Climate Policy Transition Risk and the Macroeconomy

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Abstract

Uncertainty surrounding if the U.S. will implement a federal climate policy introduces risk into the decision to invest in capital used in conjunction with fossil fuels. To quantify the macroeconomic impacts of this climate policy transition risk, we develop a dynamic, general equilibrium model that incorporates beliefs about future climate policy. We find that climate policy transition risk lowers carbon emissions today by causing investment to fall and become relatively cleaner. This emissions reduction 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.

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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 level and composition of capital, 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 study the effects of climate policy transition risk, we analyze an equilibrium of a multi-sector, neoclassical growth model in which there is no carbon tax, but there is a positive probability that a carbon tax will be introduced in the next period. 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), a clean capital that is specialized to substitute for fossil capital or fossil fuel (e.g., a solar panel or a regenerative breaking system), and a non-energy capital that is not specialized to use or to replace fossil fuel (e.g., an office building). Once the tax is imposed, all uncertainty is resolved and the economy transitions to a new steady state with the tax in place. We capture the impacts of climate policy transition risk by comparing the pre-tax equilibrium in which agents internalize transition risk to a counterfactual pre-tax equilibrium without transition risk – i.e. an equilibrium in which there is no tax and agents assume there is zero probability of a future carbon tax.

Starting with a simple, dynamic model focusing solely on clean and fossil capital investment, we analytically highlight two key channels through which climate policy transition risk

[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 are currently considering 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/).

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, by distorting the composition of capital away from the privately optimal baseline outcome, climate policy transition risk reduces the expected marginal product of all capital. As a result, the total capital stock is smaller, further reducing both output and emissions.

To quantify the macroeconomic impacts of climate policy transition risk, we move beyond the simple, analytic setting and develop a richer general equilibrium model that adds risk-averse households, a non-energy capital, and partially-irreversible investment. Intuitively, risk-aversion amplifies the impacts of climate policy transition risk because it causes agents to hedge against the potential future carbon price by further directing investments towards clean assets. Non-energy capital accounts for the fact that capital not specialized to use or replace fossil fuel may still be affected by climate policy transition risk through the resulting general equilibrium impacts. Finally, partially-irreversible investment captures the potential losses from selling capital after the introduction of the carbon tax.[2]

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 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

[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.

decrease in the ratio of fossil to clean capital. This composition effect is responsible for almost 90 percent of the decline in emissions caused by climate policy transition risk. Second, climate policy transition risk reduces the expected marginal product of capital, leading to a 0.79 percent decrease in the total capital stock. This level effect is largely responsible for the remaining emissions reduction.

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, aggregate capital 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. 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.

We extend our model to study the interaction between climate policy transition risk and climate damage. Since climate policy transition risk reduces current and expected future emissions, it impacts 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. To explore these interactions, 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 have meaningful impacts on investment.

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 overall investment, 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.

More generally, our analysis 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. Given the dominant role that fossil fuels play in the production of goods and services, uncertainty surrounding future policies regulating carbon emissions may have similar, far reaching impacts across the macroeconomy. Thus far, however, the literature exploring the impacts of environmental policy uncertainty largely has focused on partial equilibrium impacts or on the effects within specific sectors.[3] For example, Xepapadeas (2001) and Pommeret and Schubert (2017)

[3] 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

consider the partial equilibrium impacts of environmental policy uncertainty on the investment and location decisions of affected firms while Barnett (2020a,b) examines how uncertainty surrounding future climate policy adoption affects oil market dynamics and asset prices.

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. 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.[4] 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 current U.S. economy. Section 7 extends the model to analyze the interactions with fossil fuel supply and climate damage. 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 if agents believe that the government will implement a climate policy at some unknown point in the future, then this belief can meaningfully alter 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 –

Traeger (2014)).

[4]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.

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.[5] 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.[6]

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. 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. 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 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.[7] 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

[5] 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.

[6] 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)"

[7] 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.

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 less stringent proposed by the Trump administration (Holden, 2019). Transportation is responsible for 29 percent of U.S. carbon emissions, and thus the fuel economy standards represent an important form of climate policy. Reportedly, "the companies are worried about years of regulatory uncertainty that could end with judges deciding against Trump" and implementing the stricter standards.[8]

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).[9] 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 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 aggregate 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

[8] 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).

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

of the economy, taking the interest rate and labor supply as exogenous, and abstract from investment frictions. In Section 4, we add the household and solve for the general equilibrium.

Environment. The economy is comprised of infinitely-lived entrepreneurs and workers. 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 final-good production function is a Cobb-Douglas aggregate of the two intermediate inputs and labor: $y = (x^c)^\gamma (x^f)^\theta l^{1-\gamma-\theta}$. Parameters γ and θ denote the factor shares of the clean and fossil intermediates, respectively. We normalize total labor supply to unity. The final good is the numeraire.

The clean intermediate is produced competitively from clean capital, k^c, according to the linear production function, $x^c = k^c$. The fossil intermediate is produced competitively from fossil capital, k^f, and fossil fuel, f, according to the Leontief production function, $x^f = \min[k^f, f]$. 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.

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 any capital that preforms the same function as the fossil capital, but does not use fossil fuel. Examples include capital used to produce electricity from non-fossil sources, such as a wind turbine or a nuclear reactor, and capital that increases energy efficiency, such as regenerative brakes in hybrid vehicles.

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.

The pre-tax steady state. We study a steady state designed to reflect the climate policy transition risk described in Section 2. In this steady state, there is no carbon tax, but each entrepreneur expects that the government will introduce a carbon tax, τ, with probability, ρ, next period. Importantly, in our model of transition risk, the realization of the carbon tax is an absorbing state. Once the government introduces the tax, all uncertainty is resolved and there is zero probability of returning back to the world without the carbon tax. Of course, it is always possible that the carbon tax, once introduced, could be repealed, in which case the introduction of a carbon tax would not be an absorbing state. In our subsequent quantitative analysis, we relax this assumption and show that the possibility of a carbon tax being repealed has relatively small effects on the impact of climate policy transition risk on the macroeconomy.

We focus on the steady state outcome prior to the economy transitioning to the absorbing state with the carbon tax in place. In this "pre-tax" steady state, aggregate variables are constant because the realization of the aggregate shock, the adoption of a tax, has not occurred. As discussed in Section 2, such an equilibrium is well-suited to describe the U.S. economy; while there currently is no federal carbon price, firms' actions indicate that they expect the government to introduce a climate policy in the future.

The representative final-good entrepreneur chooses the clean and fossil intermediates and labor to maximize profits, taking prices as given. The entrepreneur makes all decisions at the start of the period, after she learns if the government introduced the climate policy. The first order conditions imply the following expressions for the prices of the clean and fossil intermediates, p^c and p^f, respectively:

$$p^c = \gamma(x^c)^{\gamma-1}(x^f)^{\theta} \quad \text{and} \quad p^f = \theta(x^c)^{\gamma}(x^f)^{\theta-1}. \tag{1}$$

The representative clean entrepreneur chooses investment in next period's level of clean capital to maximize the expected present discounted value of future profits. Since capital levels are fixed in the short run, she makes her investment decision before she learns whether the government will introduce the tax next period, implying that her expectations of future climate policy affect her current investment. Let $V^c(k^c)$ denote the clean entrepreneur's value function in the pre-tax steady state, and $W_t^c(k^c)$ denote her value function in period t of the transition after the government introduces the carbon tax. The clean entrepreneur's value function in the pre-tax steady state equals:

$$V^c(k^c) = \max_{k^{c\prime}} \left\{ p^c k^c - i^c + \left(\frac{1}{1+r}\right)[\rho W_1^c(k^{c\prime}) + (1-\rho)V^c(k^{c\prime})] \right\}, \tag{2}$$

subject to the law of motion for clean capital: $k^{c\prime} = (1-\delta)k^c + i^c$.

