Climate Transition Risks and the Energy Sector*

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Abstract

We build a general equilibrium model to study how climate transition risks affect energy prices and valuations of different firms in the energy sector. We consider two types of fossil fuel firms: incumbents that have developed oil reserves they can extract today or tomorrow, and new entrants that must invest in exploration and drilling today to have reserves to extract tomorrow. Renewable energy firms produce energy without generating carbon emission but cannot currently supply non-electrifiable sectors of the economy. We analyze three sources of climate transition risk: (i) changes in the probability of a technological breakthrough that allows renewable energy firms to serve all sectors tomorrow; (ii) changes in expected future taxes on carbon emissions; and (iii) restrictions on today's development of additional fossil fuel production capacity. While a greater chance of renewable technology breakthroughs decreases energy prices—in part because incumbents fearing future competition from renewables decide to extract more of their reserves today—this need not be the case with carbon taxes and drilling restrictions. These latter transition risks make it less attractive for newly entering fossil fuel firms to create additional capacity. Therefore, if breakthrough technologies do not arrive, incumbents will face a world with less capacity and higher energy prices. This mechanism therefore can create incentives for incumbent fossil fuel firms to hold inventories and carry them to the future, with the expectation of profiting if the breakthrough technology does not materialize. In turn, this reduces supply today and therefore raises prices. The valuation of renewable energy firms generally increases upon the realization of all three types of transition risks, while valuations of fossil fuel entrants decline. Valuations of incumbent fossil fuel firms decline by less than those of new entrants, and might even increase upon the imposition of drilling restrictions that reduce competition from new entrants. We provide empirical support for the testable implications of the model, based on these heterogeneous effects of different transition risks on energy prices and stock returns of firms in different energy sub-sectors.

Keywords: Climate change, renewable energy, green transition, fossil fuel firms, brown firms, carbon tax, drilling restrictions, oil prices

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Through the burning of fossil fuels, energy production accounts for about three-quarters of global greenhouse gas emissions (Ritchie and Roser, 2020), making the energy sector a key policy focus in the fight against climate change. To encourage a transition from fossil fuels towards alternative energy sources, policy makers have employed a range of tools, including carbon taxes, renewable R&D subsidies, and restrictions on the development of new fossil fuel capacity. This paper aims to understand the effects of these different policies on the dynamics of prices, inventories, investment, production, and valuations in the energy sector. We find that different policies—while often jointly referred to as "transition risks" for energy firms and the economy more broadly—can have very different implications for these equilibrium outcomes.

We build a two-period general equilibrium model to understand the impact of different climate transition risks on the energy sector (our model periods can be thought of as being about a decade apart). We consider two types of fossil fuel firms: (i) incumbents with developed reserves that can be produced at low cost either today or tomorrow, and (ii) new entrants who need to invest today to develop reserves for possible extraction tomorrow.[1] Renewable firms invest in capacity today—say by building a wind farm—to produce at zero marginal cost tomorrow. With current technologies, the ability of renewable energy to power the economy is limited both by the intermittency of renewable supply and the fact that many sectors of the economy are hard to electrify. This means that some share of economy-wide energy demand will need to be supplied by fossil fuel firms, independent of the total capacity of renewable firms.

We consider three sources of climate transition risk for fossil fuel firms: (i) the possibility of technological breakthroughs in storage and electrification that improve renewable energy firms' ability to reliably meet a larger share of economy-wide energy demand; (ii) the introduction of taxes on carbon emissions; and (iii) restrictions on new fossil fuel production capacity, including restrictions on drilling and pipeline development. Each transition risk type has a different effect on energy prices and valuations across the various parts of the energy sector.

First, consider the effects of restrictions on new fossil fuel capacity, which can be analyzed by considering only the interaction between incumbent and newly entering fossil fuel firms. All else equal, a reduction in investments in additional fossil fuel capacity today—for example, due to a tax on new drilling—puts upwards pressure on future energy prices. The anticipation of these higher future energy prices leads fossil fuel producers to delay exploiting some of their reserves, reducing extraction today and increasing it tomorrow. This inter-temporal inventory management raises energy prices today, leading to what the European Central Bank's Isabel Schnabel (2022) called "fossilflation." Higher energy prices today and tomorrow raise the value of the production capacity that incumbent fossil fuel firms have in place, and thus increase their valuations; at the same time, restrictions on new capacity reduce valuations of new entrant fossil fuel firms. Therefore, this type of transition risk has heterogeneous effects for different types of fossil fuel firms.

