces of information from the literature. First, Lemoine (2017) provides an estimate of how coal futures prices responded to the collapse of support for a proposed federal climate policy, the American Power Act, in the U.S. Senate in April, 2010. Focusing on the weeks immediately surrounding the collapse, Lemoine (2017) finds that the 1-year future price of coal increased by 1 percent.

Second, the analysis of prediction market prices from Meng (2017) suggests that the collapse of Senate support studied by Lemoine (2017) effectively reduced the *three*-year probability of the climate policy by 10 percentage points, from 0.3 to 0.2. In particular, The American Power Act would have established a cap-and-trade system for the US economy in 2013, three years after it was debated in the U.S. Senate. Thus, from Lemoine (2017) and Meng (2017), we infer that a 10 percentage point decrease in the three-year probability of a carbon price increases fossil fuel prices by 1 percent.[29] Turning to our model, our calibrated value of the annual probability of 0.13 corresponds to a three-year probability of 0.34. The above evidence

[28]Fully capturing how the supply of fossil fuels could shift over time in response to climate policy transition risk would require modeling not only the dynamic extraction decision across multiple fuels, but also the costly exploration process required to identify reserves of each fuel type. Such an endeavor is beyond the scope of our analysis.

[29]We assume that the estimated one percent increase in the coal price applies to the price of all fossil fuels. This assumption is obviously not perfect given that coal is only one of the fossil fuels that would potentially be affected. However, there are reasons to believe that this may serve as a reasonable upper bound on the impact of transition risk on the other key fossil fuels. Unlike coal, natural gas would not obviously be negatively affected in the medium run from the introduction of a climate policy because a carbon price would cause a sizable short-run shift away from coal towards natural gas. Therefore, we may not expect to see natural gas prices move as much as coal prices in response to a change in the probability of future climate policy. Moreover, unlike coal, which has region-specific prices, oil is traded in a world market. Consequently, we may expect the world price of oil to be less responsive to changes in the probability of U.S. climate policy.

implies that reducing this three-year probability to zero, its value in the pre-tax steady state without transition risk, would increase fossil fuel prices by 3.4 percent.

To quantify the effects climate policy transition risk with a supply-side response, we consider an alternative pre-tax steady state without transition risk in which the fossil fuel price is 3.4 percent higher than in the pre-tax steady state with transition risk. We compare outcomes from the pre-tax steady state with transition risk to this higher-price pre-tax steady state without transition risk. Again, by inflating the fossil fuel price, the higher-price pre-tax steady state accounts for the fact that eliminating the threat of a future climate policy could cause resource owners to shift fossil fuel supply to future periods, pushing today's price up.

Even after accounting for this supply-side response, we find that climate policy transition risk still reduces emissions today. Like before, this emissions reduction occurs because climate policy transition risk depresses output and shifts the composition of the capital stock towards cleaner capital. Given that the fossil fuel price now falls with the introduction of climate policy transition risk, the incentives to dis-invest in fossil capital and invest in clean capital are slightly muted. Consequently, climate policy transition risk leads to a smaller reduction in emissions than in our main analysis, 0.99 percent instead of the original 2.12 percent. In order for the Green Paradox effect to dominate and cause climate policy transition risk to increase emissions would require that the supply-side response be almost twice as large as the evidence from Lemoine (2017) and Meng (2017) suggests. Thus, even if there is a supply-side response to climate policy transition risk, the net effect of climate policy transition risk accounting for supply and demand factors is still to reduce emissions today. These results highlight the importance of not focusing exclusively on how climate policy transition risk may affect fossil fuel supply decisions, but more generally on understanding how transition risk affects investment decisions across a wide range of capital assets.

7. Extensions and sensitivity

We examine how our main results vary over different carbon tax specifications and over a range of different probabilities of a future carbon tax. Additionally, we consider an extension of our model in which we analyze the implications of climate policy transition risk in an economy with two types of fossil capital: a fossil capital with high carbon intensity that is specialized for coal and a fossil capital with low carbon intensity that is specialized for oil and natural gas.