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 entrepreneur's flow profits, $p^c k^c - i^c$, equal the total revenue from production, $p^c k^c$, minus investment expenses, i^c. The continuation value in equation (2) 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 pre-tax steady state, $V^c(k^{c\prime})$. 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.

The clean entrepreneur's value function in period t of the transition equals:

$$W_t^c(k^c) = \max_{k^{c\prime}} \left\{ p^c k^c - i^c + \left(\frac{1}{1+r}\right) W_{t+1}^c(k^{c\prime}) \right\}, \tag{3}$$

subject to the law of motion for clean capital. 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 investment in next period's level of fossil capital to maximize the expected, present-discounted value of future profits. Like the clean entrepreneur, she chooses investment before she learns whether the government will introduce the tax next period. Using notation parallel to that for the clean entrepreneur, the fossil entrepreneur's value function in the pre-tax steady state equals:

$$V^f(k^f) = \max_{k^{f\prime}, f} \left\{ p^f k^f - \zeta f - i^f + \left(\frac{1}{1+r}\right) [\rho W_1^f(k^{f\prime}) + (1-\rho) V^f((k^f)')] \right\}, \tag{4}$$

subject to the law of motion for fossil capital: $k^{f\prime} = (1-\delta)k^f + i^f$, and 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, $p^f k^f - \zeta f - i^f$, equal her total revenue, $p^f k^f$, minus her expenses on fossil fuel, ζf, and minus investment, i^f. Since there is no carbon tax in the pre-tax steady state, the entrepreneur only pays the extraction cost, ζ, for each unit of fossil fuel.

The value function for the fossil entrepreneur in period t of the transition equals:

$$W_t^f(k^f) = \max_{k^{f\prime}, f} \left\{ p^f k^f - (\zeta + \tau) f - i^f + \left(\frac{1}{1+r}\right) W_{t+1}^f(k^{f\prime}) \right\}, \tag{5}$$

subject to the law of motion for fossil capital and 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.

Ultimately, we are interested in understanding how the steady state outcome, prior to the adoption of a carbon tax, differs as a function of ρ, the probability of a carbon tax being adopted in the next period. We focus on comparing the pre-tax steady with climate policy transition risk (i.e. $0 < \rho < 1$) to a pre-tax steady state without climate policy transition risk (i.e. $\rho = 0$). Generally, we define a *pre-tax steady state* for this economy as a set of prices for the clean and fossil intermediates and for labor $\{p^c, p^f, w\}$, allocations for the clean and fossil entrepreneurs, $\{k^c, k^f, f\}$, and allocations for the final good entrepreneur, $\{x^c, x^f, l\}$, such that given an exogenous interest rate, r, and a probability, ρ, of a carbon tax, τ, next period, the following conditions hold:

1. Given prices, the final-good entrepreneur chooses clean and fossil intermediates and labor to maximize profits.
2. Given prices, the clean and fossil entrepreneurs solve the expected-profit maximization problems described by the value functions in equations (2) and (4).
3. The markets for labor and the clean and fossil intermediate inputs clear.
4. Prices and allocations are constant from one period to the next.

The aggregate effects of climate policy transition risk. Solving for the pre-tax steady state, 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. Second, it reduces to the total level of the capital stock. Focusing first on the composition channel, the ratio of fossil to clean capital in the pre-tax steady state equals:

$$\frac{K^f}{K^c} = \left(\frac{\theta}{\gamma}\right)\left(\frac{r+\delta}{r+\delta+\zeta+\rho\tau}\right), \tag{6}$$

where uppercase letters denote aggregate quantities.[10] 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 simply equals the ratio of the factor shares, θ/γ. A positive price of fossil fuel, $\zeta > 0$, raises the operating costs 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 to the second channel, the reduction in the level of capital from climate policy transition risk, the levels of clean and fossil capital in the pre-tax steady state equal:

$$K^c = \left(\frac{\gamma}{r+\delta}\right)^{\frac{1}{1-\gamma-\theta}}\left(\frac{r+\delta}{r+\delta+\zeta+\rho\tau}\right)^{\frac{\theta}{1-\gamma-\theta}}\left(\frac{\theta}{\gamma}\right)^{\frac{\theta}{1-\gamma-\theta}} \quad \text{and} \tag{7}$$

$$K^f = \left(\frac{\gamma}{r+\delta}\right)^{\frac{1}{1-\gamma-\theta}}\left(\frac{r+\delta}{r+\delta+\zeta+\rho\tau}\right)^{\frac{1-\gamma}{1-\gamma-\theta}}\left(\frac{\theta}{\gamma}\right)^{\frac{1-\gamma}{1-\gamma-\theta}}. \tag{8}$$

[10] See Appendix A for the derivation. We assume that $\tau < (r+\delta)/(1-\rho)$ to ensure an equilibrium exists.

The expressions for K^c and K^f are both decreasing in the probability, ρ, and the size of the carbon tax, τ, implying that climate policy transition risk reduces the levels of both clean and fossil capital, leading to a fall in the aggregate capital stock. The actual introduction of the carbon tax reduces the marginal product of capital because it shifts the economy away from the privately optimal allocations of capital, labor, and fossil fuel. By introducing the possibility of a carbon tax, climate policy transition risk reduces the expected marginal product of capital, causing total capital to fall. The fall in total capital is exacerbated by the fact that the transition risk itself also moves the ratio of fossil to clean capital (equation (6)) away from the privately optimal outcome in the baseline, further reducing the expected marginal product of capital.

Like climate policy transition risk, a carbon tax would operate through the same 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 level of capital would still be defined by equations (6)-(8). However, 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 level and composition of capital, 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, it is important to reemphasize the analytical 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 and level of capital and consequently reduce 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 analytical model in several ways, but leave the fundamental intuition for the level and composition effects unchanged. First, we model the household-side of the economy with risk-averse agents. 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 include non-energy capital since much of the U.S. capital stock is not directly related to 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.

Production. We model the allocation of labor across the different intermediate sectors. Unlike capital, each entrepreneur hires labor after the realization of the tax. 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 analytical 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. Parameter α denotes capital's share, and parameters A^c and A^f denote total factor productivity in clean and fossil production. Leontief parameter μ determines fossil energy's share of fossil-intermediate production.

The majority of capital used in most production processes is not directly related to energy. 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. We classify this type of capital as non-energy, since it is not specialized to use fossil fuel or to replace fossil fuel.[11] The law of motion for non-energy capital is symmetric to that for fossil and clean capital: $k^{n\prime} = (1-\delta)k^n + i^n$, where i^n denotes investment in non-energy capital.

To incorporate 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 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.

[11] 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.

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

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.

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 disutility from hours, and parameter θ is the Frisch elasticity of labor supply.

The pre-tax steady state. The workers and the clean, fossil, non-energy, and final-good entrepreneurs in each representative household make decisions to maximize the household's expected present discounted value of lifetime utility, taking prices as given. The representative final-good entrepreneur chooses the clean, fossil, and non-energy intermediates. Like in the analytic model, the final-good entrepreneur makes all decisions at the start of the period, after she learns if the government introduced a carbon tax. Since the final-good entrepreneur simply maximizes flow demands for the intermediate inputs within a time period, her optimization problem is equivalent to a static profit-maximization problem. 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 focus instead on the dynamic decisions made by clean, fossil, and non-energy entrepreneurs under climate policy transition risk.

