The Macro Effects of Climate Policy Uncertainty

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Abstract

The uncertainty surrounding if and when the U.S. government will implement a federal climate policy introduces risk in the decision to invest in long-lived capital assets that are used in conjunction with fossil fuels. To understand how the macroeconomy responds to this climate policy risk, we develop a quantitative model that includes investment in long-lived, sector-specific assets such as coal power plants or wind farms. We infer firms' beliefs about the likelihood of a future carbon tax, using the observed internal carbon prices firms voluntarily levy on themselves. We find that the risk of climate policy in the future reduces emissions today by distorting investment towards a cleaner mix of capital and by depressing overall investment. The emissions reduction caused by climate policy risk is equivalent to the reduction that would be achieved by imposing a carbon tax of \$3.21/ton of CO_2. More generally, our results demonstrate that, by ignoring the impacts of climate policy risk, existing studies have overstated both the welfare costs and emissions reductions resulting from a carbon tax policy.

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1 Introduction

Economists have developed a wide range of 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.[1] Importantly, in modeling the current state of the world, the existing literature assumes that agents and firms are proceeding 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. We use the term climate policy risk to refer to the anticipation of a potential future policy along with the uncertainty surrounding if and when a carbon price will be imposed. In this paper, we quantify how this climate policy risk affects emissions in the present U.S. economy and its' implications for how we evaluate the cost and effectiveness of potential future climate policies.

Analytically, we first highlight how the risk of climate policy in the future can reduce emissions today. We introduce a simple, dynamic model that focuses on the production-side of the economy. Output is produced by profit maximizing firms using two forms of capital: (1) fossil capital that is specialized to use fossil fuel (e.g., a coal boiler or an internal combustion engine), and (2) clean capital that is specialized to substitute for fossil capital or fossil fuel (e.g., a solar panel or a regenerative breaking system). To model climate policy risk, we define a stochastic steady state in which there is a small, constant probability that a carbon tax will be imposed in the next period. Entrepreneurs choose each period's investment before they learn whether the government will introduce the carbon tax in the subsequent period. Once the government introduces the tax, all uncertainty is resolved and the economy transitions to a new long-run steady state with the carbon tax in place.[2] This

[1] For example, see Parry et al. (1999), Rausch et al. (2011), and Williams et al. (2015).

[2] Several theoretical papers in the environmental literature take an alternative approach to modeling the general equilibrium impacts of climate policy risk. In particular, Bretschger et al. (2018) models climate policy risk as a stochastic process that is constantly subject to change. Rezai and van der Ploeg (2018) models uncertainty over whether a climate policy will be introduced (or strengthened) at a known future date. In contrast, in our model of climate policy risk, the uncertainty arises because agents do not know if and when a climate policy will be adopted. However, conditional on being adopted, the policy is known and

model of aggregate uncertainty differs from the standard approach in the macro literature in which economy-wide, stochastic shocks (e.g., TFP shocks) generate uncertainty that is never resolved.[3] Importantly, unlike TFP shocks, our climate policy shock is designed to be permanent.

Solving for pre-tax, stochastic steady state, we show that climate policy risk operates through two key channels to reduce emissions. First, climate policy risk raises the expected return to clean capital relative to fossil, shifting the composition of capital toward cleaner production and thus reducing emissions. Second, climate policy risk reduces the expected marginal product of capital because it distorts the composition of capital away from the privately optimal outcome in the baseline. As a result, the total capital stock falls, reducing both output and emissions.

To quantify the macroeconomic impacts of climate policy risk, we build on the simple analytic model and study the stochastic steady state outcome in a richer, general equilibrium model. The quantitative model adds labor as a production input that, unlike capital, entrepreneurs can adjust after they learn whether the government has introduced the carbon tax. Additionally, we include the household-side of the economy with risk-averse agents. Finally, we incorporate a third type of capital into the production process for the final good that is not directly related to fossil fuel (e.g., a factory building). Moreover, all capital is sector-specific – e.g., fossil-based capital cannot be sold and costlessly transformed into clean capital.[4] This friction creates the potential for some assets to be stranded when a carbon

constant (e.g., it does not follow a stochastic process as in Bretschger et al. (2018). Within the environmental literature, Xepapadeas (2001) and Pommeret and Schubert (2017) consider the effect of policy uncertainty on firms' investment and location decisions. However, these previous studies do not focus on the general equilibrium impacts of environmental policy uncertainty.

[3]For example, Kydland and Prescott (1982) and King and Rebelo (1999) explore the impact of stochastic TFP shocks in real-business cycle models. Similarly, Krusell and Smith (1998) focus on stochastic TFP shocks in a model with heterogeneity. Fernández-Villaverde et al. (2015) and Born and Pfeifer (2014) also examine general equilibrium impacts of uncertainty, however rather than stemming from stochastic TFP shocks, the uncertainty arises from stochastic policy shocks. Uncertainty surrounding the timing of future policy changes has been studied using dynamic GE models in different settings. For example, Caliendo et al. (2015) and Kitao (2018) study the impact of uncertainty surrounding future reforms to social security policies. Similarly, Kydland and Zarazaga (2016) demonstrate that anticipating future capital tax increases can explain the slow recovery following the Great Recession.

[4]In related work, Baldwin et al. (2019) examine how irreversibility in "dirty" and "clean" capital affects the optimal trajectory of a carbon price as well as environmental subsidies. However, the authors focus on

tax is introduced.

To uncover the general equilibrium impacts of climate policy risk on the current U.S. economy, we need to capture firms' beliefs regarding the level and likelihood of a future tax. To pin down the expected level of the potential future carbon tax, we draw from the current U.S. policy environment and assume that, if adopted, a federal carbon tax would be set at 45 dollars (in 2017 dollars) per ton of CO_2.[5] To infer firms' subjective probability of a carbon price being adopted, we exploit the information revealed by internal carbon prices. The internal carbon price is a unique tool that firms voluntarily implement to distort their investment decisions to reduce their future carbon emissions (Ahluwalia (2017)).[6] Using our model, we solve for the subjective probability of a future carbon tax that would rationalize a profit-maximizing firm's decision to voluntarily impose the observed internal carbon prices. The result implies that firms' are behaving as though they believe there is a 50 percent chance of a federal carbon tax being adopted within the next eight years.

We use the quantitative model and the inferred carbon-tax probability to quantify the effects of climate policy risk on the macroeconomy. As a point of reference, we find that adopting a \$45/ton tax on CO_2 would reduce U.S. emissions by 15 percent relative to a world without climate policy risk. The risk of the future climate policy implies that the U.S. economy has already achieved 8 percent of the ultimate 15 percent reduction in emissions, even though there is no federal climate policy in place. This pre-tax reduction in emissions results from the two channels highlighted in the analytic model: (1) climate policy risk increases the expected return to clean relative to fossil-based capital investment, leading to a 4 percent increase in the ratio of clean to fossil capital and (2) climate policy risk reduces the expected marginal product of capital, leading to a 0.8 percent decrease in the total capital stock.

