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The Macro Effects of Climate Policy Uncertainty

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Abstract

Uncertainty surrounding if and when the U.S. government 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 risk, we develop a dynamic, general equilibrium model that incorporates beliefs about future climate policy. We find that climate policy risk reduces carbon emissions by causing the capital stock to shrink and become relatively cleaner. Our results reveal, however, that a carbon tax could achieve the same reduction in emissions at less than half the cost.

Email: sdfried@asu.edu, knovan@ucdavis.edu, william.b.peterman@frb.gov. The views expressed in this paper are our own and do not reflect the views of the Federal Reserve System or its staff. For helpful comments we thank seminar and conference participants at SED, the San Francisco Fed Conference on Climate Change, the Federal Reserve Energy System Meeting, Midwest Macro, ASSAs, Berkeley Climate Economics Workshop, UCSB, Harvard, and Universidad del Rosario. All potential errors are our own.

1. Introduction

While the U.S. does not have a federal price on carbon emissions, there is widespread awareness that such a policy could be adopted in the future. The possibility of a future carbon price introduces risk into the decision to invest in capital used in conjunction with fossil fuels. Given the dominant role that fossil fuels play in the production of goods and services, the looming threat of a carbon price may have far reaching impacts across the macroeconomy. Despite this possibility, the economics literature has largely ignored the macro effects of this climate policy risk. Studies of the potential macro impacts of carbon taxes almost exclusively assume that agents proceed as if there is zero probability of future climate policy. Instead, this paper develops a dynamic, general equilibrium model of the U.S. economy that incorporates beliefs about future climate policy, allowing us to quantify the impacts of climate policy risk. We show that climate policy risk behaves much like a carbon tax, reducing emissions by causing the capital stock to shrink and become relatively cleaner. Compared to a carbon tax however, we find that climate policy risk relies more heavily on shrinking the capital stock to reduce emissions, making it more costly than a tax. Moreover, we highlight that, by ignoring the response to policy risk, existing studies overstate the emissions reductions from a carbon tax.

To study the effects of climate policy risk, we analyze an equilibrium of a multi-sector, neoclassical growth model in which there is no carbon price, 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) as well as in clean capital that is specialized to substitute for fossil capital or fossil fuel (e.g., a solar panel or a regenerative braking system). 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 risk by comparing the pre-tax equilibrium in which agents internalize policy risk to a naïve, counterfactual pre-tax equilibrium without policy 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 focused on clean and fossil capital investment, we highlight two theoretical channels through which climate policy risk reduces emissions. First, climate policy risk reduces the expected return to fossil capital relative to clean capital, shifting the economy towards cleaner production. Second, climate policy risk reduces the expected marginal product of capital because it distorts the composition of capital away from the privately optimal baseline outcome. As a result, the total capital stock falls, further reducing both output and emissions.

To quantify the macroeconomic impacts of climate policy risk, we move beyond the simple, analytic setting and develop a richer general equilibrium model that adds risk-averse house-

holds, a non-energy capital, and partially-irreversible investment. Intuitively, risk-aversion amplifies the impacts of climate policy 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 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.¹

To discipline firms' beliefs regarding the level and likelihood of a future tax, we use a novel approach that exploits the information revealed by internal carbon prices.² An internal carbon price is a tool that firms voluntarily use to reduce their carbon emissions by distorting their investment decisions (Ahluwalia, 2017).³ Consistent with current policy proposals, we first assume that, if adopted, a carbon tax would be set at \$45 (in 2017 dollars) per ton of CO₂.⁴ We then solve for the subjective probability of the tax being adopted that rationalizes a firm's decision to impose the observed internal carbon price within our model. The result implies that firms behave as though they believe there is a 50 percent chance that the federal government will introduce the carbon tax within the next eight years.

We use the calibrated model to quantify how the risk of future climate policy affects the macroeconomy. As a point of reference, we find that the steady state CO₂ emissions would be 15 percent lower with a \$45/ton tax on CO₂ compared to a naïve baseline world without a tax and without climate policy risk. Importantly, we find that the economy's response to climate policy risk implies that the U.S. has already attained 8 percent of the total drop in emissions, even though there is not an actual climate policy in place. This reduction in emissions from climate policy risk is equivalent to the reduction that would be achieved in a steady state with no policy risk and a carbon tax equal to \$3.21/ton.

The emissions reductions caused by climate policy risk stem from the two channels highlighted in the analytic model. First, climate policy risk decreases the expected return to investments in fossil capital relative to clean capital, leading to a 3.9 percent decrease in the ratio of

¹Baldwin 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.

²Previous work examines how beliefs about future events can be recovered through prediction markets (Wolfers and Zitzewitz, 2004). Meng (2017) uses a prediction market to infer the expected probability of the adoption of a federal climate policy, the Waxman-Markey bill. Similarly, Langer and Lemoine (2019) explore how, after an event occurs, options markets can be used to infer the expected probability of a specific event. However, these approaches cannot be used to infer the beliefs about an unspecified future U.S. climate policy.

³There are additional factors that may motivate the use, and level, of internal carbon prices – e.g., the desire to differentiate products as being environmentally friendly or the private benefits from warm glow. To account for these ulterior motives, we conservatively adjust the observed internal carbon price downward.

⁴This value is approximately equal to the EPA's estimates for the social cost of carbon (EPA, 2016) and it is in line with the 40 dollar per ton tax proposed by the Climate Leadership Council (Baker III et al., 2017) – a proposal that has garnered considerable support from across the political spectrum.

fossil to clean capital. This composition effect is responsible for three quarters of the decline in the pre-tax steady-state emissions. Second, climate policy risk reduces the expected marginal product of capital, leading to a 0.8 percent decrease in the total capital stock. This level effect is largely responsible for the remaining emissions reductions.

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 policy risk leads to reductions in emissions, the environmental costs of delaying policy action are smaller than previously thought. However, it is important to also consider the non-environmental welfare costs incurred by achieving these emissions reductions. Our analysis reveals that the non-environmental welfare cost of the emissions reductions from policy risk are double the welfare costs incurred by achieving the same emissions reductions using a \$3.21/ton tax. This higher cost stems from the fact that, with risk-averse agents, aggregate capital falls by much more in response to policy 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 risk does not reduce the non-environmental welfare costs of adopting a carbon price. At first glance, it might seem that climate policy risk will reduce the non-environmental welfare cost because it transitions the economy part of the way to a world with the carbon tax in place. However, because climate policy risk reduces the aggregate stock of capital, 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 climate policy risk has moved the economy part of the way to the ultimate steady state with a carbon tax.

Our findings also have important implications with regards to evaluating the impacts of adopting a climate policy. To evaluate the macroeconomic impacts of adopting a carbon price, the existing literature implicitly assumes that we begin in a state of the world where there is no anticipation of a potential future policy. This assumption is imposed in work studying the impacts of optimal carbon taxes (e.g., [Nordhaus \(2008\)](#), [Acemoglu et al. \(2012\)](#), [Golosov et al. \(2014\)](#), [Barrage \(2019\)](#)), studies comparing the efficiency and distributional impacts of alternative uses of carbon tax revenues (e.g., [Bovenberg and Goulder \(1996\)](#), [Carbone et al. \(2013\)](#), [Williams et al. \(2015\)](#), [Fried et al. \(2018\)](#)), as well as studies comparing alternative policy tools – e.g., renewable energy policies, emissions standards ([Goulder et al. \(1999\)](#), [Goulder et al. \(2016\)](#)). However, given that forward-looking agents make investments with an understanding that a future climate policy is a real possibility, these previous analyses will misrepresent the true effects of introducing a carbon tax. In particular, our results suggest that analyses that fail to account for the effects of policy risk will overstate the effectiveness of a carbon tax at reducing emissions and its impacts on aggregate macroeconomic outcomes (e.g.,

capital, consumption, etc.). Moreover, we show that the quantitative impacts of climate policy risk grow if the probability of a carbon tax being adopted increases. This pattern suggests that the magnitude of the errors introduced by abstracting from climate policy risk could increase in the future if agents place a greater weight on the likelihood of the government introducing a carbon price as climate change progresses.

More generally, our analysis contributes to a growing literature studying the impacts of environmental policy uncertainty.⁵ Recent work by [Barnett \(2020a,b\)](#) explores how the risk of future climate policy can affect oil market dynamics and asset prices. These studies build on an earlier ‘green paradox’ literature (e.g., [Sinn \(2008\)](#)) arguing the threat of future environmental regulation would increase near-term emissions by accelerating the rate at which fossil fuels are extracted. However, the scope for such a supply-side response, 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-burning plants). Our paper contributes to this line of work by highlighting that climate policy 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. Importantly, even when we allow the threat of future climate policy to shift fossil fuel supply forward in time, we find that the reduction in the demand for fossil energy dominates, leading to a decrease in emissions today.