The representative clean entrepreneur chooses clean capital investment and clean labor demand, the representative fossil entrepreneur chooses fossil capital investment, fossil labor demand, and fossil fuel, and the representative non-energy entrepreneur chooses non-energy capital investment and non-energy labor demand. The collective investment decisions by all three entrepreneurs determine the household's level of saving. The worker chooses hours of labor supply. The entrepreneurs and the workers all make decisions subject to the same household budget constraint:

$$c=wh+\pi^{n}+\pi^{f}+\pi^{c}. \tag{9}$$

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:

$$\begin{aligned}&\pi^{c}=p^{c}x^{c}-wl^{c}-i^{c}-G(i^{c}),\quad \pi^{f}=p^{f}x^{f}-\zeta f-wl^{f}-i^{f}-G(i^{f}),\\ \text{and}\quad &\pi^{n}=p^{n}x^{n}-wl^{n}-i^{n}-G(i^{n}).\end{aligned} \tag{10}$$

We write the optimization problem for the workers and the clean, fossil, and non-energy entrepreneurs in the pre-tax steady state as a single household value function. Let $V(k^c,k^f,k^n)$

denote the household's value function in the pre-tax steady state, and $W_t(k^c,k^f,k^n)$ 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 steady state equals:

$$V(k^c,k^f,k^n) = \max_{k^{c\prime},k^{f\prime},k^{n\prime},h,l^c,l^f,l^n,f} u(c,h) + \beta\left[\rho W_1(k^{c\prime},k^{f\prime},k^{n\prime}) + (1-\rho)V(k^{c\prime},k^{f\prime},k^{n\prime})\right], \quad (11)$$

subject to the budget constraint in equation (9). 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:

$$W_t(k^c,k^f,k^n) = \max_{k^{c\prime},k^{f\prime},k^{n\prime},h,l^c,l^f,l^n,f} u(c,h) + \beta W_{t+1}(k^{c\prime},k^{f\prime},k^{n\prime}), \quad (12)$$

subject to the budget constraint over the transition,

$$c = wh + \pi^n + \pi^f + \pi^c + T. \quad (13)$$

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:

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

The expressions for the clean and non-energy entrepreneurs' profits over the transition are the same as in the pre-tax steady state (equation (10)).

Using this model, we examine two general types of steady states. First, we consider a pre-tax steady state that occurs prior to the adoption of a carbon tax. Analogous to the analytic model, the pre-tax steady state consists of constant prices $\{p^f,p^c,p^n,w\}$ and household allocations $\{k^c,k^f,k^n,f,x^c,x^f,l\}$ such that with probability ρ of a carbon tax τ next period, households optimize, labor and capital markets clear, and all variables are constant from one period to the next. Again, this pre-tax steady state can incorporate climate policy transition risk (i.e. $0<\rho<1$) or it could be a pre-tax steady state without climate policy transition risk (i.e. $\rho=0$). Second, we also consider a post-tax steady state that is reached following the adoption of a carbon tax equal to τ. The full definitions of the pre- and post-tax steady states are in Appendix B.

5. Calibration

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 result from the external and internal calibrations, respectively.

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
CRRA coefficient: 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.

Climate policy 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 $\rho = 0.13$. To understand how the probability of a carbon tax affects our results, we also recalibrate the model assuming that there is 5, 25, 50, 95, and 99 percent chance that the carbon tax will be implemented within the next 10 years. At the end of Section 5, we compare the emissions reduction implied by our model under different carbon tax probabilities with the voluntary emissions reduction effort that we observe among firms. The results suggest that our baseline value of $\rho = 0.13$ is broadly consistent with firms' observed behavior.

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.

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). Following Fried (2018), we design the model so that the elasticity of substitution between the non-energy and energy intermediates, ϕ, is very 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 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 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.[12]

[12]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).

We set the discount rate, β, equal to 0.97 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 Kaplan (2012), 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. Appendix Table C1 summarizes the empirical and model values for the calibration targets. The model matches the calibration targets quite closely.

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 emission reduction targets to infer the firms' beliefs surrounding the stringency or likelihood of a future climate policy.

As an alternative to setting targets for the quantity of emissions, a large number of firms are using internal carbon prices.[13] 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).[14] 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

[13] 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.

[14] 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.

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 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 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 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).

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.

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.

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 the results across the range of 10-year carbon tax probabilities (from 0.05 to 0.99) in Section 6.

6. Results

We first use our calibrated model to quantify the impacts climate policy transition risk has on the current U.S. economy and to explore the implications for delaying action on climate change. We then examine how our main results vary over different carbon tax specifications and over a range of different probabilities of a future carbon tax.

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.[15]

Climate policy transition risk reduces emissions through the two key channels highlighted in the analytic model: the total level of the capital stock falls and the composition of the capital stock becomes relatively cleaner. Focusing first on the level effect, 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, and hence the expected return to saving, because it distorts the economy away from the privately optimal allocations of capital and labor. Working in the other direction, the introduction of a carbon tax in the future will lead to a reduction in future consumption, increasing the marginal utility of future consumption and, consequently, 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. This level effect is responsible for 12 percent of the reduction in emissions caused by climate policy transition risk.[16]

[15] Our baseline model assumes that it is costly to sell used capital. 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 risk and no tax. After the first period, fossil entrepreneurs decrease their capital, however the size of this decrease is not much larger than depreciation, making the impact of the adjustment cost small.

[16] To quantify the impact of the level effect alone, we hold the relative composition of capital and labor across

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
Emissions			
Fossil fuel: F	-2.12	-2.12	-20.34
Level effect			
Total capital: K	-0.79	-0.43	-3.88
Total labor: L	-0.00	-0.06	-0.45
Composition effect			
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
Output and consumption			
Output: Y	-0.34	-0.26	-2.58
Consumption: C	-0.13	-0.12	-1.30

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.

Turning next to 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 effect of this change in the composition of capital on emissions 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 policy 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 88 percent of the drop in emissions caused by climate policy transition risk.[17]

The emissions reductions caused by the response to transition risk are equal to the emissions

sectors constant in the pre-tax steady state without climate policy transition risk and reduce the aggregate capital and labor to the aggregate levels observed in the pre-tax steady state with climate policy transition risk.

[17]To quantify the impact of the compositional changes, we hold aggregate capital and labor constant in the pre-tax steady state without transition risk and impose the ratios of $K^c/K, K^f/K, K^n/K, L^c/L, L^f/L$, and L^n/L observed in the pre-tax steady state with climate policy transition risk.

reductions that would be achieved in a steady state with no 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 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 the same level and composition channels as climate policy transition risk to reduce emissions. The tax reduces the level of capital by 0.43 percent and decreases the ratio of fossil to clean capital by 5.05 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 capital and a larger reduction in the ratio of fossil to clean intermediates. While the level effect alone was responsible for 12 percent of the emissions reductions stemming from climate policy transition risk, the level effect only accounts for 9 percent of the emissions reductions achieved with the emissions-equivalent tax.[18]

Climate policy transition risk relies more heavily on a decrease in capital 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 the capital and labor decisions. The distorted capital-labor ratio under climate policy transition risk further reduces the expected marginal product of capital, leading to a larger decrease in capital.

Second, risk-aversion amplifies the effects of climate policy transition risk, resulting in an even larger decrease in the marginal product of capital 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 the privately optimal action if the carbon tax is not implemented next period (i.e. relatively less clean capital) versus the privately optimal action if the tax is implemented the next period (i.e. relatively more clean capital). Risk aversion causes

[18]The compositional changes in capital and labor across sectors caused by the emissions-equivalent tax account for 92 percent of the reduction in emissions in the emissions-equivalent steady state. Note, aggregating the share of emissions reductions attributable to the level and composition effects yields a percentage change that is only slightly different from 100 percent, suggesting that the emissions changes stemming from any other general equilibrium channels are not substantial.

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 privately optimal outcome, leading to an even more pronounced decrease in the total capital stock 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 the total capital stock to reduce emissions.