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a setting where the future policy environment in known.

[5] This 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.

[6] However, there 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.

The result that climate policy risk reduces emissions runs counter to the standard "Green Paradox" narrative that has focused exclusively on the resource extraction sector (e.g., Sinn (2008)). Building on the Hotelling Model of resource extraction, the Green Paradox literature suggests that the expectation of a future environmental tax will cause forward-looking resource owners to increase the rate of fossil fuel extraction today. Our results highlight that there has been an important and overlooked response on the demand-side that works in the opposite direction. Firms anticipating a potential carbon price will invest in relatively less fossil-based capital, reducing the current demand for fossil fuel.

The findings from our quantitative analysis have important implications with regards to evaluating the impacts of climate policies. To predict the macroeconomic impacts of adopting a carbon tax, the existing literature implicitly assumes that we are starting from a state of the world where there is no anticipation of a potential future climate policy. However, given that forward-looking agents make investments with an understanding that a future carbon price is a real possibility, then such a comparison 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 emission reductions achieved by adopting a carbon tax. Moreover, we show that the emission reductions achieved in the stochastic steady state grow as the probability of a carbon tax being adopted increases. This suggests that the magnitude of the errors introduced by abstracting from climate policy risk will increase with time as agents' place greater weight on the likelihood of a carbon price being implemented.

More generally, our quantitative analysis provides new insights surrounding the cost of inaction with regards to climate policy. On one hand, our results reveal that, by responding to climate policy risk, firms reduce emissions and begin to mitigate the social costs incurred by leaving carbon emissions unpriced. Indeed, we find that the reduction in emissions in the stochastic steady state is equivalent to the reduction that would be achieved in a deterministic steady state with a carbon tax equal to \$3.21/ton. While our results suggest that the investment response to climate policy risk leads to a cleaner portfolio of capital and a reduction in emissions, our quantitative analysis also reveals that the cost of the emission reductions stemming from climate policy risk far exceed the cost of the emission reductions that would be achieved using a carbon tax. In particular, the welfare costs incurred by achieving the stochastic steady state emission reductions are more than double the welfare costs that would be incurred by achieving the same emission reductions using a $3.21/ton tax on carbon emissions.

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, at some unknown point in the future, a climate policy may be implemented, how will investments today be distorted? 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 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]

[7]For 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% of Americans believe climate change is a problem the federal government should address and 57% would support paying higher energy bills to do so.

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

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 for insights, the European Union's Emission Trading Scheme has established a price on carbon emissions that, as of 2019, has hovered around 25 Euros (or 27 USD) per ton of CO_2. At this price, there is already clear evidence that fossil-fuel intensive capital, such as a coal-fired electricity generator, is experiencing a dramatic reduction in profitability (IEEFA 2019). Policy proposals that are garnering the greatest support in the U.S. currently call for even stronger actions to reduce emissions. For example, the proposal put forth by the Climate Leadership Council (CLC) calls for a CO_2 tax on carbon emissions set at 40 dollars per ton (Baker III et al. 2017). The Green New Deal and the leading democratic presidential candidates support U.S. carbon neutrality by 2050. Such a goal would require far more dramatic reductions in emissions than what would be achieved with the CLC's proposed 40 dollar per ton tax. The combination of growing public support combined with the current policy proposals suggest that both the likelihood and expected stringency of a future U.S. climate policy are large enough to impact firms' investment decisions.

There is ample anecdotal evidence demonstrating that firms across a wide range of industries 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] Similarly, many firms have voluntarily adopted stricter regulations than those imposed by the federal government. For example, automakers Ford, Honda, Volkswagen, and BMW choose to adopt California's

[9]For 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, Kroeger'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).

stricter fuel economy standards, which require an average fuel economy for new cars and trucks equal to 54.5 miles per gallon, instead of the laxer regulations proposed by President Trump (Holden 2019). Transportation is responsible for 29 percent of US 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. Similarly, BP, Shell, and Exxon Mobil were among several major oil and gas companies to oppose President Trump'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).

The anecdotal evidence summarized above suggests that firms meaningfully alter their investments in response, at least in part, to climate policy risk. However, these types of examples don't provide a clear approach for us to systematically quantify how the level and composition of capital investment are affected by the climate policy risk and the corresponding implications for U.S. carbon emissions. Ultimately, to quantify the effects of the climate policy risk, we need to calibrate the fundamentally unobservable beliefs firms have surrounding the likelihood of future climate policy. To do so, 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 returns or 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 CO_2 – which has reportedly resulted in the decision to pass on many potential CO_2-intensive investment opportunities.

The second type of internal carbon price is a carbon fee. In contrast to the shadow price, the carbon fee is actually an internal tax a firm levies on its direct emissions (or emissions embodied in its energy use). The revenue raised by this internal tax can be transfered within the organization or, in some cases, used to pay for emission offsets or renewable energy credits. For example, Microsoft imposes an internal carbon fee of \$10/ton of CO_2 on the emissions resulting from its energy use – with the revenue being used to purchase carbon offsets and renewable energy credits.

The use of internal carbon prices has become widespread. In a recent survey of nearly 5,000 firms performed by CDP (formerly Carbon Disclosure Project), 517 firms reported using internal carbon prices and another 732 have plans in place to adopt internal prices within two years. Notably, over half of the surveyed firms in the energy sector, which are the most exposed to climate-policy risk, were using internal carbon prices. Similarly, 35 percent of firms in the materials sector and 23 percent of firms in the industrial sector reported the use of internal carbon prices. Many of these firms are either located in the U.S. or do business in the U.S.

There are certainly many possible reasons why firms might want to reduce their carbon emissions using an internal carbon price or other company policy. To some degree, firms may be motivated by a desire to differentiate their product(s) as being "green" or to mitigate reputation risks. The use of the internal carbon fees to raise revenues for pro-social or pro-environmental objectives may also be motivated in part by a belief in corporate social responsibility. However, surveys of firms that are using internal carbon prices find 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))." Effectively, firms are responding to the threat of a future climate policy by electing to distort their current capital portfolios. This is exactly the behavior we seek to model in this analysis.

In our subsequent quantitative analysis, we utilize the observed internal carbon fees publicly reported by firms to infer firms' subjective probability of a climate policy being adopted. Among the firms that publicly report their internal carbon fees, there is a modal price of 10 dollars per ton of CO_2. 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.[10] 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 the firms' expected level of the tax. It provides no information on the probability that the firm places on whether the government will introduce the tax. 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 carbon price of 45. 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, the carbon fee determines how firms actually allocate investment in the face of climate policy risk. Unlike the shadow price, 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 this tax.