7.1. Alternative carbon tax specifications

Table 5: Alternative Tax Specifications

	Baseline	Tax repealed after				Growing
		1 yr	2 yrs	4 yrs	8 yrs	tax
Aggregates						
Fossil fuel: F	-2.12	-1.44	-1.72	-1.97	-2.05	-2.15
Output: Y	-0.34	-0.10	-0.15	-0.21	-0.27	-0.35
Consumption: C	-0.13	-0.02	-0.04	-0.07	-0.10	-0.13
Total capital: K	-0.79	-0.13	-0.25	-0.40	-0.57	-0.80
Total labor: L	-0.00	0.00	0.00	0.00	-0.00	-0.00
Composition						
Capital: K^f/K^c	-8.86	-6.62	-7.79	-8.72	-8.86	-8.99
Labor: L^f/L^c	-3.08	-2.40	-2.76	-3.04	-3.08	-3.12
Inputs: X^f/X^c	-5.03	-3.82	-4.45	-4.95	-5.03	-5.10

Note: This table reports the percentage changes in outcomes in the pre-tax steady state with transition risk relative to the pre-tax steady state without transition risk in (1) the baseline model and when we re-calibrate the model (2)-(5) assuming that the carbon tax is repealed after one, two, four, or eight years and (6) assuming a carbon tax that grows at 1.7 percent per year.

Thus far, we have assumed that, once adopted, a carbon tax would be permanent and constant. We examine the sensitivity of the results to both of these assumptions. To begin, we examine how the effects of climate policy transition risk change if the carbon tax does not remain in place forever. We re-calibrate our model assuming that firms know that once the tax is adopted it will be permanently repealed after a given number of years.[30] Columns 2-5 of Table 5 display how transition risk affects the pre-tax steady state outcomes if firms know the carbon tax would be repealed one, two, four, or eight years after its adoption. Intuitively, the possibility of a carbon tax being adopted has somewhat more muted effects on investment and output when the policy is known to be temporary, leading to slightly smaller emissions reductions from climate policy transition risk. However, even the risk of a carbon tax that only lasts a single year still reduces emissions by 1.44 percent.

The reason that the probability of a short-lived tax still leads to substantial emissions reductions in the pre-tax steady state is because the initial period immediately following the introduction of the tax is the most costly for entrepreneurs. In the initial period, entrepreneurs must use the capital that they chose in the prior period, the pre-tax steady state with risk. After

[30] In practice, if the tax is adopted, firms do not know with certainty that it will be repealed, and, if it is repealed, there will again be a chance that it would be adopted in the future. However, by modeling the tax policy as having a known and permanent termination following its adoption, this experiment bounds how much smaller the impacts of transition risk would be if there is a chance of repeal.

the initial period, entrepreneurs know the carbon tax is in place and can adjust their investment in response, reducing the costs of the carbon tax in later periods. Thus, a large part of the economy's response to climate policy transition risk is driven by the near-term effects once the tax is introduced.

In addition to slightly muting the impact of climate policy risk, the longevity of the tax also effects the relative importance of the composition and output channels. In particular, the output effect is notably smaller when the policy only lasts a single year, implying that the emissions reduction primarily results from the composition channel. The intuition stems from the fact that climate policy risk reduces investment because the introduction of the carbon tax decreases the average return to capital over its entire lifetime. If the carbon tax is known to be repealed after a single year, then its introduction has a smaller effect on the lifetime return to capital. Consequently, investment, and hence output, fall by less when the carbon tax is known to be short-lived.