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 leads to reductions in 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.

To quantify the non-environmental welfare costs of climate policy transition risk, we calculate the consumption-equivalent variation (CEV) in the pre-tax steady state with risk.[19] The CEV in the pre-tax steady state with risk equals the percent change in consumption an agent would need in the pre-tax steady state without 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. The non-environmental welfare cost equals the negative of the CEV. 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 in the pre-tax steady state with transition risk is -0.13 while the CEV in the emissions-equivalent steady state is -0.07. This higher cost results from two factors. First, households are risk averse, implying that the introduction of risk from climate policy transition risk reduces welfare. Second, unlike the emissions-equivalent tax, climate policy transition risk does not induce the level and composition effects that achieve the most efficient emissions reductions. Rather, climate policy transition risk operates more heavily through reductions in total capital. 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 transition risk affects the non-environmental welfare costs incurred by adopting a carbon tax. We calculate a transitional CEV to measure the non-environmental welfare costs. Specifically, we compare an economy in one of the pre-tax

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

steady states (with or without climate policy transition risk) to an economy that undergoes the dynamic transition towards the eventual policy steady state. The non-environmental welfare costs from adopting this carbon tax equal the negative of the transitional CEV. 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 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 risk, reducing the non-environmental welfare cost of adopting the tax. Second, introducing the tax from the pre-tax steady state with 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. Because climate policy transition risk reduces the total capital stock (i.e. the level effect), agents are less able to dis-save over the transition to the policy steady state, raising the non-environmental welfare cost when the economy begins in the steady state with 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.

Alternative carbon tax specifications. Thus far, we have assumed that, once adopted, a carbon tax would be constant and permanent. We examine the sensitivity of the results to both of these assumptions. To begin, 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 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. Column 2 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).

Next, we examine how the effects of climate policy transition risk change if the carbon tax does not remain in place forever. We assume that firms know that once the tax is adopted it will be permanently repealed after a given number of years. We re-calibrate our model under this alternative assumption. Of course, 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 again 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.

Table 5: Alternative Tax Specifications

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

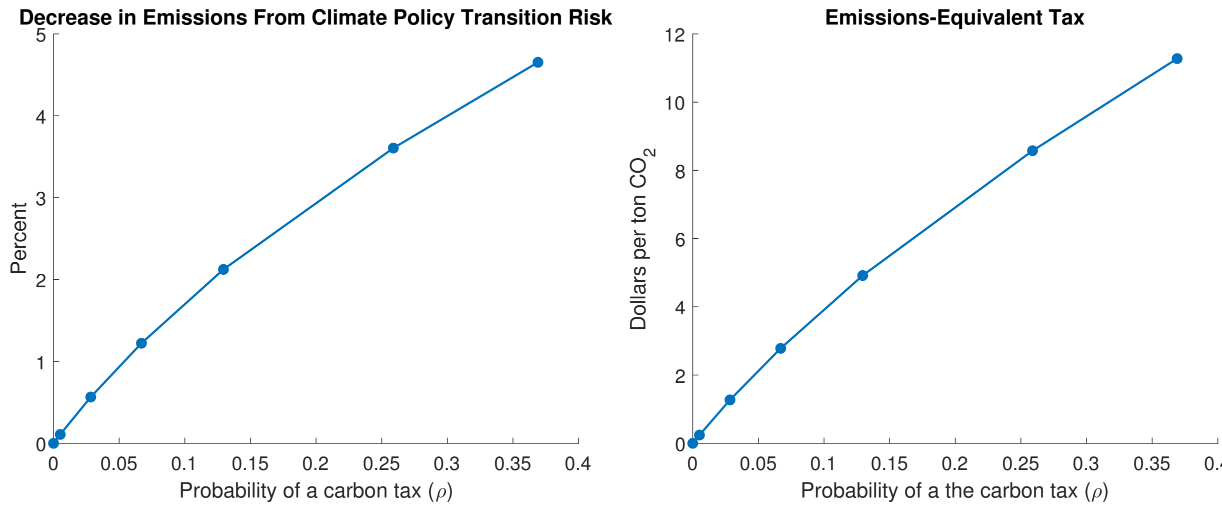
Note: This table reports the percentage changes in outcomes in the pre-tax steady state with risk relative to the pre-tax steady state without risk in (1) the baseline model and when we re-calibrate the model (2) assuming a growing carbon tax and (3)-(6) assuming that the carbon tax is repealed after one, two, four, or eight years.

The last four columns of Table 5 display how transition risk affects the pre-tax steady state outcomes assuming that a carbon tax would be repealed one, two, four, or eight years after its adoption. Intuitively, the threat of a carbon tax being adopted has somewhat more muted effects on overall investment when the policy is known to be temporary, leading to slightly smaller emissions reductions from climate policy transition risk. For example, climate policy transition risk reduces emission by 1.44 percent when the policy ends after a single year, compared to 2.12 percent when the policy lasts forever.[20]

Overall, while we find that changes in the time path and longevity of the carbon tax can have small effects on the macro response to climate policy transition risk, we continue to see the same mechanisms at play. The possibility of a carbon tax that takes any of the forms in

[20]The differences in the impacts with a permanent tax versus a tax that will be repealed are dictated in large part by the rate of depreciation. Intuitively, if depreciation is high, then the differences between the permanent tax and the repealed tax will be small.

Figure 1: Emissions' Reduction From Climate Policy Risk



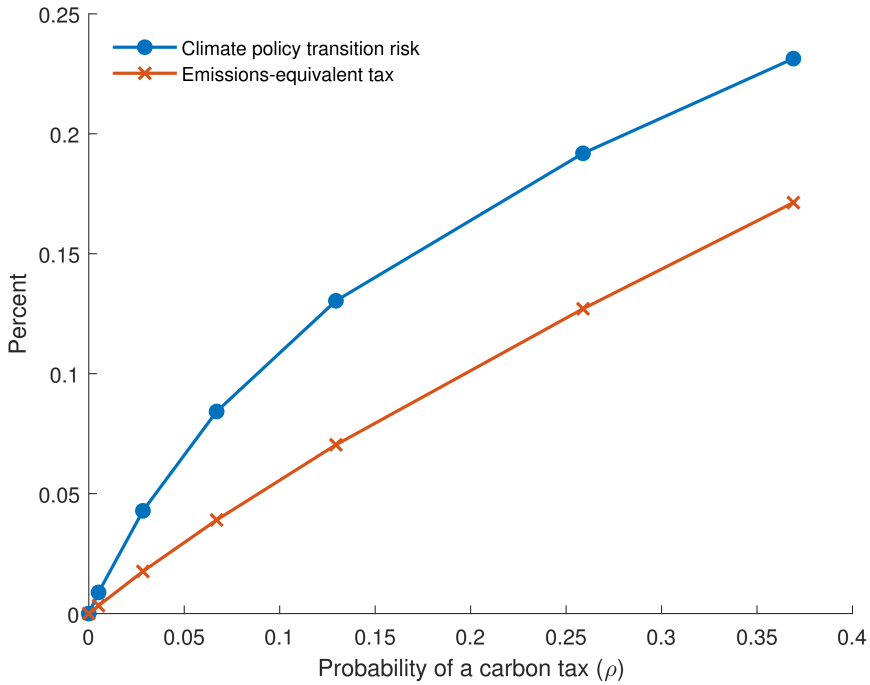
Note: For each carbon tax probability, the left panel plots the emissions reductions in the pre-tax steady state with climate policy transition risk relative to the pre-tax steady state without climate policy transition risk. The right panel displays the corresponding carbon tax that would achieve the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

Table 5 reduces the total level of capital and shifts the economy towards clean capital, reducing emissions.