While the modal carbon fee is 10 dollars per ton of CO_2, this price level may be motivated by more than simply climate policy risk. For example, "green-washing" or warm-glow motives may inflate the carbon fee relative to the level the firm would set purely to address the climate policy risk. To address this concern, we use two approaches. First, we conservatively deflate the observed carbon fees, effectively assuming that only a portion of the fee is motivated by climate policy risk. In addition we explore how the quantitative impacts vary using a wider 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 in order to rationalize the voluntary use of a given internal carbon fee. With these inferred beliefs, we explore how capital investment responds to climate policy risk.

[10] We 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 the risk of future climate policy reduces emissions. In particular, we model simple two-sector economy with a carbon-emitting "fossil" sector and a non-carbon emitting "clean" sector. We focus only on the production-side of the economy, taking the interest rate and labor supply as exogenous and abstracting from the investment frictions. In Section 4 we introduce the household along with relaxing all of these assumptions.

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,

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

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-based 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,

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

Fossil fuel is produced from units of final good at constant marginal cost, ζ.

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 or a polymerisation reactor to manufacture plastics, and capital used in fossil fuel extraction, such as an oil rig. Clean capital refers to any capital that preforms the same function as the fossil capital, but does not use fossil fuel. Examples include capital used to produce electricity from non-fossil sources, such as a wind turbine or a nuclear reactor, capital that increases energy efficiency, such as regenerative brakes in hybrid vehicles, and capital that allows for an alternative production process that does not use fossil fuel, such as the fermentors used to make bioplastics.

The Leontief production function for the fossil-based 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 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 stochastic steady state

We study a stochastic steady state designed to capture the climate policy risk described in Section 2 and how the firm may respond to such risk. In the stochastic 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 climate 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 in which there is no carbon tax. We study the long-run equilibrium (i.e. stochastic steady state) before the economy transitions to this absorbing state. In this stochastic steady state, aggregate variables are constant because the realization of the aggregate shock, the carbon tax, has historically always been zero. As discussed in Section 2, such an equilibrium is well-suited to describe the U.S. economy. While there currently is no federal carbon price, firms' actions indicate that they expect the government to introduce a climate policy in the future.

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

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

The representative clean entrepreneur chooses investment in next period's level of clean capital to maximize the expected present discounted value of future profits. 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 $V^c(k^c; 0)$ denote the clean entrepreneur's value function in the stochastic steady state without a carbon tax, and $V_t^c(k^c; 1)$ 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 stochastic steady state equals,

$$V^c(k^c; 0) = \max_{(k^c)'} \left\{ p^c k^c - i^c + \left(\frac{1}{1+r}\right) \left[\rho V_1^c((k^c)'; 1) + (1-\rho)V^c((k^c)'; 0)\right] \right\} \tag{4}$$

subject to the law of motion for clean capital,

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

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 not introduce the carbon tax and the economy remains in the stochastic steady state, $V^c((k^c)'; 0)$, and the continuation value if the government does introduce the carbon tax and the economy is in the first period of the transition, $V_1^c((k^c)';1)$. 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,

$$V_t^c(k^c;1) = \max_{(k^c)'} \left\{ p^c k^c - i^c + \left(\frac{1}{1+r}\right) V_{t+1}^c((k^c)';1) \right\} \tag{6}$$

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 sector 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 stochastic steady state equals,

$$V^f(k^f;0) = \max_{(k^f)',f} \left\{ p^f k^f - \zeta f - i^f + \left(\frac{1}{1+r}\right) \left[\rho V_1^f((k^f)';1) + (1-\rho) V^f((k^f)';0)\right] \right\} \tag{7}$$

subject to the law of motion for fossil capital,

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

and the Leontief constraint that the fossil intermediate producer 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 stochastic steady state, the entrepreneur only pays the extraction cost, ζ, for each unit of fossil fuel.

The value function for the fossil entrepreneur in the first period of the transition equals,

$$V_1^f(k^f;1) = \max_{(k^f)',f} \left\{ p^f k^f - (\zeta+\tau) f - i^f + \left(\frac{1}{1+r}\right) V_2^f((k^f)';1) \right\} \tag{9}$$

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.

We define a *stochastic steady state* for this economy as a set of prices for the clean and fossil intermediates and labor, $\{p^c, p^f, w\}$, allocations for 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.

3.3 The aggregate effects of climate policy risk

The risk climate policy in the future operates through two key channels to reduce emissions today. First, it shifts the composition of the capital stock towards cleaner capital and second it reduces to the total level of the capital stock. Focusing first on the composition channel, the ratio of clean to fossil capital in the stochastic steady state equals[11],

$$\frac{K^c}{K^f} = \left(\frac{\gamma}{\theta}\right)\left(\frac{1 + r + \zeta + \rho\tau}{r + \delta}\right). \tag{10}$$

If the probability of a tax and the fossil fuel extraction cost both equal zero, $\rho = \zeta = 0$, then the ratio of clean to fossil capital simply equals the ratios of the factor shares, γ/θ. A positive price of fossil fuel, $\zeta > 0$, raises the operating costs of fossil capital, increasing the ratio of clean to fossil capital. Similarly, the possibility of a future carbon tax, $\rho > 0$,

[11]See Appendix A for the derivation.

raises the expected operating costs of fossil capital next period, further increasing the ratio of clean to fossil capital. Since equilibrium fossil fuel use equals the level of fossil capital, the increase in the ratio of clean to fossil capital from the risk of future climate policy decreases 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 stochastic steady state equal,

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

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

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 aggregate capital stock falls because the policy risk moves the ratio of clean to fossil capital (equation (10)) away from the privately optimal outcome in the baseline. This change in composition reduces the expected marginal product of capital, causing total capital to fall.

Like climate policy risk, an actual carbon tax would operate through the same two channels to reduce emissions. In particular, in a deterministic steady state with carbon tax $\tilde{\tau}$, the composition and level of capital would still be defined by equations (10)-(12). However, the risk of climate policy 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, $\tilde{\tau}$ equal to the expected tax in the stochastic steady state, $\rho\tau$.