Also related to our paper, [Bretschger and Soretz \(2018\)](#) study the general equilibrium impacts of climate policy uncertainty, but 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

⁵Related work by [Xepapadeas \(2001\)](#) and [Pommeret and Schubert \(2017\)](#) considers the partial equilibrium impacts of environmental policy uncertainty on firms’ investment and location decisions. 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 Traeger \(2014\)](#)).

models. Similarly, [Krusell and Smith \(1998\)](#) focus on stochastic TFP shocks in a model with heterogeneity. [Fernández-Villaverde et al. \(2015\)](#) and [Born and Pfeifer \(2014\)](#) examine the impacts of uncertainty arising from stochastic policy shocks.⁶ 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. As a result, we are able to quantify the impacts of climate policy risk on the current U.S. economy in which there is no existing federal climate policy, but there is the possibility that climate policy 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 risk and discusses how we use the observed responses to infer firms' beliefs about future climate policy. Section 3 analytically demonstrates the channels through which climate policy risk reduces carbon emissions. Building on the analytic model, Section 4 introduces a richer, general equilibrium model that allows us to quantify the impacts of climate policy risk on the U.S. economy. Section 5 discusses the calibration of the key parameters. Section 6 summarizes the impacts of climate policy risk on emissions and macro aggregates and discusses the resulting implications surrounding the costs of delaying climate policy action. Section 7 concludes.

2. Evidence of climate policy risk

Our objective in this analysis is to quantify the macroeconomic impacts of climate policy risk. Specifically, if agents believe that the government will implement a climate policy at some unknown point in the future, how will they change their investments today? This section summarizes the anecdotal evidence suggesting that this climate policy risk can meaningfully alter investments today. In addition, we discuss how we use the observed evidence to calibrate firms' fundamentally unobservable beliefs surrounding the likelihood of a future climate policy.

Intuitively, for the risk of a future climate policy to meaningfully affect investment, two conditions must be met. First, the likelihood of a federal climate policy being adopted in the near future – i.e. in a period of time that is shorter than the lifespan of the capital investments – cannot be trivially small. While there is no direct measure of the economy-wide probability of a U.S. carbon policy, there is certainly anecdotal evidence suggesting that the probability is not fleetingly small. For one, recent surveys demonstrate that a majority of U.S. adults now support increasing energy prices to combat climate change.⁷ Additionally, several federal climate policy

⁶Also related are [Caliendo et al. \(2019\)](#) and [Kitao \(2018\)](#) which use dynamic, general equilibrium models to examine the uncertainty surrounding the timing and structure of future changes to social security.

⁷For example, 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.

proposals were nearly adopted over the past decade (e.g., Waxman-Markey, the Clean Power Plan). This broad base of public support suggests that there is widespread awareness that a federal climate policy could be adopted in the near future.⁸

The second condition that must be met for climate policy 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 CO₂. 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 CO₂ (Baker III et al., 2017). 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 the CLC's proposed \$40/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 ample anecdotal evidence across a wide range of industries that firms adjust investment at least partly in response to climate policy risk. For example, some firms have begun to set their own internal emissions targets.⁹ In a recent survey of 138 of the largest firms in the highest emitting sectors, Dietz et al. (2018) note that 85 percent have established internal policies committing them to reduce carbon emissions using a range of alternative approaches (e.g., energy efficiency targets). Similarly, many firms have voluntarily adopted stricter regulations than those imposed by the federal government. For example, automakers Ford, Honda, Volkswagen, and BMW chose to adopt California's proposed, stricter fuel economy standards, which would have required an average fuel economy for new cars and trucks equal to 54.5

⁸Indeed, 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)"

⁹For example, Walmart launched Project Gigaton in 2017 to reduce emissions throughout its supply chain. The company reduced emissions by 6.1 percent in 2017 and 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). Similarly, Kroger's 2020 sustainability goals include reducing electricity consumption by 40 percent from a year 2000 baseline. To meet the target, the company invests in energy efficient features in both new and existing stores (Kroger, 2019). Likewise, Mars Inc.'s climate action plan includes reducing greenhouse gas emissions across its value chain by 27 percent by 2025 and by 67 percent by 2050 (Mars, 2018).

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.¹⁰

While the anecdotal evidence above suggests that firms meaningfully alter their investments in response to climate policy risk, these examples don’t provide a clear approach to systematically quantify how the level and composition of capital investment are affected by the climate policy risk. Ultimately, to quantify the effects of the climate policy risk, we would need to calibrate the fundamentally unobservable beliefs firms have surrounding the likelihood of future climate policy. To provide our best approximation of these unobservable beliefs, we take advantage of a unique, voluntary mechanism a large number of firms have begun using to reduce their carbon intensity – internal carbon prices.

There are two broad types of internal carbon price instruments, the most common being an internal “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](#)). For example, to guide long-term capital investment decisions, Shell uses a shadow price of \$40/ton of CO₂ – which has reportedly resulted in the decision to pass on many potential CO₂-intensive investment opportunities. The second type of internal carbon price is a carbon fee. In contrast to the shadow price, the fee is actually an internal tax a firm levies on its direct emissions, or on the emissions embodied in its energy use. The revenue raised by this internal tax can be transferred 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 CO₂ on the emissions resulting from its energy use – with the revenue being used to purchase carbon offsets and renewable energy credits.

The use of internal carbon prices has become widespread. In a survey of nearly 5,000 firms performed by CDP (Carbon Disclosure Project), 517 reported using internal carbon prices and another 732 had plans to adopt internal prices within two years ([CDP, 2016](#)).¹¹ Over half of the surveyed firms in the energy sector, which is the most exposed to climate policy risk, use internal carbon prices. Similarly, 35 percent of firms in the materials sector and 23 percent in the industrial sector reported the use of internal carbon prices.

In our subsequent quantitative analysis, we use the observed internal carbon fees publicly reported by firms to infer firms’ subjective probability of a climate policy being adopted. Among

¹⁰Similarly, 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](#)).

¹¹Many of these firms are either located in the U.S. or do business in the U.S.

the firms that publicly report their internal carbon fees, there is a modal price of \$10/ton of CO₂. This is also consistent with the average carbon fee reported by firms surveyed by the World Business Council for Sustainable Development (WBCSD, 2015). It is important to stress that there is a very small sample of internal carbon fees that we are able to observe.¹² While there are a much larger number of firms reporting internal carbon prices, these are typically shadow prices. The shadow price only contains information surrounding a firm's expected level of the tax, not the firm's beliefs surrounding 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 \$45/ton of CO₂. Whether or not the firm chooses to undertake that investment depends on the probabilities the firm places on each scenario, which we do not observe. In contrast, 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. The level that firms choose for the fee contains information on both the probability and level of the expected tax. As a result, we can use the internal carbon fee to calibrate firms' subjective probability of a future carbon tax.

Importantly, surveys of firms using internal carbon prices suggest that the “single largest motivation for adopting a shadow 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. However, firms may also be motivated to reduce emissions by a desire to differentiate their product(s) as being “green” or to mitigate reputation risks. The use of an internal carbon fee to raise revenues for pro-social/environmental objectives may also be partially driven by a belief in corporate social responsibility. Therefore, while the modal carbon fee is \$10/ton of CO₂, this price level may be motivated by more than climate policy risk. We use two approaches to address this concern. First, we conservatively deflate the observed carbon fee, assuming that only a portion of the fee is motivated by climate policy risk. Second, we explore how the quantitative impacts vary using a range of internal carbon fees. In each case, we use our model to back out what firms' beliefs about a future carbon tax must be to rationalize the use of an internal carbon fee. With these inferred beliefs, we explore the macroeconomic response to climate policy risk.

¹²We have information on the level of the internal carbon fee for the following companies: Walt Disney, Microsoft, Phillip Morris, Ben and Jerry's, and Google.

3. Model

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

3.1. Environment

The economy is comprised of 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:

$$y = (x^c)^\gamma (x^f)^\theta l^{1-\gamma-\theta}. \quad (1)$$

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 . The fossil intermediate is produced competitively from fossil capital, k^f , and fossil fuel, f . Both production functions feature constant returns to scale and are given by:

$$x^c = k^c \quad \text{and} \quad x^f = \min[k^f, f]. \quad (2)$$

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 changes in response 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 performs 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.

3.2. The pre-tax steady state

We study a steady state designed to reflect the climate policy 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 policy 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 transitioning back to the world without the carbon tax. We focus on the steady state outcome prior to the economy transitioning to this absorbing state. 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. However, there is always a chance that a carbon tax introduced in the U.S. 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 risk on the macroeconomy.

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:

$$p^c = \gamma(x^c)^{\gamma-1}(x^f)^\theta \quad \text{and} \quad p^f = \theta(x^c)^\gamma(x^f)^{\theta-1}. \quad (3)$$

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:

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

subject to the law of motion for clean capital:

$$k^{c'} = (1-\delta)k^c + i^c. \quad (5)$$

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 (4) 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, $W_1^c(k^{c'})$, and the continuation value if the government does not introduce the carbon tax and the economy remains in the pre-tax steady state, $V^c(k^{c'})$. 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:

$$W_t^c(k^c) = \max_{k^{c'}} \left\{ p^c k^c - i^c + \left(\frac{1}{1+r} \right) W_{t+1}^c(k^{c'}) \right\}, \quad (6)$$

subject to the law of motion for clean capital, equation (5). 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:

$$V^f(k^f) = \max_{k^{f'}, f} \left\{ p^f k^f - \zeta f - i^f + \left(\frac{1}{1+r} \right) [\rho W_1^f(k^{f'}) + (1-\rho)V^f((k^f)')] \right\}, \quad (7)$$

subject to the law of motion for fossil capital:

$$k^{f'} = (1-\delta)k^f + i^f, \quad (8)$$

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 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:

$$W_t^f(k^f) = \max_{k^{f'}, f} \left\{ p^f k^f - (\zeta + \tau) f - i^f + \left(\frac{1}{1+r} \right) W_{t+1}^f(k^{f'}) \right\}, \quad (9)$$

subject to the law of motion for fossil capital, equation (8), 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 risk (i.e. $0 < \rho < 1$) to a naïve pre-tax steady state without climate policy 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 (4) and (7).
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.