Changes in climate policy transition risk. While the preceding results reveal that the impacts of climate policy transition risk are largely insensitive to the unique features of the tax, we find that the results are quantitatively quite sensitive to the probability of the tax being adopted. To highlight this point, 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 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. This exercise serves two purposes. First, we examine how sensitive the quantitative and qualitative results are with regards to a key unknown parameter. Second, as time continues to pass without the adoption of a federal climate policy, it is possible that the subjective probability of a climate policy being adopted could increase at some point in the future as climate change progresses.

The left panel of Figure 1 plots the emissions reductions in the pre-tax steady state with risk for different carbon tax probabilities. All else constant, increases in the probability of the carbon tax increase the expected return to clean capital and decrease the expected return to fossil capital, resulting in larger decreases in emissions. The right panel of Figure 1 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

Figure 2: Welfare Cost of Climate Policy Transition Risk and 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.

emissions-equivalent tax grows. As in our main analysis, the emissions-equivalent tax is always less than the expected tax, equal to $\rho \times \$51$, because entrepreneurs' ability to choose labor after they learn whether or not there is a carbon tax undoes some of the emissions reduction from their choice of capital.

We also explore the non-environmental welfare impacts of climate policy transition risk across the different implied probabilities of a carbon tax. Figure 2 compares the non-environmental welfare cost (measured as the negative of the CEV) in the climate-policy-transition-risk and emissions-equivalent steady states, relative to the pre-tax steady state with no climate policy transition risk.[21] 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 effect of climate policy transition risk on the transitional

[21] 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.

welfare costs from adopting a carbon tax (measured as the negative of the transitional CEV) vary with the implied carbon-tax probability. We find that climate policy transition risk does not substantially reduce the transitional welfare cost of adopting a carbon tax. As the probability of a carbon tax increases, the transitional welfare cost of adopting the carbon tax falls only slightly, from 0.31 when there is a 5 percent chance of a carbon tax in the next 10 years to 0.28 when there is a 99 percent chance of adopting the carbon tax within the next ten years.

7. Interactions with Other Channels

Our model is designed to carefully quantify the impact of climate policy transition risk on the composition and level of investment, and to study the resulting implications for the macroeconomy. However, climate policy transition risk could also impact the economy through other channels. For example, previous literature on the Green Paradox (e.g., Sinn (2008)) has studied the possibility that climate policy transition risk will affect the level of fossil fuel supplies. Additionally, climate policy transition risk could impact current and expected future damages through its effects on emissions. We explore the interaction between each of these channels and our main results. While we find that including these channels provides interesting insights, our qualitative results are unchanged. In particular, we continue to find that climate policy transition risk shifts investment towards a relatively cleaner mix of capital, depresses aggregate investment, and ultimately reduces current emissions.

Accounting for shifts in fossil fuel supply. 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 consistent with recent evidence, the demand-side response dominates, and the net effect of climate policy transition risk is still to reduce emissions 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.[22] If climate policy transition risk is reduced to zero (i.e. there is no longer a threat of a future carbon tax), then, as our analysis demonstrates, 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.[23] 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 implies that reducing this three-year probability to zero, its value in the pre-tax steady state without risk, would increase fossil fuel prices by 3.4 percent.

[22]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.

[23]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 due to 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.

To quantify the effects climate policy transition risk with a supply-side response, we consider an alternative pre-tax steady state without risk in which the fossil fuel price is 3.4 percent higher than in the pre-tax steady state with risk. We compare outcomes from the pre-tax steady state with risk to this higher-price pre-tax steady state without 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 the total capital stock 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 (column 1 of Table 4). 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.

Accounting for climate damage. The accumulation of carbon emissions in the atmosphere leads to many different types of climate damage, including extreme temperatures, severe storms, wildfires, and drought. The environmental literature often models this climate damage as a decline in total factor productivity, where the magnitude of the productivity decline increases with the accumulated carbon emissions. Linking emissions and productivity, implicitly through climate damage, could affect with the economy's response to climate policy transition risk through two channels. First, since climate policy transition risk reduces emissions, climate damage is lower and hence productivity is higher in the pre-tax steady state with risk than in the pre-tax steady state without risk. Second, the introduction of the carbon tax also reduces emissions, implying that climate damage is lower and productivity is higher over the transition, than in the pre-tax steady state with risk.

Directly incorporating climate damage into our model 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 risk for us to study. Instead, we take a reduced form approach that's designed understand how climate damage could impact the economy's response to climate policy transition risk. Specifically, we augment our baseline model with the two emissions-productivity effects discussed above: (1) higher productivity in the pre-tax steady state with risk and (2) higher productivity over the transition after the carbon tax is introduced. As an illustrative example, we approximate the size of these emissions-productivity effects for an economy in year 2019, the most recent year for which the necessary data is available.

To approximate how much higher productivity is in the pre-tax steady state with risk, we compare climate damage in year 2019 with climate damage in a counterfactual year 2019 in which there is no climate policy transition risk. We measure climate damage in year 2019 based on cumulative emissions in 2019, reported in IPCC (2021), and the climate damage specification from Dietz and Venmans (2019).[24] To measure climate damage in the counterfactual year 2019 without climate policy transition risk, we increase historical emissions over the previous ten years by 0.9 percent, the amount that climate policy transition risk reduces emissions in our main results (see Table 4). This approach assumes that the decrease in emissions from climate policy transition risk in the model affects global emissions as opposed to only US emissions, providing an upper bound on the impact of climate damage on our main results. Comparing climate damage in year 2019 with climate damage in the counterfactual year 2019 implies that productivity is 0.0044 percent higher in 2019 as a result of climate policy transition risk.[25]

Next, we approximate the increase in productivity over the transition following the introduction of the carbon tax. From the perspective of a firm in year 2019, we measure the increase in productivity if a carbon tax is introduced in 2020, relative to expected future productivity if the carbon tax is not introduced in 2020, but could be introduced with probability ρ each year from 2021 onward. Once the carbon tax is introduced, we assume that it reduces emissions in each period relative to the business-as-usual emissions pathway from the scientific literature, RCP 8.5. The size of the reduction in emissions equals the percentage decrease in emissions between the transition and the pre-tax steady state with risk in our main results from Section 6. Comparing the time path of productivity when the carbon tax is introduced in 2020 with

[24] Dietz and Venmans (2019) model the effects of climate damage on productivity using the exponential-quadratic damage function, $D(T_t) = \exp\left(-\frac{\gamma}{2}T_t^2\right)$, which multiplies output. Variable T_t is the increase in global mean temperature from pre-industrial levels and parameter $\gamma = 0.01$ controls the magnitude of the climate damage.

[25] Cumulative emissions in 2019 equal 2390 $GtCO_2$ (IPCC, 2021). Cumulative emissions in 2019 in our counterfactual scenario without climate policy transition risk equal 2398 $GtCO_2$. To account for warming from other non-CO_2 Greenhouse gases, we increase cumulative emissions by 10 percent in both scenarios (Dietz and Venmans, 2019). The increase in global mean temperature is directly proportional to the adjusted cumulative emissions, with a factor of proportionality equal to 0.45^oC per 1000 $GtCO_2$ (IPCC, 2021).The implied temperature increase in year 2019 equals 1.183^oC and in the counterfactual year 2019 without climate policy transition risk equals 1.187^oC.

the time path of expected productivity if the carbon tax is not introduced in 2020, reveals that the introduction of the carbon tax in 2020 increases year 2020 productivity by 0.0015 percent. This productivity increase grows to 0.15 percent by 2100 because the effect of the tax on cumulative emissions increases over time.