4 Quantitative model

To quantify the effects of climate policy risk on the U.S. economy, we develop a richer, general equilibrium model. The quantitative model differs from the analytic model on several dimensions. First, we allow for the allocation of labor across the different intermediate input sectors, providing entrepreneurs with a mechanism to adjust production after they learn whether the government introduced the carbon tax. Second, we include a non-energy-related form of capital, since much of the U.S. capital stock is not directly related to fossil fuel. Third, we model investment as partially irreversible to capture the potential losses from selling fossil-based capital after the introduction of the carbon tax. And fourth, we model the household-side of the economy with risk averse agents. Finally, we analyze the full general equilibrium effects of climate policy risk. 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,

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

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.[12]

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,

$$x^n = A^n (k^n)^\alpha (l^n)^{1-\alpha} \tag{14}$$

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,

$$y = \left((x^e)^{\frac{\phi-1}{\phi}} + (x^n)^{\frac{\phi-1}{\phi}} \right)^{\frac{\phi}{\phi-1}} \quad \text{where} \quad x^e = \left((x^c)^{\frac{\varepsilon-1}{\varepsilon}} + (x^f)^{\frac{\varepsilon-1}{\varepsilon}} \right)^{\frac{\varepsilon}{\varepsilon-1}}. \tag{15}$$

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 climate policy decreases demand for fossil-based capital. This fall in demand could be extremely costly if the entrepreneur cannot recover the full value of capital that she re-sells. An entrepreneur might not recover the full value of re-sold capital because there are transactions and physical costs of re-sale and because of buyers' potential concerns that the used capital is a "lemon" (Bloom 2009). These losses are exacerbated if the entrepreneur sells the used capital across sectors (Ramey and Shapiro (1998); Ramey and Shapiro (2001)). For example, suppose a entrepreneur in the fossil sector sells a used coal boiler to a clean entrepreneur. The clean entrepreneur's valuation of the boiler's parts is likely considerably less than the value of the boiler.

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

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

$$G(i) = \frac{\lambda}{2}\left[-i + (i^2 + \eta)^{\frac{1}{2}}\right], \tag{16}$$

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,

$$H(i) = \begin{cases} 0 & : i \geq 0 \\ |\lambda i| & : i < 0 \end{cases} \tag{17}$$

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

Unlike capital, labor is fully fungible across the different sectors. While assuming zero adjustment costs on investment would be overly simplistic, the absence of any type of labor adjustment costs is defensible given 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 workers and entrepreneurs. The worker in each household is endowed with one unit of time which is divided between leisure and labor, which is supplied to any entrepreneur, 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,

$$u(c, h) = \frac{c^{1-\sigma}}{1-\sigma} - \chi\frac{h^{1+\frac{1}{\theta}}}{1+\frac{1}{\theta}}, \tag{18}$$

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 stochastic steady state

The workers, and the final-good, clean, fossil, and non-energy 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 the climate policy. 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 determines 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,

$$c_t = w_t h_t + \pi_t^n + \pi_t^f + \pi_t^c. \tag{19}$$

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

$$\pi^c_t = p^c_t x^c_t - w_t l^c_t - i^c_t - G(i^c_t) \tag{20}$$

$$\pi^f_t = p^f_t x^d_t - \zeta f_t - w_t l^f_t - i^f_t - G(i^f_t) \tag{21}$$

$$\pi^n_t = p^n_t x^n_t - w_t l^n_t - i^n_t - G(i^n_t) \tag{22}$$

We write the optimization problem for the workers and the clean, fossil, and non-energy entrepreneurs in the stochastic steady state as a single household value function. Let $V(k^c, k^f, k^n; 0)$ denote the household's value function in the stochastic steady state without a carbon tax, and $V_t(k^c, k^f, k^n; 1)$ denote her value function in period t of the transition after the government introduces the carbon tax. The household's value function in the stochastic steady state equals,

$$\begin{aligned} V(k^c, k^f, k^n; 0) = &\max_{(k^c)',(k^f)',(k^n)',h,l^c,l^f,l^n,f} \frac{c^{1-\sigma}}{1-\sigma} - \chi \frac{h^{1+\frac{1}{\theta}}}{1+\frac{1}{\theta}} \\ &+ \beta \left[\rho V_1((k^c)', (k^f)', (k^n)'; 1) + (1-\rho) V((k^c)', (k^f)', (k^n)'; 0)\right] \end{aligned} \tag{23}$$

Parameter β is the household's discount factor. If the government does introduce the carbon tax, then the household's value function in period t of the resulting transition equals,

$$V_t(k^c, k^f, k^n; 1) = \max_{(k^c)',(k^f)',(k^n)',h,l^c,l^f,l^n,f} \frac{c^{1-\sigma}}{1-\sigma} - \chi \frac{h^{1+\frac{1}{\theta}}}{1+\frac{1}{\theta}} + \beta V_{t+1}((k^c)', (k^f)', (k^n)'; 1) \tag{24}$$

The household's budget constraint over the transition includes includes the transfers, T_t, from the carbon tax revenue,

$$c_t = w_t h_t + \pi^n_t + \pi^f_t + \pi^c_t + T_t. \tag{25}$$

Similarly, the fossil sector 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,

$$\pi_t^f = p_t^f x_t^f - (\zeta + \tau) f_t - w_t l_t^f - i_t^f - g(i_t^f)$$

The expressions for the clean and non-energy entrepreneurs' profits over the transition are the same as in equations (20) and (22).

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

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

2. Given prices, the representative household maximizes the value function equation (23), subject to the budget constraints (equations (19) and (25)), 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, clean, fossil, and non-energy intermediate inputs all clear.

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, our model of a stochastic steady state allows agents in the current state of the world to place a positive probability on a federal carbon price in the future. Moreover, the evidence presented in Section 2 suggests that agents do indeed place a positive probability future climate policy. To capture this fact, we calibrate the model's stochastic steady state to match the current U.S. economy. We assume that, if adopted, the future carbon tax will be set at \$45 (in 2017 dollars) per ton of CO_2, approximately equal to the EPA's estimates of the social cost of carbon (EPA 2016).[13]

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 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. All of the moments match the empirical targets up to four decimal places. Tables 1 and 2 report the parameter values that result from the direct calibration and the method-of-moments procedure, respectively.

Much of the calibration approach is standard in the macro literature. The important novelty is specifying firms' beliefs over the likelihood of the future tax. Section 5.1 details the calibration of ρ. Sections 5.2 and 5.3 discuss the calibration of the remaining parameters. Appendix B reports additional details and describes all data sources used in the calibration.

Table 1: Parameter Values: Direct Calibration

Stochastic	Value
Production	
Capital share: α	0.33
Clean and fossil substitution elasticity: ε	3
Energy and non-energy substitution elasticity: ϕ	0.10
Adjustment cost: λ	0.43
Perturbation parameter: η	1.0e-09
Preferences	
Frisch labor supply elasticity: θ	0.5
CRRA coefficient: σ	2

[13] Using a three percent discount rate, the EPA reports the social cost of carbon equal in 2015 equal to 42 dollars and in 2002 equal to 49 dollars (both values are in year 2017 dollars). This value of the tax is slightly higher than the 40 dollars per ton proposed by the CLC and considerably lower than what would be required to achieve the Green New Deal and democratic presidential candidates' target of carbon neutrality by 2050.