Next, we study what happens when a carbon tax is introduced. The tax is introduced in period 1 with probability p_T. We call T the state of the world where the tax is introduced, and NT the state of the world with no tax. As it turns out, the effects of changes in this tax on energy prices is ambiguous, and depends on the level of expected tax rate. Suppose first

[1] In practice, some new exploration may also be done by incumbents. Separating the problem of how much to extract from current reserves from the problem of how many new reserves to add allows us to develop insights into how various transition risks might differentially influence firms with more developed vs. undeveloped reserves. In our empirical tests we place energy firms on a continuum between pure entrants and pure incumbents.

that the tax in the T state is exactly zero. Then, obviously there are no differences between the T and NT states of the world, and the expected tax is also zero. In this case, incumbent fossil fuel producers solve the same intertemporal problem to divide their production capacity across the two periods as if there was no tax at all. Notably, this implies that incumbents will always optimally exhaust their production capacity in period 1: if any inventory ended end up being "stranded" (which will happen in both states of the world since they are identical), the incumbent would be better off extracting and selling it today.

Now consider an increase in the tax in the T state from zero to a (small) positive number, which in turn implies a decline in post-tax expected oil prices in T. This change results in new entrants reducing the capacity they choose to install, because they expect to profit less in the T state. Similarly, incumbents will respond by extracting more oil today, so oil prices today also decrease. The valuations of both incumbents and new entrants fall.

As the tax rate in T increases, however, it eventually reaches a threshold τ_{strand} where the incumbent energy firm may choose not to extract all its reserves in state T—the marginal cost of extracting the last units exceeds the post-tax price $(1 - \tau_{strand})P_T$, resulting in reserves that are "stranded". If T was the only possible future state, then it would clearly be optimal for the incumbent to extract that oil today. However, potential profits in the NT state may still make it advantageous for the incumbent to carry forward inventory rather than extracting and selling it today. This is the case if the *expected* marginal revenue of the inventory carried forward, $(1 - p_T)P_{NT}$, exceeds the energy price today. A central insight gained here is that once some reserves are stranded in the T state, the incumbent's expected price for a *marginal* unit of reserves is only dependent on prices in the NT state, since these additional units will be stranded if the T state is realized (and thus, on the margin, worthless).

On the other hand, the new entrant incurs higher costs to generate capacity in the future, since they still need to pay for exploration. Further increases in taxes beyond τ_{strand} will result in further declines in capacity investments by new entrants, and hence reduce energy supply and raise prices in the NT state. Incumbents with large initial reserves who are more willing to bear the risk of stranded assets in the T state for the opportunity of capturing higher profits in the NT state can capitalize on this by extracting less today and bringing more reserves into the future. This leads us to our counterintuitive result: increases in the expected carbon tax in the T state beyond τ_{strand} lead to price *increases* today. It is crucial to note that higher taxes continue to reduce the valuation of all fossil fuel firms, though this drop in valuation is attenuated for incumbents.

Finally, consider the effects of the third type of transition risk, the possibility of a technological breakthrough in renewable energy (to see the intuition, assume there were no carbon taxes or restrictions on drilling). Renewable energy firms need to invest in capacity today to provide energy in the future. With some probability p_{BT}, a technological breakthrough occurs that allows renewable firms to provide energy to the whole economy; we denote this scenario as Breakthrough Technology, or BT, state. With probability $1-p_{BT}$ no such breakthrough occurs, and renewable firms can provide energy to only fraction q of future demand, perhaps because renewable supply is intermittent and because many economic sectors are not electrifiable. We call this the Current Technology (CT) scenario. Without loss of generality, set $q = 0$ such that absent a technological breakthrough, renewable firms cannot supply any energy. Changes in the possibility of such a technological breakthrough constitutes a key source of transition risk. As p_{BT} increases, the expected price of oil tomorrow declines. As a result, new entrants restrict

Table 1: Summary of model predictions.