3.3. The aggregate effects of climate policy risk

Solving for the pre-tax steady state, we find that climate policy risk operates through two key channels to reduce emissions today. First, policy 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:

$$\frac{K^f}{K^c} = \left(\frac{\theta}{\gamma}\right) \left(\frac{r + \delta}{r + \delta + \zeta + \rho\tau}\right), \quad (10)$$

where uppercase letters denote aggregate quantities.¹³ 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 policy risk reduces the carbon intensity of current production and the associated emissions.

Turning next to the second channel, the reduction in the level of capital from climate policy risk, the levels of clean and fossil capital in the pre-tax steady state equal:

$$K^c = \left(\frac{\gamma}{r + \delta}\right)^{\frac{1}{1-\gamma-\theta}} \left(\frac{r + \delta}{r + \delta + \zeta + \rho\tau}\right)^{\frac{\theta}{1-\gamma-\theta}} \left(\frac{\theta}{\gamma}\right)^{\frac{\theta}{1-\gamma-\theta}} \quad \text{and} \quad (11)$$

$$K^f = \left(\frac{\gamma}{r + \delta}\right)^{\frac{1}{1-\gamma-\theta}} \left(\frac{r + \delta}{r + \delta + \zeta + \rho\tau}\right)^{\frac{1-\gamma}{1-\gamma-\theta}} \left(\frac{\theta}{\gamma}\right)^{\frac{1-\gamma}{1-\gamma-\theta}}. \quad (12)$$

The expressions for K^c and K^f are both decreasing in the probability, ρ , and the size, τ , of the carbon tax, implying that climate policy risk reduces 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 risk reduces the expected marginal product of capital, causing total capital to fall. The decline in the total capital is exacerbated by the fact that the policy risk itself also moves the ratio of fossil to clean capital (equation (10)) away from the privately optimal outcome in the baseline, further reducing the expected marginal product of capital.

Like climate policy 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 risk, the composition and level of capital would still be defined by equations (10)-(12). However, the climate policy risk term, $\rho\tau$, would be replaced with the actual carbon tax, $\tilde{\tau}$. Indeed, in this simple model, the effects of climate policy 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

¹³See Appendix A for the derivation. We assume that $\tau < (r + \delta)/(1 - \rho)$ to ensure that an equilibrium exists.

tax, $\rho\tau$, from the pre-tax steady state with climate policy risk.

4. Quantitative model

We develop a richer, general equilibrium model to quantify the effects of climate policy risk on the U.S. economy. The quantitative model differs from the analytic model in several dimensions. 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.

4.1. 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:

$$x^c = A^c (k^c)^\alpha (l^c)^{1-\alpha} \quad \text{and} \quad x^f = A^f \min[(k^f)^\alpha (l^f)^{1-\alpha}, \mu f]. \quad (13)$$

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.¹⁴ The law of motion for non-energy

¹⁴If 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.

capital is symmetric to that for fossil and clean capital:

$$k^{n'} = (1 - \delta)k^n + i^n, \quad (14)$$

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:

$$x^n = A^n (k^n)^\alpha (l^n)^{1-\alpha}. \quad (15)$$

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:

$$y = \left((x^e)^{\frac{\phi-1}{\phi}} + (x^n)^{\frac{\phi-1}{\phi}} \right)^{\frac{\phi}{\phi-1}} \quad \text{where} \quad x^e = \left((x^c)^{\frac{\varepsilon-1}{\varepsilon}} + (x^f)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}. \quad (16)$$

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

4.2. Partially irreversible investment

The analytical results in Section 3 demonstrate that the introduction of a carbon tax decreases demand for fossil capital. This could be extremely costly for the 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:

$$G(i) = \frac{\lambda}{2} \left[-i + (i^2 + \eta)^{\frac{1}{2}} \right], \quad (17)$$

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 :

$$H(i) = \begin{cases} 0 & : i \geq 0 \\ |\lambda i| & : i < 0. \end{cases} \quad (18)$$

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

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

4.3. Households

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

$$u(c, h) = \frac{c^{1-\sigma}}{1-\sigma} - \chi \frac{h^{1+\frac{1}{\theta}}}{1+\frac{1}{\theta}}, \quad (19)$$

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

4.4. 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

(3) in the analytic model. We focus our attention instead on the dynamic decisions made by clean, fossil, and non-energy entrepreneurs under climate policy 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:

$$c = wh + \pi^n + \pi^f + \pi^c. \quad (20)$$

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

$$\pi^c = p^c x^c - wl^c - i^c - G(i^c), \quad (21)$$

$$\pi^f = p^f x^f - \zeta f - wl^f - i^f - G(i^f), \quad \text{and} \quad (22)$$

$$\pi^n = p^n x^n - wl^n - i^n - G(i^n). \quad (23)$$

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 without a carbon tax, 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:

$$\begin{aligned} V(k^c, k^f, k^n) = & \max_{k^{c'}, k^{f'}, k^{n'}, h, l^c, l^f, l^n, f} \frac{c^{1-\sigma}}{1-\sigma} - \chi \frac{h^{1+\frac{1}{\theta}}}{1+\frac{1}{\theta}} \\ & + \beta [\rho W_1(k^{c'}, k^{f'}, k^{n'}) + (1-\rho)V(k^{c'}, k^{f'}, k^{n'})]. \end{aligned} \quad (24)$$

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:

$$W_t(k^c, k^f, k^n) = \max_{k^{c'}, k^{f'}, k^{n'}, h, l^c, l^f, l^n, f} \frac{c^{1-\sigma}}{1-\sigma} - \chi \frac{h^{1+\frac{1}{\theta}}}{1+\frac{1}{\theta}} + \beta W_{t+1}(k^{c'}, k^{f'}, k^{n'}). \quad (25)$$

The household's budget constraint over the transition includes the transfers, T , from the carbon

tax revenue:

$$c = wh + \pi^n + \pi^f + \pi^c + T. \quad (26)$$

Similarly, 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:

$$\pi^f = p^f x^f - (\zeta + \tau)f - wl^f - i^f - G(i^f). \quad (27)$$

The expressions for the clean and non-energy entrepreneurs' profits over the transition are the same as in equations (21) and (23).

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 $\{p^f, p^c, p^x, w\}$ and household allocations $\{k^c, k^f, k^x, f, x^c, x^f, l\}$ 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 risk (i.e. $0 < \rho < 1$) or it could be a naïve pre-tax steady state without climate policy 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 described in Appendix B.

5. Calibration

Recall that the existing general equilibrium analyses of climate policies implicitly assume that in the current, baseline state of the world, agents do not expect a federal carbon price in the future. In contrast, the evidence presented in Section 2 suggests that agents do indeed place a positive probability on the adoption of future climate policy. To capture this fact, 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 federal carbon tax in the future. We assume that, if adopted, the future carbon tax will be set at \$45 (in 2017 dollars) per ton of CO₂, approximately equal to the EPA's estimates of the social cost of carbon (EPA, 2016).¹⁵

The model time period is one year. We calibrate seven parameters, $\{\alpha, \varepsilon, \phi, \lambda, \eta, \theta, \sigma\}$ directly from the data and existing literature. Given these directly calibrated parameters, we

¹⁵Using a three percent discount rate, the EPA reports the social cost of carbon equal in 2015 equal to \$42/ton and in 2020 equal to \$49/ton (both values are in year 2017 dollars). This value of the tax is slightly higher than the \$40/ton proposed by the CLC and considerably lower than what would be required to achieve the Green New Deal and some presidential candidates' target of carbon neutrality by 2050.

jointly calibrate the remaining seven parameters $\{\mu, A^c, A^f, \delta, \beta, \chi, \rho\}$ so that seven moments in the model match a set of seven empirical targets. Tables 1 and 2 report the parameter values that result from the direct calibration and the method-of-moments procedure, respectively.

Table 1: Parameter Values: Direct Calibration

Parameter	Value
<i>Production</i>	
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
<i>Preferences</i>	
Frisch labor supply elasticity: θ	0.5
CRRA coefficient: σ	2
<i>Policy risk</i>	
Size of the carbon tax: τ	0.61

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

Much of the calibration approach is standard in the macro literature. The important novelty is specifying firms’ beliefs, ρ , surrounding the likelihood of the future tax. While we do the best that we can to pin down the perceived probability of the tax from firms’ behavior, we do not directly observe the probability itself. The quantitative results should be interpreted with this data limitation in mind. Section 5.1 calibrates the carbon tax probability and Section 5.2 calibrates the remaining parameters. Appendix C reports additional details and describes all data sources used in the calibration.

5.1. Climate policy risk

As discussed in Section 2, there is ample evidence that firms incorporate the risk of future climate policy into their investment decisions. The data on internal carbon fees provides a tool to directly measure how firms respond to future climate policy risk. The modal carbon fee used by U.S. firms is approximately \$10/ton. While this internal fee is used primarily to address climate policy risk, firms may also be motivated to use internal carbon fees to achieve warm glow, or to differentiate their products as being “green”. These additional motives – which we cannot quantify – could inflate the carbon fee relative to the level the firms would set purely to address the climate policy risk. Moreover, we only observe carbon fees for a small

subset of firms. We use two approaches to address these concerns. First, to be conservative, we assume that half of the internal carbon fee is to address alternative motives and half is to address climate policy risk; we use an internal fee of \$5/ton in the main calibration. Second, we report a range of results corresponding to different assumptions regarding the extent to which the level of the \$10/ton internal carbon fee is motivated by climate policy risk.