Table 2: Parameter Values: Method of Moments

Stochastic	Value
Production	
Leontief parameter: μ	7.09
Clean productivity: A^c	1.23
Fossil productivity: A^f	1.97
Depreciation rate: δ	0.09
Preferences	
Discount factor: β	0.97
Disutility of labor: χ	118.16
Policy risk	
Probability of the carbon tax: ρ	0.10
Size of the carbon tax: τ	0.61

5.1 Climate policy risk

As discussed in Section 2, many US firms incorporate the risk of future climate policy into their long-run investment decisions. The data on internal carbon prices – and in particular, 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 dollars per 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 simply cannot be quantified – likely inflate the carbon fee relative to the level the firms would set purely to address the climate policy risk. To address this concern, we use two approaches. First, to be conservative, we assume that half of the internal carbon fee is motivated by warm glow and "green washing" while the other half is to address climate policy risk. Consequently, we choose ρ such that it is optimal for firms to impose a carbon price of 5 dollars per ton of CO_2 when making their investment decisions. In addition, we report a range of results corresponding to different assumptions regarding the extent to which the level of the 10 dollar per ton internal carbon fee is motivated by climate policy risk.

We take the following steps to calibrate ρ. First, we calculate the ratio of clean to fossil capital, $\hat{K}^c/\hat{K}^f$ in a deterministic steady state with a carbon tax equal to the internal carbon fee of 5 dollars per ton. We use "hat" to denote the values of macro aggregates in this deterministic steady state. Second, we calculate the value of ρ such that the ratio of clean to fossil capital, K^c/K^f in the stochastic steady state with no internal carbon tax, equals the corresponding ratio in the deterministic steady state with the carbon tax equal to the internal carbon fee: $K^c/K^f = \hat{K}^c/\hat{K}^f$. The resulting value of ρ equals 0.098. This value implies approximately a 50 percent probability that a 45 dollar per ton carbon tax will be implemented within the next eight years.

5.2 Production

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. 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, instead of the non-energy intermediate. Therefore, we set the elasticity of substitution between the non-energy and energy intermediates to be very close to zero, $\phi = 0.1$.

Parameter λ determines the cost firms incur from selling stranded capital. Based on the estimates in Bloom (2009), we set $\lambda = 0.43$, implying that capital looses almost half of its value when it is resold. We choose the perturbation parameter in the adjustment cost function to be very small, $\eta =$ 1e-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. 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-based capital, and we count "special industrial machinery" as fossil capital in sectors that directly relate to fossil energy, such as oil and gas extraction. See Appendix B for a full description of the calculation of fossil capital. Our calculated ratio of K^f/K equals 0.183.

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 US 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 in light-trucks (including sport utility vehicles) (see Appendix B). 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 of vehicle miles traveled by light trucks as fossil-based. We classify all vehicle miles traveled by motorcycles, buses, single-unit trucks and combination trucks as fossil-based. The resulting ratio of fossil to clean vehicle miles traveled equals 2.63.

The ratio of fossil-based to clean intermediate production equals 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.[14] The resulting weighted average yields the calibration target, $X^f/X^c = 2.17$.

5.3 Preferences

We choose 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 total time endowment working.

6 Results

6.1 The effects of climate policy risk on the macroeconomy

We solve the model for four steady states: (1) a deterministic steady state in which there is no carbon tax and no risk of a future carbon tax, (2) a stochastic steady state in which there is a 9.8 percent probability of a 45 dollar per ton carbon tax, (3) an emissions-equivalent steady state in which there is a carbon tax in place that achieves the same reduction in emissions as the stochastic steady state and no uncertainty about future policy, and (4) a policy steady state with a 45 dollar per ton carbon tax in place and no uncertainty about future policy.

Columns (1)-(3) of Table 3 report the percentage changes in a number of variables relative to the pre-policy deterministic steady state in the stochastic, emissions-equivalent, and policy steady states, respectively. Column one, the stochastic steady state, quantifies the effects of

[14]Combined, 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).

climate policy risk. Comparing column one with column two, the emissions-equivalent steady state, highlights how reducing emissions through climate policy risk differs from reducing emissions with an actual carbon tax. Finally, column three, the policy steady state, is designed to provide a familiar point of reference. It shows the effects of introducing a carbon tax from a baseline with no climate policy risk.

Table 3: Effects of Climate Policy Risk on Macro-Aggregates
(Percent change from deterministic steady state)

	Stochastic SS	Emissions-equivalent SS	Policy SS
Emissions			
Fossil fuel: F	-1.15	-1.15	-15.13
Composition effect			
Clean to fossil capital: K^c/K^f	3.97	2.54	40.41
Clean to fossil labor: L^c/L^f	1.43	2.54	40.41
Clean to fossil intermediates: X^c/X^f	2.26	2.54	40.41
Level effect			
Total capital: K	-0.81	-0.32	-4.09
Total labor: L	-0.02	-0.05	-0.57
Output and consumption			
Output: Y	-0.32	-0.18	-2.45
Consumption: C	-0.11	-0.08	-1.22

The risk of climate policy in the future reduces emissions today. Emissions are 1.15 percent lower in the stochastic steady state than in the deterministic steady state. For comparison, the actual introduction of the carbon tax would reduce emissions by 15.13 percent from the deterministic steady state. Thus, the simple risk of future policy implies that the economy has already achieved approximately eight percent of the decrease in emissions from the deterministic steady state that would occur if the government actually introduced the tax.

Climate policy risk reduces emissions because of its effects on the two key channels highlighted in the analytic model: (1) it shifts the composition of the capital stock towards cleaner capital and (2) it decreases the total level of the capital stock. The second segment of the first column of Table 3 reports the effect of climate policy risk on the composition channel. The potential for a carbon tax in the future raises the expected return to investment in clean capital relative to fossil capital, increasing the equilibrium ratio of clean to fossil capital by 3.97 percent.

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, suppose that the government does not introduce the tax, implying that the economy remains in the stochastic steady state. In this outcome, fossil entrepreneurs have too little capital relative to the level they would have chosen, had they known that the government would not introduce the carbon tax. To compensate for the sub-optimally low fossil capital, the fossil entrepreneurs hire additional labor, which increases production of the fossil-based intermediate and emissions. This labor-demand response implies that climate policy risk has a smaller effect on the composition of labor than on capital; the ratio of clean to fossil labor is only 1.43 percent higher in the stochastic steady state, less than half of the increase in the ratio of clean to fossil capital. Combined, the changes in the composition of labor and capital cause the ratio of clean to fossil intermediates to increase by 2.26 percent.

The third segment of the first column of Table 3 reports the effect of climate policy risk on the level channel; climate policy risk reduces the level of capital by 0.81 percent. The introduction of the carbon tax distorts the economy away from the privately optimal allocations of capital and labor, reducing the marginal product of capital. Thus, the potential for a future carbon tax reduces the expected return to capital investment, resulting in a lower total capital stock.