Putting this all together, we approximate the links between climate policy transition risk and climate damage by including (1) an increase in productivity in the pre-tax steady state with risk by 0.0044 percent and (2) increases in productivity in each period following the introduction of the carbon tax by the amount implied by time path of the productivity increase from the introduction of a carbon tax in our above calculations. We stress again that our goal is to account for the positive productivity effects from the reductions in emissions caused by both the risk of climate policy and the actual implementation of the policy. We do not attempt to fully integrate climate damages into the main analysis.

The first column of Table 6 reports the effects of climate policy transition risk on macro-aggregates when we include this interaction between climate damage and climate policy transition risk. The second column of Table 6 reports the effects of climate policy transition risk on macro aggregates from our main analysis, which abstracts from climate damage (repeated from Table 4). Comparing the two columns of Table 6 reveals that the effects of climate policy transition risk are similar, regardless of the inclusion climate damages.

Including climate damage has no impact on the composition of capital and labor in the initial steady state; the ratios of clean to fossil capital, labor, and intermediates are identical across columns of Table 6. Since we assume that climate damage affects productivity in all sectors equally, it does not affect the relative return from investing in one sector versus another.

Including climate damage does slightly increase the magnitude of the level effect; in the pre-tax steady state with risk, total capital falls by 0.82 percent with climate damage, compared to 0.79 percent without climate damage. All else constant, the higher productivity in the pre-tax steady state with risk increases investment, which, by itself, would reduce the level effect. However, all else constant, the higher productivity over the transition reduces incentives for investment in the pre-tax steady state with risk, ultimately leading to a larger level effect from the inclusion of climate damages.

The intuition for why higher productivity over the transition reduces total capital in the pre-tax steady state with risk stems from its effects on the household's expected return to saving, which depends on the expectation of both the marginal product of capital and the marginal utility of consumption. In isolation, including climate damage implies that productivity is higher when the carbon tax is introduced, because emissions and the ensuing climate damages are lower. This higher productivity has opposing effects on the expected return to saving. The higher productivity raises the marginal product of capital, increasing the expected return to saving. Working in the other direction, the higher productivity raises consumption, reducing the marginal utility of consumption, leading to a lower expected return to saving. The consumption response dominates; including climate damage reduces the expected return to saving in the pre-tax steady state with risk, leading to a smaller capital stock, and a larger level effect.

Table 6: Effects of Climate Policy Transition Risk on Macro-Aggregates
(Percent change from pre-tax, no-risk steady state)

	Pre-tax risk SS w/ climate damage	Pre-tax risk SS w/o climate damage
Emissions		
Fossil fuel: F	-2.13	-2.12
Level effect		
Total capital: K	-0.82	-0.79
Total labor: L	-0.00	-0.00
Composition effect		
Fossil to clean capital: K^f/K^c	-8.86	-8.86
Fossil to clean labor: L^f/L^c	-3.08	-3.08
Fossil to clean intermediates: X^f/X^c	-5.03	-5.03
Output and consumption		
Output: Y	-0.35	-0.34
Consumption: C	-0.13	-0.13

Note: This table reports the percentage changes in outcomes in the pre-tax steady state with risk relative to the pre-tax steady state without risk in (1) the baseline model augmented to include the effects of climate damage and (2) the baseline model, repeated from column (1) of Table 4.

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 the aggregate capital stock. In sum, climate policy transition risk reduces emissions both because output falls and because the remaining output is produced with less fossil fuel.

While the response to climate policy transition risk has caused a modest reduction in emissions, we find that this represents 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. 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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Online Appendix

A. Analytic model

We solve for the values of clean and fossil capital in the steady state with no carbon tax, but risk of a future carbon tax. The clean entrepreneur's first order condition for next period's level of clean capital, $k^{c\prime}$ equals:

$$\frac{\partial V^c(k^c)}{\partial k^{c\prime}} = -1 + \left(\frac{1}{1+r}\right)\left[\rho \frac{\partial W_1^c(k^{c\prime})}{\partial k^{c\prime}} + (1-\rho)\frac{\partial V^c(k^{c\prime})}{\partial k^{c\prime}}\right] = 0. \tag{A1}$$

The derivatives of the continuation value in the first period of the transition, $\frac{\partial W_1^c}{\partial k^{c\prime}}$, and in the steady state with risk and no carbon tax, $\frac{\partial V^c}{\partial k^{c\prime}}$, equal:

$$\frac{\partial W_1^c(k^{c\prime})}{\partial k^{c\prime}} = p^{c\prime}(1) + 1 - \delta \quad \text{and} \quad \frac{\partial V^c(k^{c\prime})}{\partial k^{c\prime}} = p^{c\prime}(0) + 1 - \delta, \tag{A2}$$

where we use the notation $p^{c\prime}(1)$ and $p^{c\prime}(0)$ to denote the value of next period's clean intermediate price in the states of the world in which the government does and does not introduce a carbon tax, respectively. Combining equations (A1) and (A2) yields the first order condition for next period's clean capital:

$$r + \delta = \rho p^{c\prime}(1) + (1-\rho)p^{c\prime}(0). \tag{A3}$$

Similarly, the fossil entrepreneur's first order condition for next period's level of fossil capital, $k^{f\prime}$ equals:

$$\frac{\partial V^f(k^f)}{\partial k^{f\prime}} = -1 + \left(\frac{1}{1+r}\right)\left[\rho \frac{\partial W_1^f(k^{f\prime})}{\partial k^{f\prime}} + (1-\rho)\frac{\partial V^f(k^{f\prime})}{\partial k^{f\prime}}\right] = 0. \tag{A4}$$

The derivatives of the continuation value in the first period of the transition, $\frac{\partial W_1^f}{\partial k^{f\prime}}$, and in the steady state with risk and no carbon tax, $\frac{\partial V^f}{\partial k^{f\prime}}$ equal:

$$\frac{\partial W_1^f(k^{f\prime})}{\partial k^{f\prime}} = p^{f\prime}(1) - (\zeta + \tau) + 1 - \delta \quad \text{and} \quad \frac{\partial V^f(k^{f\prime})}{\partial k^{f\prime}} = p^{f\prime}(0) - \zeta + 1 - \delta, \tag{A5}$$

where, as before, $p^{f\prime}(1)$ and $p^{f\prime}(0)$ denote the values of the fossil intermediate price in the states of the world in which the government does and does not introduce a carbon tax, respectively. Combining equations (A4) and (A5) yields the first order condition for next period's fossil capital:

$$r+\delta=\rho p^{f\prime}(1)+(1-\rho)p^{f\prime}(0)-\zeta-\rho\tau. \tag{A6}$$

It remains to solve for the equilibrium prices of clean and fossil intermediates in the states of the world in which the government does and does not introduce the carbon tax. The first order conditions for the final-good entrepreneur imply the following expressions for the prices of the clean and fossil intermediates, p^c and p^f, respectively (equation (1) in the main text):

$$p^c=\gamma(x^c)^{\gamma-1}(x^f)^{\theta} \quad \text{and} \quad p^f=\theta(x^c)^{\gamma}(x^f)^{\theta-1}. \tag{A7}$$

Note that $x^c=k^c$ and in an interior optimum (ensured by the assumption $\tau<(r+\delta)/(1-\rho)$), $x^f=k^f$, implying that the prices of the clean and fossil intermediates depend only on the levels of clean and fossil capital. Since next period's levels of capital are independent of whether the government introduces a tax in that period, it follows that next period's prices of clean and fossil intermediates are also independent of whether or not the government introduces the tax: $p^{c\prime}\equiv p^{c\prime}(0)=p^{c\prime}(1)$ and $p^{f\prime}\equiv p^{f\prime}(0)=p^{f\prime}(1)$. Using this relationship, the first order conditions for clean and fossil capital collapse to:

$$r+\delta=p^{c\prime} \quad \text{and} \quad r+\delta=p^{f\prime}-\zeta-\rho\tau. \tag{A8}$$