Table 2: Parameter Values: Method of Moments

Parameter	Value
<u>Production</u>	
Leontief parameter: μ	6.98
Clean productivity: A^c	1.25
Fossil productivity: A^f	2.00
Depreciation rate: δ	0.09
<u>Preferences</u>	
Discount factor: β	0.97
Disutility of labor: χ	117.32
<u>Policy risk</u>	
Probability of the carbon tax: ρ	0.10

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.

The \$5/ton internal carbon fee allows us to quantify firms' investment response to climate policy risk. Consider a simple numerical example to illustrate the intuition. Suppose that the \$5/ton internal fee reduces the ratio of fossil to clean capital by 10 percent from a world in which there is no risk of future policy. We interpret this change in the capital mix as firms' optimal response to climate policy risk. We then find the probability that firms would have to place on the \$45/ton tax, such that it is optimal to reduce the ratio of fossil to clean capital by 10 percent, relative to a world with no risk of future policy. We use this probability as our calibrated value of ρ .

In sum, we choose ρ so that it is optimal for firms to apply a \$5/ton internal fee when they make their investment decisions. Mechanically, we solve for a steady state in which there is no risk, but there is a \$5/ton internal fee. We solve for a second steady state in which there is no internal fee, but there is a probability, ρ , that the government will introduce a carbon tax in the next period. We choose ρ (jointly with the other parameters) so that the ratio of fossil to clean capital is the same in both steady states. The resulting value of ρ equals 0.098. This value implies approximately a 50 percent probability that the government will implement the \$45/ton carbon tax within the next eight years.

5.2. Production and preferences

We set capital’s income share, α , equal to one third. We choose Leontief parameter μ so that the fossil energy share of GDP equals 0.04 (Golosov et al., 2014). We normalize the fossil fuel extraction cost, ζ , to unity. This amounts to an implicit choice of units. We calculate that the \$45/ton carbon tax is approximately 61 percent of the 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 choose the depreciation rate on capital, δ , to match the investment to output ratio of 23.3 percent. 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 loses 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 0.18.

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, 2019). 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 66 percent of autos and 80 percent of light trucks are fossil capital. Thus, we classify 66 percent of vehicle miles traveled by autos and 80 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 2.63. The ratio of fossil to clean intermediate production targeted in our calibration equals $X^f/X^c = 2.17$, 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.¹⁶

Table 3: Model Fit

Moment	Model	Target
Fossil-total capital ratio: K^f/K	0.18	0.18
Fossil-clean intermediates ratio: X^f/X^c	2.17	2.17
Fossil-energy share: $\zeta F/Y$	0.04	0.04
Capital-output ratio: K/Y	2.6	2.6
Investment-output ratio: I/Y	0.23	0.23
Fraction of time endowment spent working	0.33	0.33

Note: This table reports the empirical and model values of six of the seven moments that we use for the calibration. The seventh moment is the requirement that the ratio of fossil to clean capital in the pre-tax steady state with policy risk equals the ratio in a deterministic steady state with a \$5/ton internal carbon fee.

We set the discount rate, β , equal to 0.97 to match the U.S. capital-output ratio of 2.6. 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, θ_2 , equal to 0.5. We choose the dis-utility of hours so that workers spend one third of their time endowment working. Table 3 summarizes the empirical and model values for six of the seven moments used in the calibration. The seventh moment is the requirement that the ratio of fossil to clean capital in

¹⁶Combined, electricity and transportation produced 3,267 million metric tons of carbon dioxide in 2017; 48 percent of these emissions were from the electricity sector and the remaining 52 percent were from the transportation sector (EIA, 2019).

the pre-tax steady state with policy risk equals the ratio in the deterministic steady state with a \$5/ton internal carbon fee, as described in Section 5.1.

6. Results

We first use our calibrated model to quantify the impacts of climate policy risk on outcomes in the current U.S. economy. We next explore the implications of climate policy risk for delaying action on climate change and for how we evaluate climate policies. We examine how our main results would change over a range of different probabilities of a future carbon tax. Lastly, we study how our focus on the demand-side response to climate policy risk compares to the Green Paradox literature’s focus on the supply-side response to climate policy risk.

6.1. The effects of climate policy risk on the macroeconomy

We solve the model for four steady states. First, we solve for a pre-tax steady state without climate policy risk (i.e. $\tau = 0$ and $\rho = 0$). Second, we solve for a pre-tax steady state with climate policy risk. We assume that there is a 9.8 percent probability that the government will introduce a \$45/ton tax in the next period. Third, we solve for an “emissions-equivalent” steady state in which we remove policy risk and impose a carbon tax that results in the same level of emissions as the pre-tax steady state with climate policy risk. Finally, we solve for a policy steady state with a \$45/ton tax in place and no climate policy risk. Table 4 reports the percentage changes in various outcomes in (1) the pre-tax steady state with climate policy risk, (2) the emissions-equivalent steady state, and (3) the policy steady state, all relative to the pre-tax steady state without climate policy risk.

Focusing on Column (1), we see that climate policy risk reduces emissions by 1.15 percent. For comparison, emissions fall by 15.24 percent in the policy steady state. Hence, climate policy risk by itself is responsible for approximately 8 percent of the total drop in emissions going from a world with no risk of a future carbon tax to a world with a carbon tax in place.

Climate policy 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, climate policy risk distorts the economy away from the privately optimal allocations of capital and labor, reducing the marginal product of capital. The first column of Table 4 highlights that this results in a 0.8 percent decrease in the total stock of capital. This level effect is responsible for 25 percent of the reduction in emissions caused by climate policy risk.¹⁷

¹⁷To quantify the impact of the level effect alone, we hold the relative composition of capital and labor across sectors constant in the pre-tax steady state without climate policy risk and reduce the aggregate capital and labor to the aggregate levels observed in the pre-tax steady state with risk.

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

	Pre-tax risk SS	Emissions- equivalent SS	Policy SS
<i>Emissions</i>			
Fossil fuel: F	-1.15	-1.15	-15.24
<i>Level effect</i>			
Total capital: K	-0.80	-0.32	-4.09
Total labor: L	-0.02	-0.05	-0.57
<i>Composition effect</i>			
Fossil to clean capital: K^f / K^c	-3.85	-2.49	-28.97
Fossil to clean labor: L^f / L^c	-1.42	-2.49	-28.97
Fossil to clean intermediates: X^f / X^c	-2.23	-2.49	-28.97
<i>Output and consumption</i>			
Output: Y	-0.32	-0.18	-2.46
Consumption: C	-0.11	-0.08	-1.22

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

Turning next to the composition effect, Table 4 highlights that the ratio of fossil to clean capital falls by 3.85 percent in response to climate policy risk. The effect of this change in the composition of capital on emissions is partly undone by the entrepreneurs' ability to adjust labor after they learn 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 risk; the drop in the ratio of fossil to clean labor is roughly a 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 2.23 percent.¹⁸

The emissions reductions caused by the response to policy risk are equal to the emissions reductions that would be achieved in a steady state with no risk and a carbon tax of \$3.21/ton.

¹⁸The compositional changes in capital and labor across sectors are responsible for 77 percent of the drop in emissions caused by climate policy risk. To quantify the impact of the compositional changes, we hold aggregate capital and labor constant in the pre-tax steady state without policy 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 risk.

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 $\rho \times \tau = 0.098 \times \$45 = \$3.45$ which is greater than the \$3.21 carbon tax required to achieve the reductions in emissions from climate policy risk.

Referring to the second column of Table 4, the emissions-equivalent tax operates through the same level and composition channels as climate policy risk to reduce emissions. The tax reduces the level of capital by 0.32 percent and decreases the ratio of fossil to clean capital by 2.49 percent. However, the magnitudes and relative importance of the channels differ between the pre-tax steady state with climate policy risk and the emissions-equivalent steady state. In particular, the emissions reductions from the \$3.21 tax are achieved with a smaller reduction in capital. While the level effect alone was responsible for 25 percent of the emissions reductions stemming from climate policy risk, the level effect only accounts for 13 percent of the emissions reductions achieved with the emissions-equivalent tax.¹⁹

Climate policy 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 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 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 risk, resulting in an even larger decrease in the marginal product of capital in the pre-tax steady state with climate policy risk. Intuitively, when entrepreneurs make investment decisions in the presence of policy 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 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,

¹⁹The compositional changes in capital and labor across sectors caused by the emissions-equivalent tax account for 89 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.

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 risk. Combined, the different timing of the labor and capital decisions and the risk-averse households imply that climate policy risk relies more heavily on the decrease in the total capital stock to reduce emissions.

Our baseline model assumes that it is costly to sell used capital and that the carbon tax, once implemented, is in place forever. Table 5 reports the sensitivity of our results to both of these assumptions. Column 2 of Table 5 shows how the pre-tax steady state outcomes change in response to climate policy risk when we re-calibrate the model under the assumption that there are no adjustment costs ($\lambda = 0$). Compared to the original baseline results (repeated in Column 1 of Table 5), we find that removing the adjustment cost has negligible impacts on the quantitative results. The intuition stems from the fact that 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 costs relatively small.

To explore how the results are affected by the possibility that the carbon tax is repealed, we continue to assume that, prior to a policy being adopted, firms believe their is a constant probability, ρ , of a carbon tax being imposed in the subsequent period. However, once the tax is adopted, we now assume that it is known that the policy will be permanently repealed after a given number of years. We re-calibrate our model under this alternative assumption. Of course, in the real world, 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 policy risk would be if there is a chance of repeal. The last four columns of Table 5 display how policy 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. 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 risk. For example, climate policy risk reduces emission by 0.93 percent when the policy ends after a single year, compared to 1.15 percent when the policy lasts forever.