Risk aversion magnifies the effects of climate policy risk on both the composition and the level channels. When entrepreneurs make investment decisions, they must weigh the optimal action if the tax is not implemented next period, relatively less clean capital and more total capital, versus the optimal action if the tax is implemented the next period, relatively more clean capital and less total capital. Risk aversion causes entrepreneurs to hedge against the outcome with the lowest utility which corresponds to the government introducing the tax. Therefore, entrepreneurs place a higher weight on the outcome that the government introduces the tax than the probability that it actually occurs. Thus, risk aversion pushes the economy even closer to the policy steady state, increasing the magnitudes of both the composition and the level channels.

The emissions reduction from the climate policy risk is equal to the emissions reduction that would be achieved in a deterministic steady state with a carbon tax of 3.21 (in 2017 dollars) per ton of CO_2. In the analytic model, the emissions-equivalent tax exactly equals the expected tax in the stochastic steady state. However, the allocation of labor after entrepreneurs learn if there is a carbon tax undoes some of the emissions reduction implied by allocation of capital. Consequently, the size of the emissions-equivalent tax is less than the expected tax in the stochastic steady state. The expected tax in the stochastic steady state equals $\rho \times \tau = 0.098 \times 45 = 3.45$ which is greater than the 3.21 dollar carbon tax required to achieve the reduction in emissions from climate policy risk.

Referring to the second column of Table 3, the emissions-equivalent tax operates through the same composition and level channels as the climate policy risk to reduce emissions. The tax increases the ratio of clean to fossil capital by 2.54 percent and reduces the total level of capital by 0.32 percent. However, the relative importance of the channels differ between the stochastic and emissions-equivalent steady states. In particular climate policy risk relies more heavily on the decrease in the total capital stock to reduce emissions. This result is partly due to the different timing of the capital and labor decisions. 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 the total capital stock. Additionally, risk aversion magnifies the 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. Consequently, output and consumption are lower in the stochastic steady state than in the emissions-equivalent steady state (last segment of Table 3).

To quantify the welfare costs of the climate policy risk, the emissions-equivalent tax, and the actual policy, Table 4 reports the consumption-equivalent variation (CEV) of each steady state, using the deterministic pre-policy steady state as a baseline. For example, the CEV in the stochastic steady state equals the percent increase in consumption an agent would need in every period in the deterministic steady state so that she is indifferent between living in the deterministic or the stochastic steady states. The resulting CEV equals -0.094 percent, implying that the welfare cost of climate policy risk equals 0.094 percent of consumption. Comparing the first and second columns of Table 4 reveals that the welfare cost of reducing emissions through climate policy risk is over twice as high as using an actual tax. This higher cost stems from the fact that climate policy risk relies more heavily on reductions in total capital (and hence in output and consumption) to reduce emissions and because risk aversion implies that there are welfare costs of the uncertainty created by the climate policy risk.

Table 4: Welfare costs relative to the pre-policy deterministic steady state (CEV, percent)

Stochastic steady state	Emissions-equivalent steady state	Policy steady state
-0.09	-0.04	-0.72

A possible interpretation of these results is that since climate policy risk leads to a reduction in emissions, the costs of delaying action on climate change are smaller than previously thought. However, the welfare cost of reducing emissions through climate policy risk is over twice as high as the welfare cost of the 3.21 dollar carbon tax that achieves the same reduction in emissions. Thus, while delayed action combined with expectations of future policy can actually reduce current emissions, it is a very costly way to achieve this emissions reduction.

6.2 Climate policy evaluation

Our results demonstrate that climate policy risk has meaningful impacts on the macroeconomy. Yet, the existing literature largely abstracts from the effects of climate policy risk when they evaluate carbon tax policy. Implicitly, these studies evaluate climate policy using the pre-policy, deterministic steady state as a baseline, instead of the stochastic steady state. However, if the world is more accurately represented by the stochastic steady state, then such a comparison would misrepresent the true impacts from the carbon tax. To demonstrate the importance of the choice of the baseline for climate policy evaluation, we compare the emissions and welfare effects of the 45 dollar per ton carbon tax using the deterministic steady state as a baseline, with the corresponding effects using the stochastic steady state as a baseline.

We find that using the deterministic steady state as a baseline, and thus failing to account for the effects of climate policy risk, overstates the emissions reduction from the carbon tax by 8.2 percent. Intuitively, this overestimation occurs because climate policy risk reduces emissions in the stochastic steady state. Since emissions are already lower in the stochastic steady state, measuring the emissions reduction between the policy steady state and the stochastic steady state implies a smaller effect of the carbon tax then measuring the emissions reduction between the policy steady state and the deterministic steady state.

The choice of the baseline can also matter for the welfare costs of introducing the climate policy. Following the quantitative public finance literature (e.g., Conesa et al. (2009)), we consider two measures of the welfare cost: (1) a long-run CEV in which we compare the an economy in the baseline steady state with an economy in the policy steady state and (2) a transitional CEV in which we compare an economy in the baseline steady state with an economy that undergoes the dynamic transition to the eventual policy steady state. Table 5 reports these two welfare measures. The first column uses the pre-policy deterministic steady state as the baseline and the second column uses the stochastic steady state as the baseline. The third column reports the error from incorrectly using the deterministic steady state as the baseline, measured as the difference between columns one and two.

Table 5: Effect of the Baseline Steady State on the Welfare Costs of Climate Policy

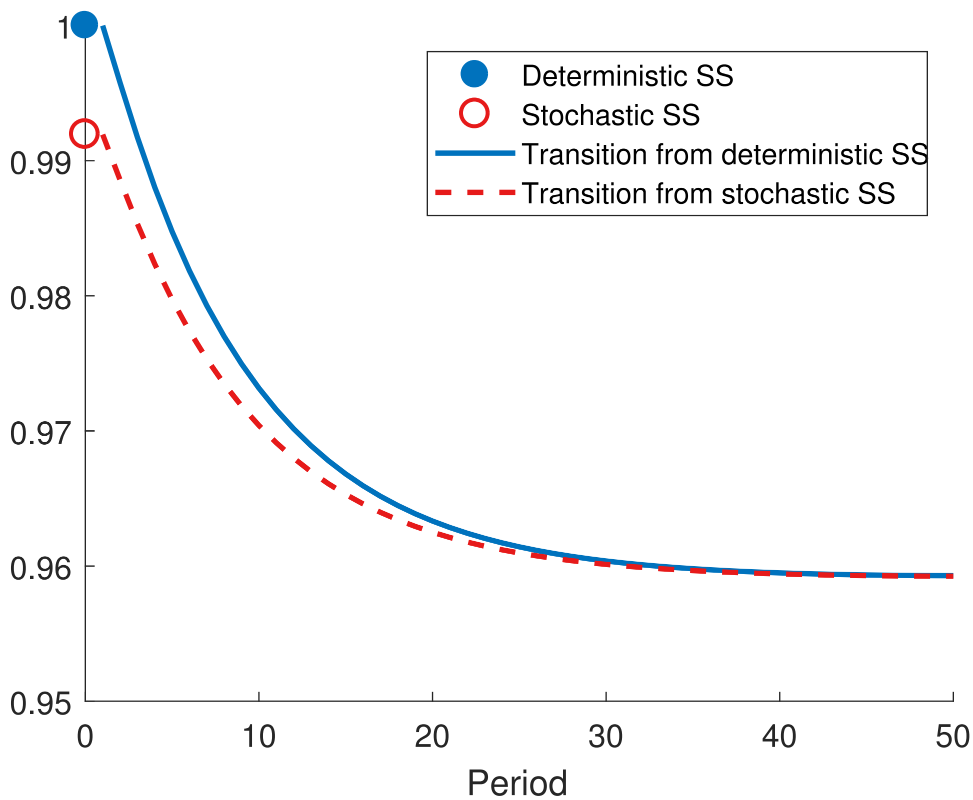
	Baseline equals deterministic SS	Baseline equals stochastic SS	Error
Long-run welfare cost (CEV)	-0.72	-0.63	-0.09
Transitional welfare cost (CEV)	-0.25	-0.24	-0.00