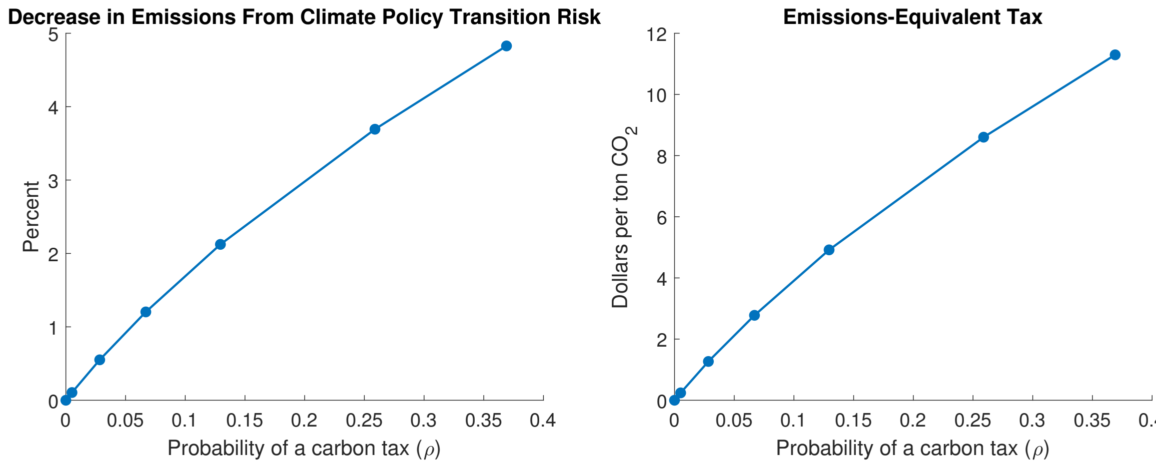
Next, we study how the effects of climate policy transition risk change when the carbon tax becomes more stringent over time. We assume that the carbon tax is set at $51/ton in the initial period and grows at a constant rate of 1.7 percent to $85/ton in 30 years, in line with the interim estimates for the time path of the social cost of carbon from the Biden administration (IWG, 2021), and continues growing at the same constant rate thereafter. The last column of Table 5 reports the results if the carbon tax, once implemented, grows over time. The possibility of a growing carbon tax is a more stringent climate policy, leading to a slightly larger reduction in emissions than in our baseline results (-2.15 compared to -2.12 percent). This result echoes our findings for a temporary tax; a change in the policy after the initial period has relatively small quantitative effects on the pre-tax steady state with risk.

Overall, we find that the majority the impact of climate policy transition risk on the macroeconomy stems from the initial period after the tax is introduced, when entrepreneurs must produce with the capital they choose before the tax was implemented. Even so, changes in the longevity and time path of the carbon tax do have small effects on the macro response to climate policy transition risk. However, we continue to see the same mechanisms at work. The possibility of a carbon tax that takes any of the forms in Table 5 reduces output and shifts the economy towards clean capital, decreasing emissions.

7.2. Changes in climate policy transition risk

The subjective probability of a climate policy being adopted could increase in the future as climate change progresses. To understand the macro implications of future changes in the carbon tax probability, we explore how our results differ across a range of assumed probabilities of a future carbon tax. We consider probabilities that the government introduces a carbon tax

Figure 2: Effects of Changes in the Carbon Tax Probability



Note: For each carbon tax probability, the left panel plots the emissions reductions in the pre-tax steady state with climate policy transition risk relative to the pre-tax steady state without climate policy transition risk. The right panel displays the corresponding carbon tax that would achieve the same steady state emissions reductions as the climate-policy-transition-risk outcome.

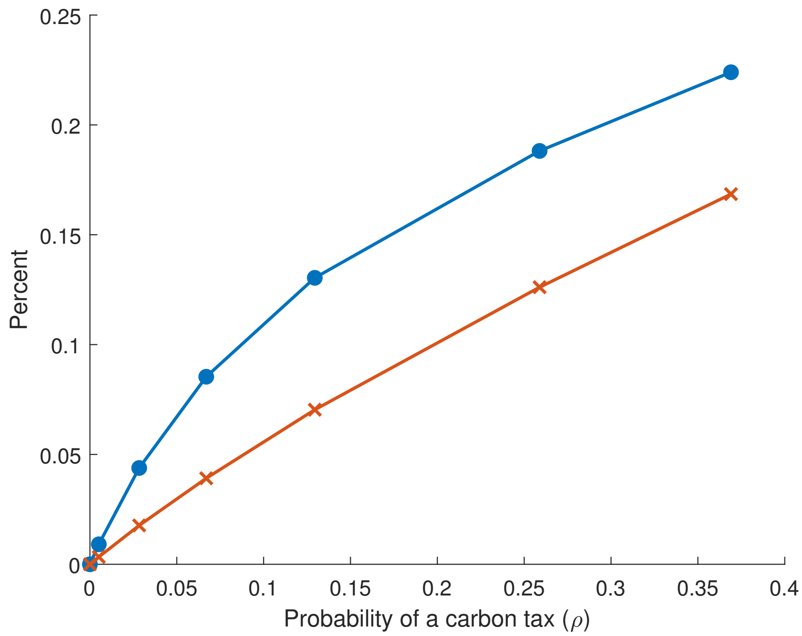
within 10 years ranging from 5 to 99 percent, corresponding to the annual probability in our model, ρ, ranging from 0.5 to 37 percent.