Table 5: Sensitivity: Adjustment Costs and Repeal

	Baseline	No adjustment cost	Tax repealed after			
			1 yr	2 yrs	4 yrs	8 yrs
<u>Emissions</u>						
Fossil fuel: F	-1.15	-1.17	-0.93	-0.96	-1.01	-1.07
<u>Level effect</u>						
Total capital: K	-0.80	-0.87	-0.15	-0.25	-0.39	-0.58
Total labor: L	-0.02	-0.02	-0.00	-0.01	-0.01	-0.01
<u>Composition effect</u>						
Fossil to clean capital: K^f / K^c	-3.85	-3.85	-3.85	-3.85	-3.85	-3.85
Fossil to clean labor: L^f / L^c	-1.42	-1.44	-1.44	-1.43	-1.42	-1.42
Fossil to clean inputs: X^f / X^c	-2.23	-2.24	-2.24	-2.23	-2.23	-2.23
<u>Output and consumption</u>						
Output: Y	-0.32	-0.34	-0.09	-0.12	-0.17	-0.24
Consumption: C	-0.11	-0.12	-0.02	-0.04	-0.06	-0.08

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 zero adjustment costs and (3)-(6) assuming that the carbon tax is repealed after one, two, four, or eight years.

6.2. Implications for the costs delaying action on climate change

Our quantitative findings provide new insights surrounding the costs of delaying action on climate change. One interpretation of the results is that, since climate policy 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 risk.

To quantify the non-environmental welfare costs of climate policy risk, we calculate the consumption-equivalent variation (CEV) in the pre-tax steady state with risk.²⁰ 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. We find the non-environmental welfare cost of reducing emissions through climate policy risk is over twice as high as using an actual tax. The CEV in the pre-tax steady state with policy risk is -0.09 while the CEV in the emissions-equivalent steady state is -0.04 . This higher cost stems from the fact that, unlike the emissions-equivalent tax, climate policy risk does not induce the level and composition effects that achieve the most efficient emissions reductions. Rather,

²⁰These CEV measures do not capture any welfare changes stemming from the environmental benefits of lower emissions.

climate policy risk relies more heavily on reductions in total capital. Thus, while climate policy risk reduces emissions, it is a very costly way to achieve the emissions reductions.

It is also important to consider how climate policy 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 steady states (with or without policy risk) to an economy that undergoes the dynamic transition towards the eventual policy steady state. Climate policy risk has almost no effect on this transitional welfare cost; the CEV if the economy begins in the pre-tax steady state with policy risk equals -0.24 while the CEV if the economy begins in the pre-tax steady state without risk equals -0.25 .

This near equivalence in the transitional CEVs stems from three counteracting forces. First, climate policy 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 risk, further reducing the non-environmental welfare cost. However, the third factor works in the opposite direction. Because climate policy 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 risk will not reduce the non-environmental welfare cost after a carbon price is imposed.

6.3. Climate policy evaluation

Our results demonstrate that climate policy risk can have meaningful macroeconomic impacts. Yet, the existing literature evaluating the impacts of carbon tax policies abstracts from the effects of climate policy risk. Instead, previous studies quantify the macro impacts of carbon tax policies by comparing two states of the world – a future with a carbon tax (i.e. the policy steady state) versus a baseline world in which agents proceed as though there will never be a carbon tax (i.e. the pre-tax steady state without policy risk). Importantly, if the world is more accurately represented by the pre-tax steady state with policy risk, then such a comparison would misrepresent the true impact of adopting a carbon tax.

Table 6: Importance of the Baseline For Climate Policy Evaluation

	Predicted percent change from carbon tax		Percent error
	With risk	Without risk	
Decrease in emissions	14.3	15.2	8.2
Decrease in K^f / K^c	26.1	29.0	15.3
Decrease in total capital	3.3	4.1	24.4
Decrease in output	2.1	2.5	14.7
Decrease in consumption	1.1	1.2	10.0

Note: Columns (1) and (2) report the predicted percent change in each variable in the policy steady state with a \$45/ton carbon tax. Column (1) uses the pre-tax steady state with climate policy risk as the baseline from which to calculate the percent change, while Column (2) uses the pre-tax steady state without climate policy risk as the baseline. Column (3) reports the percent error in the response of each variable from using the pre-tax steady state without climate policy risk as a baseline. For example, the first row of Column (3) implies that the predicted decrease in emissions from the carbon tax is 8.2 percent larger when baseline equals the pre-tax steady state without climate policy risk.

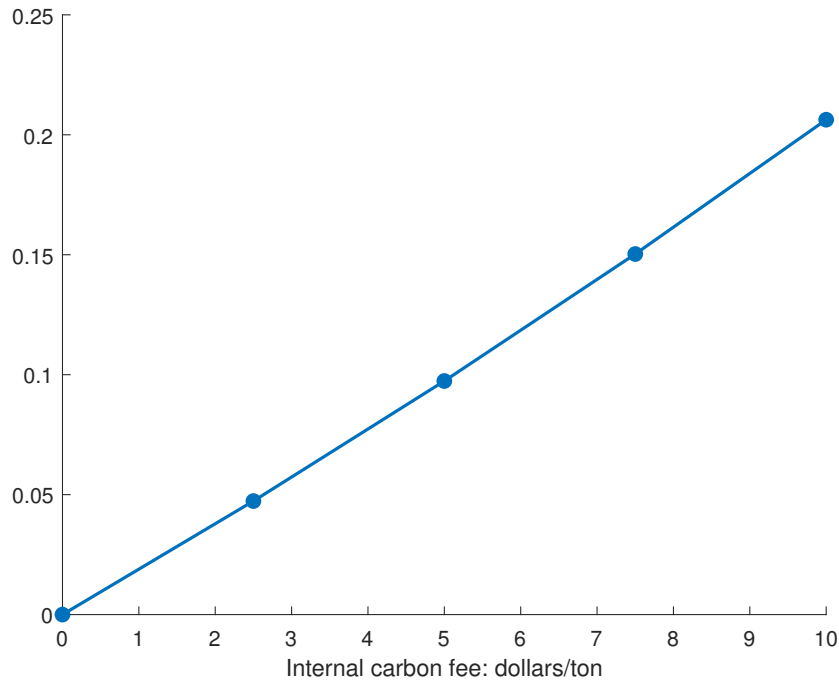
To demonstrate the importance of the choice of the baseline for policy evaluation, we compare how aggregate outcomes change between a world with a \$45/ton tax and two alternative baseline worlds – one assuming the pre-tax steady state without risk is the baseline and the second assuming the pre-tax steady state with policy risk is the baseline. Table 6 displays the predicted changes caused by the carbon tax using the two alternative baselines.

Focusing first on emissions, we find that failing to account for climate policy risk by using the pre-tax steady state without climate policy risk as the baseline, overstates the emissions reductions by 8.2 percent. Intuitively, since emissions are already lower in the pre-tax steady state with risk, measuring the emissions reductions between the policy steady state and the pre-tax steady state without risk implies a larger effect of the carbon tax. Similarly, we find that abstracting from the impacts of climate policy risk will cause policy evaluations to meaningfully overstate the impacts of a carbon tax on a range of important macro aggregates (e.g., capital, output, consumption).

6.4. Changes in climate policy risk

We explore how our results differ across a range of assumed probabilities of a future carbon tax. 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.

Figure 1: Probability of a Carbon Tax

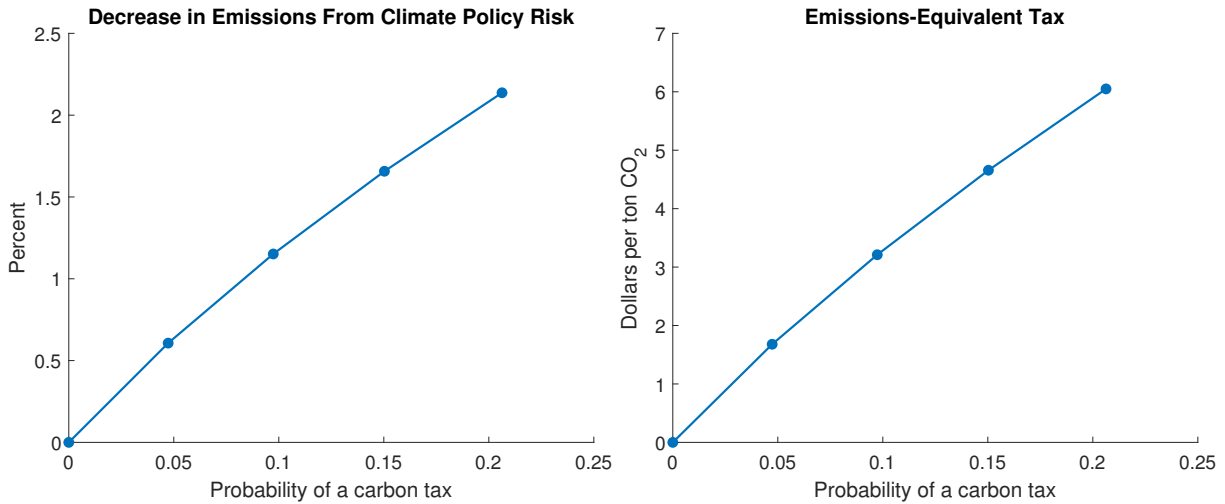


Note: This figure plots the calibrated probability of a carbon tax consistent with a given internal carbon fee. We recalibrate the model for internal carbon fees equal to 2.5, 5, 7.5, and 10 dollars per ton CO₂.