The results in Table 5 reveal that failing to account for climate policy risk would cause policymakers to overstate the long-run welfare costs of the policy. The long-run welfare costs are lower when measured relative to the stochastic steady state because the economy is already part-way to the policy steady state. For example, in the stochastic steady state, the economy has already incurred some of the costs from the eventual reallocation of capital in response to the carbon tax. Additionally, introducing the carbon tax from the stochastic steady state eliminates the uncertainty caused by the climate policy risk. This benefit further reduces the cost of the carbon tax measured from the stochastic steady state baseline.

In contrast to the results for long-run welfare, failing to account for climate policy risk has almost no effect on the transitional welfare costs. The CEVs in the last row of Table 5 are nearly identical across the two different baselines. This near-equivalence stems from two counteracting forces. First, the same mechanism that reduces the long-run welfare cost measured from the stochastic steady state also applies to the transitional welfare cost. Climate policy risk implies that economy is already part way to the policy steady state. Consequently, less adjustment is required over the transition when the economy begins in the stochastic steady state, reducing the transitional welfare cost.

But second, climate policy risk reduces the total capital stock, increasing the transitional welfare costs from the stochastic steady state. Figure 1 plots the time paths of the total capital stock over the transition from the deterministic steady state (solid blue line) and from the stochastic steady state (dashed red line). The lower initial level of capital in the stochastic steady state implies that agents are less able to dis-save over the transition, raising the transitional welfare cost from the stochastic steady state. Ultimately, the benefits from being part-way to the policy steady state are almost perfectly offset by the costs of the lower capital stock and thus, climate policy risk has almost no effect on the transitional welfare cost of the carbon tax.

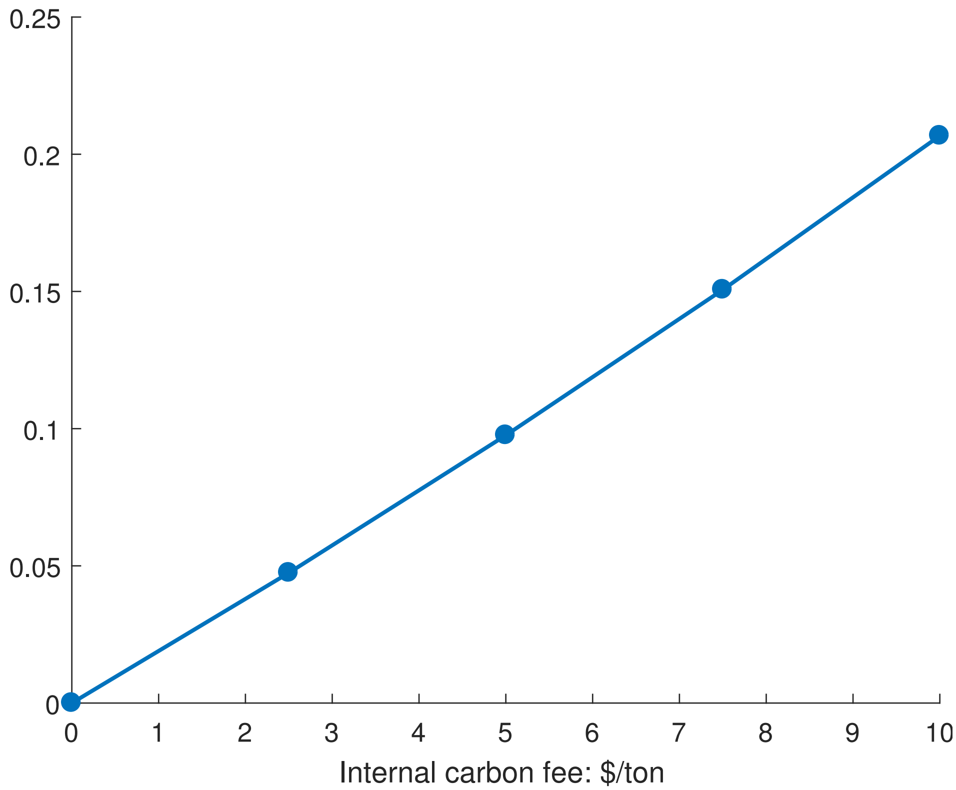
Figure 1: Total Capital Stock



6.3 Changes in climate policy risk

To calibrate the probability of a carbon tax in the model, we used an internal carbon price of 5 dollars per ton, approximately one half of the value that we observe at US 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 motives could range from anywhere between zero and one. To understand the effects of different internal carbon fees, we recalibrate the model for internal carbon fees equal to 2.5, 7.5, and 10 dollars per ton. Figure 2 plots the corresponding probability of a carbon tax for each value of the internal carbon fee.