Solve equations (A7) and (A8) for $k^{c\prime}/k^{f\prime}$:

$$\frac{k^{c\prime}}{k^{f\prime}}=\left(\frac{\gamma}{\theta}\right)\left(\frac{r+\delta+\zeta+\rho\tau}{r+\delta}\right), \tag{A9}$$

and for $k^{c\prime}$ and $k^{f\prime}$:

$$k^{c\prime}=\left(\frac{\gamma}{r+\delta}\right)^{\frac{1}{1-\gamma-\theta}}\left(\frac{r+\delta}{r+\delta+\zeta+\rho\tau}\right)^{\frac{\theta}{1-\gamma-\theta}}\left(\frac{\theta}{\gamma}\right)^{\frac{\theta}{1-\gamma-\theta}} \tag{A10}$$

$$k^{f\prime}=\left(\frac{\gamma}{r+\delta}\right)^{\frac{1}{1-\gamma-\theta}}\left(\frac{r+\delta}{r+\delta+\zeta+\rho\tau}\right)^{\frac{1-\gamma}{1-\gamma-\theta}}\left(\frac{\theta}{\gamma}\right)^{\frac{1-\gamma}{1-\gamma-\theta}}. \tag{A11}$$

There is a measure one of entrepreneurs in each sector, implying that the aggregate levels of clean and fossil capital, K^c, and K^f, equal the values for the representative entrepreneur in each sector. Thus, the aggregate values of clean and fossil capital in the steady state with no carbon tax but risk of a future tax equal:

$$K^c = \left(\frac{\gamma}{r+\delta}\right)^{\frac{1}{1-\gamma-\theta}} \left(\frac{r+\delta}{r+\delta+\zeta+\rho\tau}\right)^{\frac{\theta}{1-\gamma-\theta}} \left(\frac{\theta}{\gamma}\right)^{\frac{\theta}{1-\gamma-\theta}} \tag{A12}$$

$$K^f = \left(\frac{\gamma}{r+\delta}\right)^{\frac{1}{1-\gamma-\theta}} \left(\frac{r+\delta}{r+\delta+\zeta+\rho\tau}\right)^{\frac{1-\gamma}{1-\gamma-\theta}} \left(\frac{\theta}{\gamma}\right)^{\frac{1-\gamma}{1-\gamma-\theta}}. \tag{A13}$$

Dividing equation (A13) by equation (A12) yields equation (6) in the main text. Finally, observe that:

$$\frac{\partial K^c}{\partial \rho} < 0, \; \frac{\partial K^c}{\partial \tau} < 0, \; \frac{\partial K^f}{\partial \rho} < 0, \; \frac{\partial K^f}{\partial \tau} < 0. \tag{A14}$$

An increase in either the probability of a tax, or the size of the expected tax, reduces both the levels of clean and fossil capital in the pre-tax steady state with risk. However, the decrease in fossil capital is larger than the corresponding decrease in clean. As a result, climate policy transition risk reduces the ratio of fossil to clean capital.

B. Quantitative model

We define a *pre-tax steady state* for this economy as a set of prices for the clean, fossil, and non-energy intermediates, labor, and capital, $\{p^c, p^f, p^n, w, r\}$, allocations for households and intermediate entrepreneurs $\{k^c, k^f, k^n, l^c, l^f, l^n, f, h, c\}$ and allocations for the final-good entrepreneur, $\{x^c, x^f, x^n\}$, such that there is no existing carbon tax but given a probability, ρ, of a carbon tax, τ, next period, the following conditions hold:

1. Given prices, the final-good entrepreneur chooses the clean, fossil, and non-energy intermediates to maximize profits.

2. Given prices, the representative household maximizes the value function (equation (11)), subject to the budget constraint (equation (9)), the time endowment, $h \leq 1$, and the non-negativity constraints, $c \geq 0, k^c \geq 0, k^f \geq 0, k^n \geq 0$.

3. The markets for labor, and for the clean, fossil, and non-energy intermediate inputs all clear.

4. Prices and allocations are constant from one period to the next.

We define a *post-tax steady state* for this economy as a set of prices for the clean, fossil, and non-energy intermediates, labor, and capital, $\{p^c, p^f, p^n, w, r\}$, allocations for households and intermediate entrepreneurs $\{k^c, k^f, k^n, l^c, l^f, l^n, f, h, c\}$ and allocations for the final-good entrepreneur, $\{x^c, x^f, x^n\}$, such that given a carbon tax τ, the following conditions hold:

1. Given prices, the final-good entrepreneur chooses the clean, fossil, and non-energy intermediates to maximize profits.

2. Given prices, the representative household maximizes the value function:

$$V(k^c, k^f, k^n; 1) = \max_{k^{c\prime}, k^{f\prime}, k^{n\prime}, h, l^c, l^f, l^n, f} \frac{c^{1-\sigma}}{1-\sigma} - \chi \frac{h^{1+\frac{1}{\theta}}}{1+\frac{1}{\theta}} + \beta V(k^{c\prime}, k^{f\prime}, k^{n\prime}; 1),$$

   subject to the budget constraint (equation (13)), the time endowment, $h \leq 1$, and the non-negativity constraints, $c \geq 0, k^c \geq 0, k^f \geq 0, k^n \geq 0$.

3. The markets for labor, and for the clean, fossil, and non-energy intermediate inputs all clear.

4. Prices and allocations are constant from one period to the next.

The policy steady state and the emissions-equivalent steady states are both post-tax steady states with different values of the carbon tax.

C. Calibration

Table C1: Model Fit

Moment	Model	Target
Fossil-total capital ratio: K^f/K	0.10	0.10
Fossil-clean intermediates ratio: X^f/X^c	2.53	2.53
Fossil energy share: $\zeta F/Y$	0.04	0.04
Capital-output ratio: K/Y	3.04	3.04
Fraction of time endowment spent working	0.33	0.33

Note: This table reports the empirical and model values of the moments for the calibration.

Data on U.S. electric generation by source are from Table 1_01 of the 2021 May EIA Electric power monthly (www.eia.gov/electricity/data.php). Data on the vehicle miles traveled and fuel economy for the U.S. vehicle fleet are available from Table VM-1 of the Federal Highway Administration's 2019 highway statistics.[26] Data on fuel economy by car make and model is from fueleconomy.gov. Data on total mine production by mineral type are available from Table

[26] https://www.fhwa.dot.gov/policyinformation/statistics/2019/

1 of the U.S. Geological Survey Mineral and Commodity Summaries. Data on GDP by industry and detailed data on fixed assets and consumer durables are from the BEA.[27] We discuss the calculation of the level of fossil capital in detail below. We calculate all energy-related moments for year 2019, the most recent year with all the available data.

We use the detailed data on private fixed assets and consumer durables to construct the ratio of fossil to total capital in the U.S. economy, K^f/K.[28] The data provide information on the quantity of each type of capital in each sector and on the quantity of each type of durable good. The sectors mostly correspond to the 3-digit NAICS classification, though in some cases, several 3-digit NAICS classifications are combined into a single sector. For example, the farms sector includes NAICS codes 111 and 112.

We divide the capital into three groups: group 1 corresponds to capital that is fossil or partly fossil, regardless of the sector. Group 2 corresponds to capital that is fossil or partly fossil only in sectors that are specialized to use fossil energy. Group 3 corresponds to all other types of capital. Table C2 reports the the types of capital and consumer durables that we classify as group 1 and group 2. All types not listed in Table C2 are in group 3 and correspond to either clean or non-energy capital. We do not distinguish between clean and non-energy capital in the data; we focus only on the ratio of fossil capital relative to total capital.