Recall, to calibrate the probability of a carbon tax in the model, we used an internal carbon price of \$5/ton, half of the value that we observe at U.S. companies. This choice assumes that half of the internal carbon fee is motivated by climate policy risk and half is motivated by factors not related to climate policy risk. However, the correct share of the internal carbon fee that is motivated exclusively by climate-policy-risk could range from anywhere between zero and one. To understand the effects of assuming that different shares of the \$10/ton internal carbon fee are motivated by climate policy risk, we recalibrate the model for internal carbon fees equal to \$2.50, \$7.50, and \$10 dollars per ton.²¹ Figure 1 plots the corresponding probability of a carbon tax for each value of the internal carbon fee. The inferred probability of a carbon tax being adopted increases linearly with the size of the internal carbon fee, ranging from approximately 5 percent when the internal fee equals \$2.50/ton to 20 percent when the internal fee equals \$10/ton. The \$10/ton internal fee assumes that the entire fee is motivated by climate policy risk, serving as an upper bound on the probability that firms currently place on the introduction of the \$45/ton tax.

²¹In addition, we perform an alternative experiment in which we alter the probability of a carbon tax but do not recalibrate the model. Rather than testing the sensitivity of our findings with respect to the unknown internal carbon fee, this experiment directly examines how the outcomes differ if the subjective probability of a future carbon tax were to be different in the future. Figures corresponding to Figures 2 and 3 with and without recalibrating the model are displayed in Appendix D. Ultimately, the results are very similar regardless of whether the model is recalibrated or not.

Figure 2: Emissions' Reduction From Climate Policy Risk



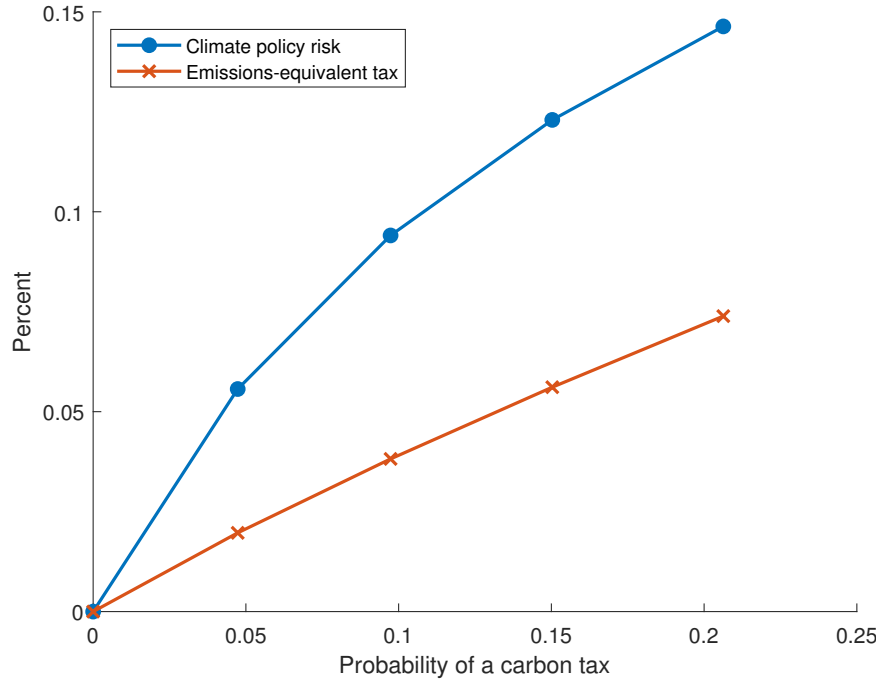
Note: For each carbon tax probability, the left panel plots the emissions reductions in the pre-tax steady state with climate policy risk relative to the pre-tax steady state without climate policy risk. The right panel displays the corresponding carbon tax that would achieve the same steady state emissions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

The left panel of Figure 2 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 2 displays the corresponding carbon tax that would achieve the same steady state emissions reductions as the climate policy risk outcome. As the inferred probability of a future carbon tax increases, the emissions-equivalent tax grows.

We also explore the non-environmental welfare impacts of climate policy risk across the different implied probabilities of a carbon tax. Figure 3 compares the non-environmental welfare changes (measured using the CEV) in the climate policy risk and emissions-equivalent steady states, relative to the pre-tax steady state with no climate policy risk. Again, the non-environmental welfare costs incurred are lower if the emissions reductions are achieved using a carbon tax instead of climate policy risk. Importantly, the gap between the the non-environmental welfare costs of climate policy risk versus the emissions-equivalent tax does not diminish as the likelihood of a future tax policy increases, implying that climate policy risk remains a very costly way to reduce emissions.

Additionally, we examine how the effect of climate policy risk on the transitional welfare costs from adopting a carbon tax vary with the implied carbon-tax probability. We find that regardless of the probability of the carbon tax being adopted, the difference in the welfare cost if the transition begins from the pre-tax steady state with or without climate policy risk

Figure 3: Welfare Cost of Climate Policy Risk and Emissions Equivalent Tax (CEV)



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

is always less than 0.01 percentage points. Hence, the non-environmental welfare costs of adopting a carbon tax do not fall as the presumed probability of a future policy increases.

Overall, we find that the impact of climate policy risk on emissions, output, and other aggregates grows with the likelihood of the policy. Consequently, as Table 7 highlights, the errors introduced by using the pre-tax steady state without policy risk as the baseline for policy evaluation increase with the probability of adoption. For example, as the probability of the carbon tax increases from 5 to 21 percent, the error in the measured emissions reductions from ignoring the effects of climate policy risk increases from 4.1 to 16.5 percent. Hence, if the future is characterized by higher carbon-tax probabilities, then it will be even more important to understand and incorporate the effects of climate policy risk going forward.

Table 7: Percent Error From Ignoring Climate Policy Risk

	Probability of a future carbon tax			
	$\rho = 0.05$	$\rho = 0.10$	$\rho = 0.15$	$\rho = 0.21$
Decrease in emissions	4.1	8.2	12.3	16.5
Decrease in K^f / K^c	7.2	15.3	24.5	35.0
Decrease in total capital	13.4	24.4	33.8	41.8
Decrease in output	8.1	14.7	20.3	25.2
Decrease in consumption	5.7	10.0	13.4	16.2

Note: Each column reports the percent error from using the pre-tax steady state without risk as a baseline for different carbon tax probabilities. For example, the first row of Column (1) implies that if the probability of a carbon tax is 5 percent, then the predicted decrease in emissions from the carbon tax is 4.1 percent larger when baseline equals the pre-tax steady state without climate policy risk instead of the pre-tax steady state with climate policy risk.

6.5. Accounting for Shifts in Fossil Fuel Supply

Our analysis highlights that climate policy 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 risk on the current demand for fossil fuels, the Green Paradox literature (e.g., [Sinn \(2008\)](#)) focuses instead on the potential impacts of policy 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 risk on emissions, we extend our model to include a reduced-form supply-side response to climate policy risk. We find that even when we allow for a supply-side response, the demand-side response dominates, and the net effect of climate policy risk is still to reduce emissions today.

To incorporate such a supply-side response in our quantitative model, we now allow the fossil fuel price to vary inversely with the level of climate policy risk.²² For example, in a setting with an upward-sloping fossil fuel supply curve and a downward-sloping demand curve, the fossil fuel price in the pre-tax steady state with policy risk represents the equilibrium price allowing both the demand and supply for fossil fuels to respond to climate policy risk. If climate policy risk was reduced to zero (i.e. there was no longer a threat of a future carbon tax), then, as our analysis demonstrates, the steady state demand for fossil fuels would increase.

²²Fully capturing how the supply of fossil fuels could shift over time in response to climate policy 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.

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, as well as 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 risk is removed. Therefore, to understand how climate policy 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 risk.

We predict how much the steady state fossil fuel price would increase if the probability of a carbon tax being adopted next period, ρ , fell from the calibrated level of 0.098 to zero. 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 a proposed federal climate policy, the American Power Act, in the U.S. Senate in April, 2010. Focusing on the weeks immediately surrounding the event that precipitated the failure of the proposed policy, [Lemoine \(2017\)](#) finds that the 1-year future price of coal increased by 1 percent.