A related exercise is to understand the sensitivity of our results with regards to the carbon tax probability that firms use today. This exercise requires us to re-calibrate our model for different values of the carbon-tax probability. We report the results from this related exercise in online appendix D.3. Ultimately, the effects of changes in the probability on our main results are similar regardless of whether we re-calibrate the model or not.

The left panel of Figure 2 plots the emissions reductions in the pre-tax steady state with transition risk for different carbon tax probabilities. All else constant, increases in the probability of the carbon tax decrease the expected return to fossil capital, leading to larger reductions in emissions. The right panel of Figure 2 displays the corresponding carbon tax that would achieve the same steady state emissions reductions as the climate-policy-transition-risk outcome. As the probability of a future carbon tax increases, the emissions-equivalent tax grows. As in our main analysis, the emissions-equivalent tax is always less than the expected value of the tax, $\rho \times \$51$.

We also explore the non-environmental welfare impacts of climate policy transition risk across the different implied probabilities of a carbon tax. Figure 3 compares the non-environmental welfare cost (measured as the negative of the CEV) for the climate-policy-transition-risk and emissions-equivalent steady states, relative to the pre-tax steady state with no climate pol-

Figure 3: Non-Environmental Welfare Cost of Climate Policy Transition Risk and the Emissions-Equivalent Tax



Note: The blue line with circle markers plots the non-environmental welfare cost of climate policy transition risk, measured in terms of the negative of the CEV, for each value of the carbon-tax probability on the x-axis. The orange line with cross markers plots the non-environmental welfare cost for the carbon tax that achieves the same emissions reductions as climate policy transition risk with probability equal to the value on the x-axis.

icy transition risk.[31] Again, the non-environmental welfare costs incurred are lower if the emissions reductions are achieved using a carbon tax instead of climate policy transition risk. Importantly, the gap between the non-environmental welfare costs of climate policy transition risk versus the emissions-equivalent tax does not diminish as the likelihood of a future tax policy increases, implying that climate policy transition risk remains a very costly way to reduce emissions.

Additionally, we examine how the probability of a future carbon tax affects the transitional welfare cost from adopting a carbon tax. We find that while increases in the likelihood of a carbon tax do reduce the cost of actually adopting the tax, the effect is small. In particular, as the probability of a carbon tax increases, the transitional welfare cost of adopting the carbon tax falls monotonically, from 0.31 when there is a 5 percent chance of adopting a carbon tax in the next 10 years to to 0.28 when there is a 99 percent chance. We extend these results in online appendix D.4, and consider how the probability of a carbon tax affects the transitional welfare cost when the economy is in the pre-tax steady state with risk for up to ten years before the tax is adopted. We find that the transitional welfare cost of adopting the carbon tax falls

[31] For a given value of ρ, the emissions are identical across the pre-tax and emissions-equivalent steady states. In contrast, as ρ increases, the reduction in emissions grows.

slightly as the probability rises, regardless of the period of delay.

7.3. Sensitivity to the Elasticity of Substitution Between Clean and Fossil Intermediates

Table 6: Alternative Elasticities of Substitution Between Clean and Fossil Intermediates

	Elasticity of Substitution: ε				
	1.25	1.5	3	5	10
Aggregates					
Fossil fuel: F	-0.84	-0.98	-2.12	-4.21	-10.65
Output: Y	-0.35	-0.34	-0.34	-0.38	-0.64
Consumption: C	-0.16	-0.15	-0.13	-0.11	-0.11
Total capital: K	-0.98	-0.95	-0.79	-0.63	-0.43
Total labor: L	-0.00	-0.00	-0.00	0.00	0.02
Composition					
Capital: K^f/K^c	-3.13	-3.82	-8.86	-16.85	-38.75
Labor: L^f/L^c	-0.05	-0.31	-3.08	-9.03	-29.22
Inputs: X^f/X^c	-1.07	-1.48	-5.03	-11.69	-32.52

Note: This table reports the percentage changes in outcomes in the pre-tax steady state with transition risk relative to the pre-tax steady state without transition risk for different values of the elasticity of substitution between the clean and fossil intermediates, ε. $\varepsilon = 3$ is the baseline specification.