We classify all group 1 capital except autos and lights trucks (including sport utility vehicles) as 100 percent fossil. We view autos and light trucks as partly clean and partly fossil. Most vehicles are specialized to use fossil fuel, making them at least partly fossil. However, many vehicles also include capital that improves fuel economy, such as regenerative breaks, which is designed specifically to substitute for fossil fuel, and thus would count 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 in light-trucks.

We define a vehicle to be 0 percent fossil if it has inverse fuel economy equal to 0 gallons/mile. At the other extreme, we define an auto or light truck to be 100 percent fossil if it has inverse fuel economy equal to the maximum in the U.S. fleet of autos or light-trucks. We interpolate between these two extreme points to find the fraction of fossil capital embodied in the auto or light-truck with the average inverse fuel economy in the U.S. fleet. The average inverse fuel economy of the U.S. fleet of short-wheel-base light duty vehicles (e.g. most autos) equals 1/24.1 gallons per mile and for long-wheel-base light duty vehicles (e.g. most pick up trucks and SUVs) equals 1/17.6 gallons per mile.

[27] Fixed assets and consumer durables: apps.bea.gov/national/FA2004/Details/Index.htm. GDP by industry: apps.bea.gov/iTable/iTable.cfm?ReqID=51&step=1

[28] We do not have detailed data on government fixed assets (e.g., public infrastructure, military capital, etc.) We assume instead that the ratio of K^f/K for government fixed assets is the same as the ratio for private fixed assets and consumer durables.

Table C2: Capital Classification

Group 1	Group 2
steam engines	special industrial machinery
other trucks and buses	custom software
truck trailers	own account software
internal combustion engines	chemical manufacturing except pharma and med
aircraft	other manufacturing
ships and boats	scientific research and development services
farm tractors	
construction tractors	
gas structures	
petroleum pipelines	
petroleum and natural gas structures	
other transportation equipment	
autos	
light trucks	

Note: The table reports the types of capital from the BEA detailed data on fixed assets and consumer durables that we classify as group 1 or group 2. All other capital types not listed in the table belong to group 3. Group 1 corresponds to capital that is fossil or partly fossil, regardless of the sector, group 2 corresponds to capital that is fossil or partly fossil only in sectors that are specialized to use fossil energy, and group 3 corresponds to all other types of capital.

To calculate the maximum inverse fuel economy among autos and light trucks in the current fleet, we use data on fuel economy by car make and model. Since fuel economy has increased over time and vehicles are long-lived, we used the fuel-economy data from model-year 2005, 15 years before 2019. We set the maximum inverse fuel economy of the current fleet equal to the 90th percentile of inverse fuel economy in model-year 2005; 1/17 gallons per mile for autos and 1/15 gallons per mile for light-trucks. Interpolating linearly between the two extremes, 0 and 100 percent fossil capital, we find that the average auto in the U.S. fleet has 70 percent fossil capital and the average light truck has 85 percent fossil capital. In our calculation of fossil capital, we multiply the stock of autos by 0.7 and the stock of light trucks by 0.85.

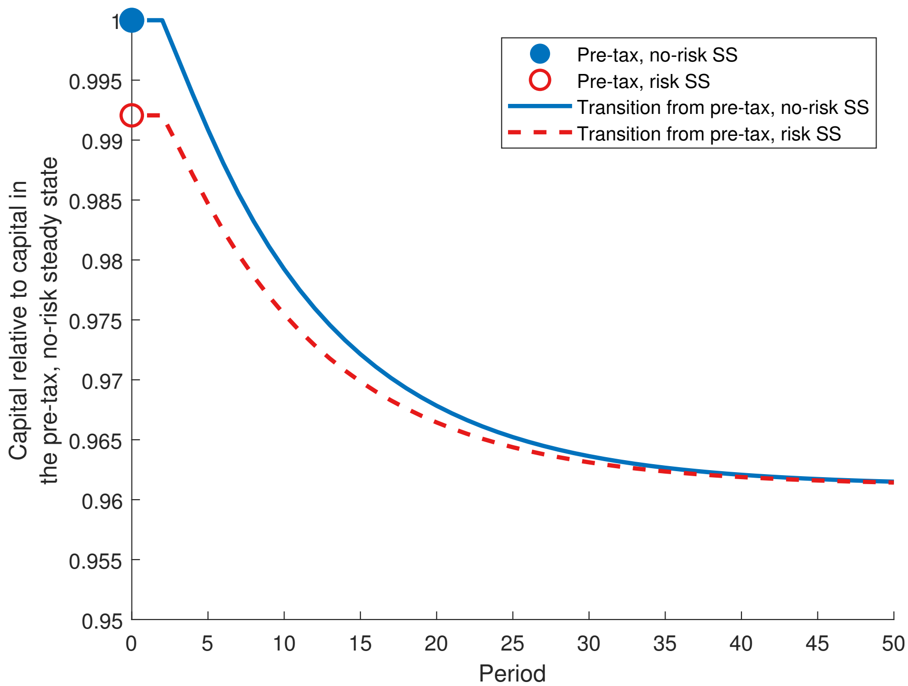
We classify group 2 capital as fossil if it is in one of the following sectors which are specialized to use fossil fuel: oil and gas extraction, petroleum and coal products, air transportation, railroad transportation, water transportation, truck transportation, pipeline transportation, other transportation and support activities. We classify group 2 capital as partially fossil if it is in the mining except oil and gas extraction (NAICS code 212), or in the support activities for mining (NAICS code 213) sectors. Sector 212 includes all coal and other mineral mining. To isolate the coal mining capital, we multiply all group 2 capital in this sector by 0.27, the fraction of total mine production that is from coal (USGS, 2020).

Sector 213 includes group 2 capital used to support oil and gas extraction (NAICS code 211) and coal mining, which we would classify as fossil, as well capital used to support other types of mining, which we would not classify as fossil. To isolate the fossil capital, we first calculate the fraction of mining-related value-added used for oil and gas extraction. This fraction equals the ratio of value added in sector 211 divided by the sum of value added in sectors 211 and 212, yielding a value of 0.76. Thus, 76 percent of group 2 capital in sector 213 corresponds to oil and gas extraction, and thus is fossil. The remaining 24 percent of group 2 capital in sector 213 includes support activities for coal mining (fossil) and other mining (not fossil). To isolate the coal mining capital, we multiply the remaining group 2 capital by 0.27, the fraction of total mine production that is from coal. In sum, let K_{213} denote the total group 2 capital in sector 213. We classify the following fraction of this capital as fossil: $0.76K_{213}+0.27(1-0.76)K_{213}$.

D. Additional results

Figure D1 plots the time paths of the total capital stock over the transition from the pre-tax steady state without risk (solid blue line) and from the pre-tax steady state with risk (dashed red line). The lower initial level of capital in the steady state with risk implies that agents are less able to dis-save over the transition, raising the transitional non-environmental welfare cost from the steady state with risk. Table D1 reports how the pre-tax steady state outcomes change 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 results.

Figure D1: Total Capital Stock



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 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 risk, respectively.

Table D1: Sensitivity to Adjustment costs

	Baseline	No adjustment cost
Emissions		
Fossil fuel: F	-2.12	-1.64
Level effect		
Total capital: K	-0.79	-0.75
Total labor: L	-0.00	-0.00
Composition effect		
Capital: K^f/K^c	-8.86	-6.61
Labor: L^f/L^c	-3.08	-2.39
Inputs: X^f/X^c	-5.03	-3.80
Aggregates		
Output: Y	-0.34	-0.31
Consumption: C	-0.13	-0.12

Note: This table reports the percentage changes in outcomes in the pre-tax steady state with risk relative to the pre-tax steady state without risk in (1) the baseline model and (2) when we re-calibrate the model assuming zero adjustment costs.