Second, we draw on the analysis of prediction market prices from [Meng \(2017\)](#) to infer how the event studied in [Lemoine \(2017\)](#) affected the probability of future climate policy. The prediction market prices fell by 10 percentage points – from 0.3 to 0.2 – following the April, 2010 collapse in Senate support for the climate policy. Effectively, in 2010, prior to losing Senate support, there was approximately a 30 percent chance that a climate policy would be in place in 2013, three years after 2010 when the policy would have begun. This predicted probability then fell to 20 percent the weekend after Senate support collapsed. In sum, we infer from [Lemoine \(2017\)](#) and [Meng \(2017\)](#), that a drop in the probability of a climate policy in three years from 30 to 20 percent raised fossil fuel prices today by 1 percent.²³

Turning to our model, our calibrated value of ρ of 0.098 implies a 27 percent chance of a policy being adopted within 3 years, similar to the 30 pre-collapse probability of passage for the 2010 federal climate policy. Reducing ρ in our model to 0.06, decreases the three-year probability of a climate policy by 10 percentage points to 17 percent, similar to the 20 percent post-collapse probability of the 2010 federal climate policy passing. Therefore, the event

²³We assume that the estimated one percent increase in the coal price applies to the price of all fossil fuels. While this assumption is obviously not perfect given that coal is only one of the fossil fuels that would be affected potentially, it likely serves as an upper bound on the price impact. Unlike coal, natural gas would not clearly be negatively affected in the medium run due to the introduction of a climate policy – a carbon price would cause a sizable short-run shift away from coal towards natural gas. Therefore, we would 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 expect the world price of oil to be less responsive to changes in the probability of U.S. climate policy.

analyzed by [Lemoine \(2017\)](#) that lead to a 1 percent increase in coal prices, is approximately equal to a 40 percent drop in our ρ , from 0.098 to 0.06. Linearly extrapolating, we predict that a 100 percent drop in rho from 0.098 to 0, would raise fossil fuel prices by 2.5 percent. Therefore, to account for a potential shift in the supply of fossil fuels in response to climate policy risk, we assume that the fossil fuel price would be 2.5 percent higher without climate policy risk.

To quantify the effects of the potential supply-side response to climate policy risk, we consider an alternative pre-tax steady state without risk in which the fossil fuel price is 2.5 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 the a supply-side response, we find that climate policy risk reduces emissions today. Like before, this emissions reduction occurs because climate policy risk depresses the total level of the 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 risk, the incentives to dis-invest in fossil capital and invest in clean capital are slightly muted. Consequently, climate policy risk leads to a smaller reduction in emissions than in our main analysis, 0.5 percent instead of the original 1.15 percent (column 1 of Table 4). Attaining the Green Paradox prediction that climate policy risk increases 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 risk, the net effect of climate policy 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 risk may affect fossil fuel supply decisions, but more generally on understanding how policy risk affects investment decisions across a wide range of capital assets.

7. Conclusion

Economists have developed different general equilibrium models to explore the impacts of adopting a carbon tax. Using these models, the effects of taxing carbon are determined by comparing two distinct states of the world – a future with a carbon tax versus the current state with no carbon tax. Importantly, in modeling the current state of the world, the existing literature assumes that agents and firms proceed as if there will never be a carbon tax. In reality, while the U.S. does not currently have a federal carbon price, there is widespread awareness that such a policy could be adopted at some point in the future. In this paper, we designed

a general equilibrium model of the U.S. economy that incorporates these beliefs over future climate policy. We use the model to study how climate policy risk affects emissions in the current economy, our understanding of the costs of delayed action on climate change, and evaluations of potential future climate policies.

We find that climate policy risk has reduced U.S. emissions by the same amount that would have occurred had the U.S. adopted a federal tax of \$3.21/ton of CO₂. This decrease in emissions occurs because climate policy risk shifts the economy towards cleaner production and reduces the aggregate capital stock. In sum, climate policy risk reduces emissions both because output falls and because the remaining output is produced with less fossil fuel.

While the emissions reductions from climate policy risk have provided environmental benefits, our results reveal that climate policy risk is a very costly way to attain these benefits. The non-environmental welfare cost of climate policy risk is over twice as large as the non-environmental welfare cost from adopting the emissions-equivalent tax of \$3.21/ton of CO₂. Moreover, we find that, because climate policy risk decreases the aggregate capital stock, it does not reduce the non-environmental welfare costs incurred by actually adopting a carbon tax, despite the fact that the economy has already moved part of the way towards the steady state with a carbon tax in place.

Overall, we find that climate policy risk can have quantitatively important impacts on investment, emissions, and welfare. Importantly, our results suggest that, by ignoring agents' responses to climate policy risk, existing studies overstate the macro impacts of taxing carbon. Furthermore, understanding and incorporating the effects of climate policy 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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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, $k^{c'}$ equals:

$$\frac{\partial V^c(k^c)}{\partial k^{c'}} = -1 + \left(\frac{1}{1+r} \right) \left[\rho \frac{\partial W_1^c(k^{c'})}{\partial k^{c'}} + (1-\rho) \frac{\partial V^c(k^{c'})}{\partial k^{c'}} \right] = 0. \quad (28)$$

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

$$\frac{\partial W_1^c(k^{c'})}{\partial k^{c'}} = p^{c'}(1) + 1 - \delta \quad \text{and} \quad \frac{\partial V^c(k^{c'})}{\partial k^{c'}} = p^{c'}(0) + 1 - \delta, \quad (29)$$

where we use the notation $p^{c'}(1)$ and $p^{c'}(0)$ 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 (28) and (29) yields the first order condition for next period's clean capital:

$$r + \delta = \rho p^{c'}(1) + (1-\rho)p^{c'}(0). \quad (30)$$

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

$$\frac{\partial V^f(k^f)}{\partial k^{f'}} = -1 + \left(\frac{1}{1+r} \right) \left[\rho \frac{\partial W_1^f(k^{f'})}{\partial k^{f'}} + (1-\rho) \frac{\partial V^f(k^{f'})}{\partial k^{f'}} \right] = 0. \quad (31)$$

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

$$\frac{\partial W_1^f(k^{f'})}{\partial k^{f'}} = p^{f'}(1) - (\zeta + \tau) + 1 - \delta \quad \text{and} \quad \frac{\partial V^f(k^{f'})}{\partial k^{f'}} = p^{f'}(0) - \zeta + 1 - \delta, \quad (32)$$

where, as before, $p^{f'}(1)$ and $p^{f'}(0)$ 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 (31) and (32) yields the first order condition for next period's

fossil capital:

$$r + \delta = \rho p^{f'}(1) + (1 - \rho)p^{f'}(0) - \zeta - \rho\tau. \quad (33)$$

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 (3) in the main text):

$$p^c = \gamma(x^c)^{\gamma-1}(x^f)^\theta \quad \text{and} \quad p^f = \theta(x^c)^\gamma(x^f)^{\theta-1}. \quad (34)$$

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: $p^{c'} \equiv p^{c'}(0) = p^{c'}(1)$ and $p^{f'} \equiv p^{f'}(0) = p^{f'}(1)$. Using this relationship, the first order conditions for clean and fossil capital collapse to:

$$r + \delta = p^{c'} \quad \text{and} \quad r + \delta = p^{f'} - \zeta - \rho\tau. \quad (35)$$

Solve equations (34) and (35) for $k^{c'}/k^{f'}$:

$$\frac{k^{c'}}{k^{f'}} = \left(\frac{\gamma}{\theta}\right) \left(\frac{r + \delta + \zeta + \rho\tau}{r + \delta}\right), \quad (36)$$

and for $k^{c'}$ and $k^{f'}$:

$$k^{c'} = \left(\frac{\gamma}{r + \delta}\right)^{\frac{1}{1-\gamma-\theta}} \left(\frac{r + \delta}{r + \delta + \zeta + \rho\tau}\right)^{\frac{\theta}{1-\gamma-\theta}} \left(\frac{\theta}{\gamma}\right)^{\frac{\theta}{1-\gamma-\theta}} \quad (37)$$

$$k^{f'} = \left(\frac{\gamma}{r + \delta}\right)^{\frac{1}{1-\gamma-\theta}} \left(\frac{r + \delta}{r + \delta + \zeta + \rho\tau}\right)^{\frac{1-\gamma}{1-\gamma-\theta}} \left(\frac{\theta}{\gamma}\right)^{\frac{1-\gamma}{1-\gamma-\theta}}. \quad (38)$$

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:

$$K^c = \left(\frac{\gamma}{r+\delta} \right)^{\frac{1}{1-\gamma-\theta}} \left(\frac{r+\delta}{r+\delta+\zeta+\rho\tau} \right)^{\frac{\theta}{1-\gamma-\theta}} \left(\frac{\theta}{\gamma} \right)^{\frac{\theta}{1-\gamma-\theta}} \quad (39)$$

$$K^f = \left(\frac{\gamma}{r+\delta} \right)^{\frac{1}{1-\gamma-\theta}} \left(\frac{r+\delta}{r+\delta+\zeta+\rho\tau} \right)^{\frac{1-\gamma}{1-\gamma-\theta}} \left(\frac{\theta}{\gamma} \right)^{\frac{1-\gamma}{1-\gamma-\theta}}. \quad (40)$$

Dividing equation (40) by equation (39) yields equation (10) in the main text. Finally, observe that:

$$\frac{\partial K^c}{\partial \rho} < 0, \quad \frac{\partial K^c}{\partial \tau} < 0, \quad \frac{\partial K^f}{\partial \rho} < 0, \quad \frac{\partial K^f}{\partial \tau} < 0. \quad (41)$$

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 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 (24)), subject to the budget constraint (equations (20) - (23), (26), and (27)), 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, $\{p^c, p^f, p^x, w, r\}$, 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:

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

subject to the budget constraints (equations (21), (23), (26), and (27)), 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

Data on U.S. GDP, investment, and capital is from NIPA Tables 1.1, 1.1.5, and 1.5, respectively. We define capital as the sum of capital in private fixed assets and consumer durables. Similarly, we define investment as the sum of investment in private fixed assets and consumer durables. We use the average value of these ratios from 2013-2017.

Data on U.S. electric generation by source are from Table 1_01 of the 2019 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 2017 highway statistics.²⁴ Data on fuel economy by car make and model is from fuelconomy.gov. Data on total mine production by mineral type are available from Table 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.²⁵ We discuss the calculation of the level of fossil capital in detail below. We calculate all energy-related moments for year 2017, the most recent year with all the available data.