Figure 2: Probability of a Carbon Tax

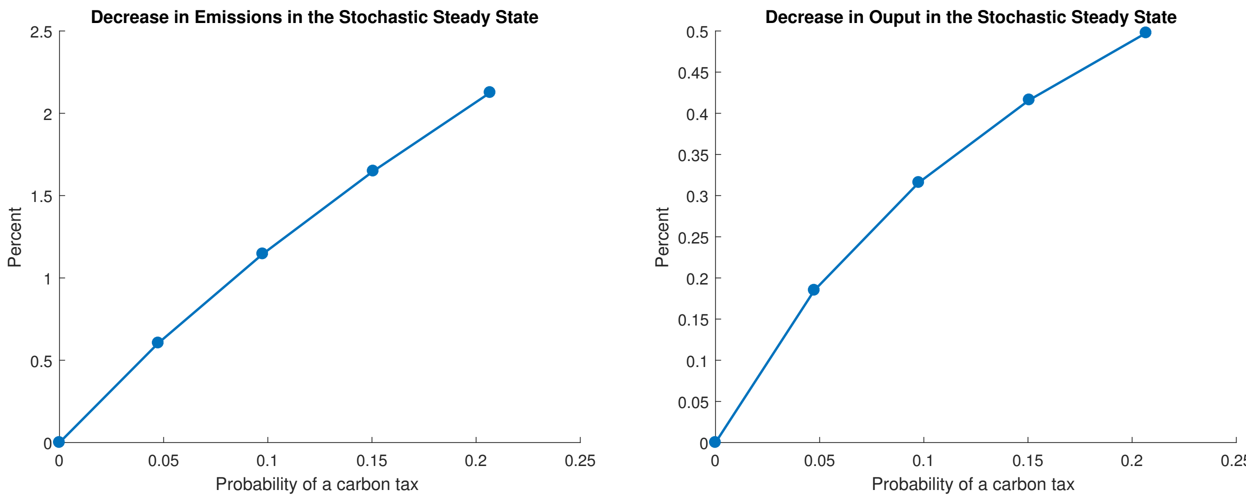


The probability of the carbon tax increases linearly with the size of the internal carbon fee, ranging from approximately 5 percent when the internal fee equals 2.5 dollars per ton to 20 percent when the internal fee equals 10 dollars per ton. The 10 dollar per ton internal fee assumes that the entire fee is motivated by climate policy risk, providing an upper bound on the probability that firms place on the introduction of the 45 dollar per ton tax.

We use the alternative calibrations for different internal carbon fees to explore how changes in the probability of the carbon tax affect the macro-implications of climate policy risk. Understanding this relationship is particularly important because the subjective probability of a climate policy being adopted is likely to increase over time as climate change progresses and public support continues to grow.

The left panel of Figure 3 plots the emissions reduction in the stochastic steady state 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 3 plots the reduction in output from the stochastic steady state. As with emissions, the decrease in output from the climate policy risk increases with the probability of the policy.

Figure 3: Emissions' Reduction and Welfare Cost in the Stochastic Steady State



In general, the macroeconomic consequences of climate policy risk grow with the likelihood of the policy. The larger macroeconomic responses imply that the errors from using the deterministic steady state, instead of the stochastic steady state, as a baseline for policy evaluation also increase with the probability of climate policy. 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.

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A Analytic model

The first order conditions for clean and fossil capital in the stochastic steady state equal,

$$1 = \left(\frac{1}{1+r}\right)(p^c + 1 - \delta) \tag{26}$$

$$1 = \left(\frac{1}{1+r}\right)\left[\rho(p^f - (\zeta+\tau) + 1 - \delta) + (1-\rho)(p^f - \zeta + 1 - \delta)\right] \tag{27}$$

Using the expressions for the equilibrium prices, (equation (3)), we can solve the first order conditions for the levels of clean and fossil capital in the stochastic steady state, K_0^c and K_0^f,

$$K_0^c = \left(\frac{\gamma}{r+\delta}\right)^{\frac{1}{1-\gamma-\theta}}\left(\frac{r+\delta}{r+\delta+\zeta+\rho\tau}\right)^{\frac{\theta}{1-\gamma-\theta}}\left(\frac{\theta}{\gamma}\right)^{\frac{\theta}{\gamma}} \tag{28}$$

$$K_0^f = \left(\frac{\gamma}{r+\delta}\right)^{\frac{1}{1-\gamma-\theta}}\left(\frac{r+\delta}{r+\delta+\zeta+\rho\tau}\right)^{\frac{1-\gamma}{1-\gamma-\theta}}\left(\frac{\theta}{\gamma}\right)^{\frac{1-\gamma}{\gamma}} \tag{29}$$

Observe that

$$\frac{\partial K_0^c}{\partial \rho} < 0,\ \frac{\partial K_0^c}{\partial \tau} < 0,\ \frac{\partial K_0^f}{\partial \rho} < 0,\ \frac{\partial K_0^f}{\partial \tau} < 0 \tag{30}$$

Thus, an increase in either the probability of a tax, or the expected size of the tax, reduces both the levels of clean and fossil capital in the stochastic steady state. However, the decrease in fossil capital is larger than the corresponding decrease in clean. Indeed, climate policy risk increases the ratio of clean to fossil capital,

$$\frac{K_0^c}{K_0^f} = \left(\frac{1 + r + \zeta + \rho\tau - (1-\delta)(\rho(1-\lambda) + 1 - \rho)}{r + \delta}\right)\left(\frac{\gamma}{\theta}\right) \tag{31}$$

□

B Calibration

Data on on US 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 US 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 US vehicle fleet are available from Table VM-1 of the Federal Highway Administration's 2017 highway statistics.[15] Data on fuel economy by car make and model is from fueleconomy.gov. Data on total mine production by mineral type are available from Table 1 of the US Geological Survey Mineral and Commodity Summaries. Data on GDP by industry and detailed data on fixed assets and consumer durables are from the BEA.[16] 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 US economy, K^d/K. The data provide information on the quantity of each type of capital in each sector and on the quantity of each type of durable

[15] https://www.fhwa.dot.gov/policyinformation/statistics/2017/

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

good. The sectors are 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 6 reports the the types of capital and consumer durables that we classify as group 1 and group 2. All types not listed in Table 6 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 6: Capital Classification

Group 1	Group 2
steam engines	special industrial machinery
other trucks buses	custom software
and 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	

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 partially clean and partly fossil. Most vehicles are specialized to use fossil fuel, making them at least partly fossil-based. 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 US 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 US 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 US fleet. The average inverse fuel economy of the US 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 pick up 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 US 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, plastics and rubber 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 the mining except oil and gas extraction (NAICS code 212), or 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 could 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: $0.763K_{213} + 0.247(1 - 0.763)K_{213}$.

C Values of macro aggregates in each steady state

Table 7: Macro Aggregates in Each Steady State

	Steady State			
	Deterministic	Stochastic	Emissions equivalent	Policy
Fossil fuel: F	0.0113	0.0112	0.0112	0.0096
Output: Y	0.2797	0.2788	0.2792	0.2729
Consumption: C	0.2030	0.2027	0.2028	0.2005
Capital: K	0.7269	0.7210	0.7246	0.6972
Labor: L	0.3331	0.3330	0.3329	0.3312
Clean Capital: K^c	0.0973	0.0987	0.0985	0.1132
Fossil Capital: K^f	0.1348	0.1316	0.1331	0.1117
Non-Energy Capital: K^n	0.4947	0.4907	0.4930	0.4722
Clean Labor: L^c	0.0446	0.0450	0.0453	0.0538
Fossil Labor: L^f	0.0618	0.0615	0.0611	0.0531
Non-Energy Labor: L^n	0.2267	0.2265	0.2265	0.2243
Clean Intermediate: X^c	0.0710	0.0717	0.0719	0.0846
Fossil Intermediate: X^d	0.1571	0.1553	0.1553	0.1334
Non-Energy Intermediate: X^n	0.2933	0.2923	0.2928	0.2868