The quantitative impact of climate policy risk on the macroeconomy depends critically on the elasticity of substitution between the fossil and clean intermediates. We re-compute our main results from Table 4 over a range of substitution elasticities between 1.25 and 10, spanning the empirical estimates from Papageorgiou et al. (2017) and the values used in recent macro studies (see e.g. Acemoglu et al., 2012; Hart, 2019; Acemoglu et al., 2019; Lemoine, forthcoming). For each value of the substitution elasticity, we re-calibrate the model to match the empirical targets from Section 5. Table 6 reports the results. The impact of climate policy risk on the macroeconomy increases considerably with the elasticity of substitution. However, the same mechanisms are always at play. For all values of the elasticity of substitution in Table 6, climate policy risk reduces output and shifts the economy towards cleaner capital.

7.4. Multiple types of fossil capital

In our main specification, fossil capital includes capital specialized to use coal, oil, and natural gas. However, climate policy risk could affect the composition of this fossil capital by shifting the economy towards lower-carbon fossil fuels, in much the same way that it shifted the economy towards clean energy in our main analysis. To explore this possibility, we extend our baseline model to include two types of fossil capital: (1) a coal capital that is specialized to use fossil fuels with a higher carbon content (e.g., coal), k^h, and (2) a gas capital that is specialized to use fossil fuels with a lower carbon content, (e.g, oil and natural gas), k^l.

Paralleling the specification in our main analysis, production of the coal and gas intermediates equals:

$$x^h = \min[A^h(k^h)^\alpha(l^h)^{1-\alpha}, \mu f^h] \quad \text{and} \quad x^l = \min[A^l(k^l)^\alpha(l^l)^{1-\alpha}, \mu f^l].$$

Variables l^h and l^l denote labor hired by entrepreneurs in the coal and gas sectors, respectively parameters A^h and A^l denote total factor productivity in each sector. We assume that coal, f^h, and gas, f^l, are produced from units of final good with constant marginal costs, ζ^h and ζ^l, respectively. The laws of motion for coal and gas capital mirror those for clean, fossil, and non-energy capital from our main specification. The fossil intermediate, x^f, equals a CES aggregate of the coal and gas intermediates,

$$x^f = \left((x^h)^{\frac{\psi-1}{\psi}} + (x^l)^{\frac{\psi-1}{\psi}}\right)^{\frac{\psi}{\psi-1}},$$

with elasticity of substitution ψ. The remainder of the model is identical to our main specification.

We calibrate the model to match the same moments in our main specification plus the fraction of fossil energy consumption from coal, which averages 0.17 over 2015-2019 (EIA Table 1.3). This additional moment allows us to discipline the difference between the coal and gas technology parameters, A^h, and A^l. We normalize the marginal extraction cost of gas, ζ^l, to unity. The marginal extraction cost of coal, ζ^h, equals 0.27, the ratio of the coal price per BTU (EIA Table ES-4) relative to an oil-gas composite price per BTU in 2019.[32] As in the main specification, we analyze a potential carbon tax of \$51/ton. This tax equals 181 percent of the 2019 coal price per BTU and 51 percent of the oil and gas composite price per BTU, where the difference stems from variation in fuel prices and carbon contents. We set the tax on coal, τ^h, equal to $2.81 \times \zeta^h = 0.76$ and the tax on gas, $\tau^l = 0.51 \times \zeta^l = 0.51$. Taking the view that it is easier to substitute within fossil inputs than between fossil and clean, we consider two values for the elasticity of substitution between the coal and gas intermediates, ψ, equal to 5 and 10, which are larger than the elasticity of substitution between fossil and clean, $\varepsilon = 3$.