We use the detailed data on fixed assets and consumer durables to construct the ratio of fossil to total capital in the U.S. economy, K^f / K . The data provide information on the quantity

²⁴<https://www.fhwa.dot.gov/policyinformation/statistics/2017/>

²⁵Fixed 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

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 8 reports the the types of capital and consumer durables that we classify as group 1 and group 2. All types not listed in Table 8 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.

Table 8: 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.

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 1/24.2 gallons per mile and for long-wheel-base light duty vehicles (e.g. most pickup trucks and SUVs) equals 1/17.5 gallons per mile.

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 2003, 15 years before 2017. We set the maximum inverse fuel economy of the current fleet equal to the 90th percentile of inverse fuel economy in model-year 2003; 1/16 gallons per mile for autos and 1/14 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 66 percent fossil capital and the average light truck has 80 percent fossil capital. In our calculation of fossil capital, we multiply the stock of autos by 0.66 and the stock of light trucks by 0.8.

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 0.247, the fraction of total mine production that is from coal.

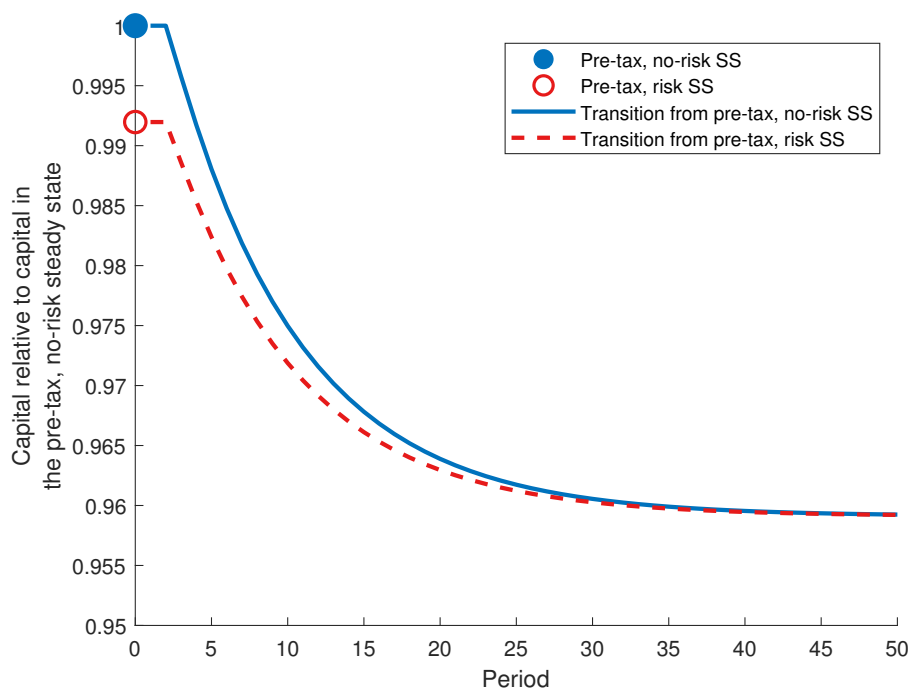
Sector 213 includes group 2 capital used to support oil and gas extraction (NAICS code 211) and coal mining, which we would classify as fossil, as well capital used to support other types of mining, which we would not classify as fossil. To isolate the fossil capital, we first calculate the fraction 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 0.763. Thus, 76.3 percent of group 2 capital in sector 213 corresponds to oil and gas extraction, and thus is fossil. The remaining 23.7 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 0.247, 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: $0.763K_{213} + 0.247(1 - 0.763)K_{213}$.

D. Additional results

Section 6.2 highlights that climate policy risk does not reduce the cost of introducing a carbon tax. This result partly stems from the fact that climate policy risk reduces the aggregate capital stock, which in turn, decreases agents' ability to dis-save over the transition. Figure 4 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.

Figure 4: Total Capital Stock

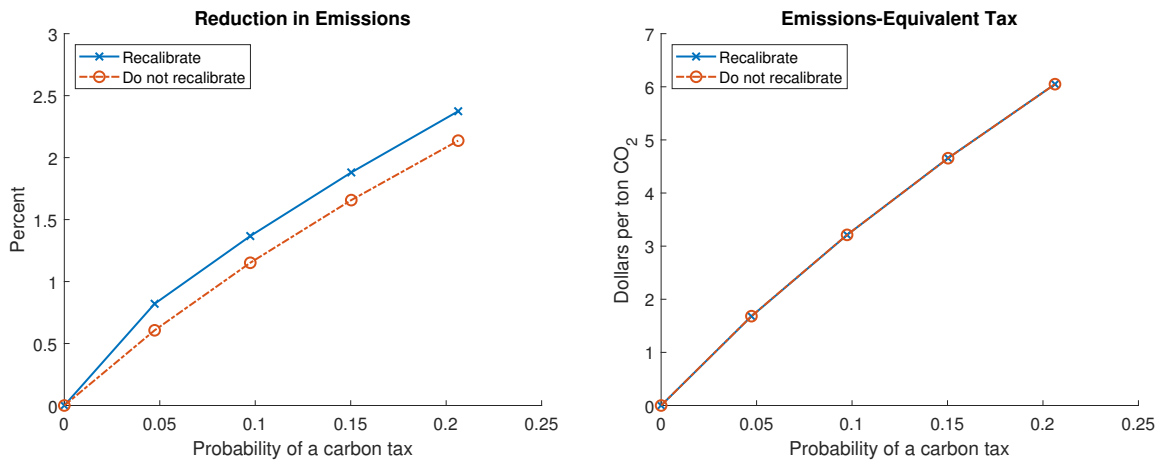


Note: We normalize the value of the capital stock in the pre-tax steady state with no climate policy risk to unity. Conditional on this normalization, the open and solid circles show the value of the capital stock in the pre tax steady states with and without risk, respectively. The dashed and solid 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.

Section 6.3 explored the effects of changes in the carbon tax probability when we recalibrate the model to match different internal carbon fees. We perform an alternative ex-

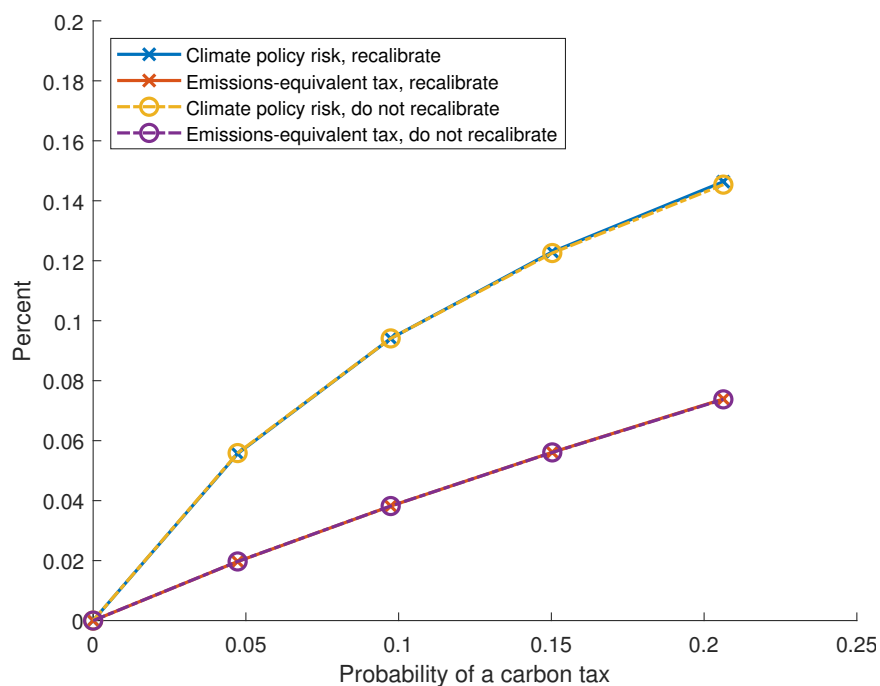
periment in which we alter the probability of a carbon tax but do not recalibrate the model. Rather than testing the sensitivity of our findings with respect to the unknown internal carbon fee, this experiment directly examines how the outcomes differ if the subjective probability of a future carbon tax were to change in the future. Figures 5 and 6 show the results in Figures 2 and 3, with and without recalibrating the model. The quantitative conclusions surrounding the changes in the carbon tax probability are not meaningfully affected by re-calibrating the model.

Figure 5: 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 risk relative to the pre-tax steady state without climate policy risk. The right panel displays the corresponding carbon tax that would achieve the same steady state emissions reductions as the climate policy risk outcome. In both panels, the lines with cross markers plot the outcomes when we recalibrate all the model parameters using a different value for the internal carbon fee. The lines with circle markers plot the outcomes when we only change the probability and do not recalibrate the model.

Figure 6: Welfare Cost of Climate Policy Risk and Emissions Equivalent Tax (CEV)



Note: The blue and yellow lines plot the welfare cost of climate policy risk, measured in terms of the consumption equivalent variation, for each value of the carbon tax probability on the x-axis. The orange and purple lines plot the welfare cost for the carbon tax that achieves the same emissions reductions as climate policy risk with probability equal to the value on the x-axis. The lines with cross markers plot the outcomes when we recalibrate all the model parameters using a different value for the internal carbon fee. The lines with circle markers plot the outcomes when we only change the probability and do not recalibrate the model.