Table 7 reports the effects of climate policy risk in our baseline model (column 1) and in the extended model that includes multiple types of capital (columns 2 and 3). The effects of climate policy risk are broadly similar between the baseline model and the multi-fossil capi-

[32]To calculate the price of the oil and gas composite, we take the weighted average of the price oil (EIA Table 9.1) and natural gas (EIA Table 3.5) with the weights equal to the relative shares of oil and gas primary energy consumption (EIA Table 1.3).

tal extension; for example, climate policy risk reduces total emissions by 2.12 percent in the baseline model and by between 2.24 and 2.75 percent in the extension.

Table 7: Multiple Types of Fossil Capital

	Baseline	Extension	
	model	$\psi = 5$	$\psi = 10$
Aggregates			
Total emissions	-2.12	-2.24	-2.75
High-carbon fossil fuel emissions	-	-3.30	-10.95
Low-carbon fossil fuel emissions	-	-1.91	0.10
Output: Y	-0.34	-0.34	-0.29
Consumption: C	-0.13	-0.13	-0.14
Total capital: K	-0.79	-0.81	-0.81
Total labor: L	-0.00	-0.00	-0.00
Composition			
Capital: K^f/K^c	-8.86	-9.39	-10.23
Fossil capital: K^h/K^l	-	-1.35	-12.82
Labor: L^f/L^c	-3.08	-3.33	-4.00
Fossil labor: L^h/L^l	-	-1.46	-10.15

Note: This table reports the percentage changes in outcomes in the pre-tax steady state with transition risk relative to the pre-tax steady state without transition risk in (1) the baseline model and when we extend the model to include coal and gas capitals with (2) substitution elasticity $\psi = 5$ and (3) substitution elasticity $\psi = 10$.

Separating fossil capital into coal and gas capital allows us to explore how climate policy risk affects the composition of fossil capital. In particular, climate policy risk causes agents to substitute gas for coal capital, leading to declines in the ratios of coal-to-gas capital and labor. If coal and gas capital are very substitutable (e.g, $\psi = 10$), this shift occurs to such an extent that climate policy risk actually increases production of the gas intermediate, causing low-carbon fossil fuel emissions to rise (third row of Table 7). Even so, the total emissions reduction from climate policy risk when coal and gas capital are very substitutable (e.g, $\psi = 10$) is larger than when they are less substitutable (e.g., $\psi = 5$). The result that climate policy risk could increase emissions from gas capital is broadly consistent with the notion that natural gas could serve as a “bridge fuel” to a zero carbon economy.

8. Conclusion

While the U.S. does not have a federal climate policy, there is ample anecdotal evidence that firms are altering their current investment decisions in response to the possibility that a climate policy could be adopted in the future. In this paper, we introduce a general equilibrium model of the U.S. economy that incorporates beliefs surrounding the likelihood of a future carbon price. We use the model to study how climate policy transition risk affects emissions, the macroeconomy, and our understanding of the costs of delayed action on climate change.

We find that if firms believe there is a 75 percent chance of a carbon price being adopted in the next decade, a belief in line with anecdotal evidence, then their responses to this transition risk have reduced U.S. emissions by the same amount that would have occurred had the U.S. adopted a federal tax of \$4.91/ton of CO_2. This decrease in emissions occurs because climate policy transition risk shifts the economy towards cleaner production and reduces output.

While the response to climate policy transition risk has caused a modest reduction in emissions, we find that this represents only a small fraction of the reduction that would be achieved by adopting the carbon price. Moreover, the emissions reductions due to climate policy transition risk come at a relatively high cost. For one, the steady state non-environmental welfare cost incurred by the response to climate policy transition risk is over twice as large as the steady state non-environmental welfare cost with the emissions-equivalent tax of \$4.91/ton of CO_2. In addition, because climate policy transition risk decreases the aggregate capital stock, there is almost no reduction in the non-environmental welfare costs incurred over the transition once a carbon price is adopted, despite the fact that the economy has already moved part of the way towards the steady state with a carbon tax in place. Finally, the overall impact of climate policy transition risk on investment, emissions, and welfare increases with the likelihood of the policy. Thus, understanding the effects of climate policy transition risk could become even more important in the future, if agents' perceived probability of climate policy increases as climate change progresses.

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