Increase in:	P(Tech Breakthrough)	Carbon tax in BT state	Drilling restrictions
Current energy price (P_0)	Decreases	Uncertain	Increases
Future energy price ($E[P_1]$)	Decreases	Increases	Increases
Incumbent fossil fuel producer			
Inventory	Decreases	Uncertain	Increases
Stock price	Decreases (less)	Decreases (less)	Increases
Entrant fossil fuel producer			
Production capacity	Decreases	Decreases	Decreases
Stock price	Decreases (more)	Decreases (more)	Decreases
Renewable energy producer			
Production capacity	Increases	Increases	Increases
Stock price	Increases	Increases	Increases

new supply and incumbents extract more today, leading to a decline in energy prices today. Valuations of renewable firms increase, while valuations of fossil fuel firms decline, though with smaller declines for incumbents than for new entrants.

Finally, we develop a model that jointly includes all three sources of transition risk. In general, the states of the world in which a carbon tax is imposed might be different from the states of the world in which the technological breakthrough occurs. However, we show that if policymakers are setting an optimal carbon policy, the states of the world with high carbon taxes are likely to coincide with "breakthrough" states of the world in which renewable firms can supply substantial amounts of energy. We can therefore simplify the full model by only considering one state of the world when the technological breakthrough occurs and carbon taxes are high, and one where the technological breakthrough does not occur and carbon taxes are low. The full model confirms the insights from considering the different climate transition risks individually, and provides testable implications of how oil prices and the stock prices of different energy-sector firms should respond in response to news relating to different climate transition risks.

Specifically, news that reveals an increase in the probability of a technological breakthrough in renewable technologies or carbon taxes should have a negative effect on the stock price of fossil fuel companies, with particularly negative effects for new entrants. It should also lead to declining oil prices. Announcements on restrictions to develop new fossil fuel capacity, such as taxes on new oil drilling, will have a negative effect on the stock price of fossil fuel companies with little capacity already in place, but may even raise the valuation of companies with large existing reserves. Our model therefore highlights how policies aimed at reducing restrictions on new oil supply are not necessarily positive for the largest producers, as they can put downward pressure on oil prices.[2] Finally, energy prices are likely to fall upon the realization of news about technological breakthroughs but may rise upon news about restrictions on fossil fuel capacity and news about future carbon taxes. These implications for different types of transition risk on energy prices and valuations of energy sub-sectors are summarized in Table 1.

We empirically test these implications by studying the reactions of prices of oil futures and

[2]For instance, the Wall Street Journal quotes an investor in the oil and gas industry after the 2024 U.S. presidential election stating that *"Our stocks will be absolutely crushed if we start growing our production the way Trump is talking about it"*. (from "Trump's Oil and Gas Donors Don't Really Want to 'Drill, Baby, Drill' ", November 22nd, 2024).

of stocks in different types of energy firm sub-sectors to news about different climate transition risks. To achieve this, we construct high-frequency transition news indexes by analyzing news reported in the New York Times (NYT) using GPT-4o Mini, one of the most advanced large language models (LLM) developed by OpenAI specialized in textual reasoning. Our analysis covers articles published over a 12-year period from 2012 to 2023. We create three weekly indices: (1) the NYT-Emission Cost News Index, which captures news about carbon pricing policies and the regulatory or financial costs of carbon emissions, including the introduction of taxes or other policies on carbon emissions; (2) the NYT-Renewable Breakthrough News Index, which covers news related to the probability of breakthroughs in renewable energy or battery storage technology, actual technological advancements in these fields, and policies subsidizing or supporting renewable energy production; and (3) the NYT-Oil Capacity News Index, which captures news regarding policies affecting the expansion of fossil fuel capacity, such as changing infrastructure permit availability, financing availability, and compliance requirements.

Figure 1 plots the time series of the three news indexes, with labels indicating key events. Positive scores indicate more restrictions on the fossil fuel industry or greater likelihoods of renewable energy breakthroughs. The NYT-Emission Cost News Index shows spikes around significant climate-related events, such as the first proposal of the Clean Power Plan in 2014, its repeal proposal in 2017, and Biden rejoining the Paris Agreement in 2021. The NYT-Renewable Breakthrough News Index spikes around events favoring renewable energy or announcing technological breakthroughs, such as advancements in industrial-scale biofuel production in the U.S. in 2014, new solar home battery technology introduced to the U.S. in 2017, and investments in expansion of electric vehicle charging networks in 2022. The NYT-Oil Capacity News Index spikes around regulations which influence fossil fuel production, like the review of the Keystone XL oil pipeline in 2017 and its permit revocation in 2021.

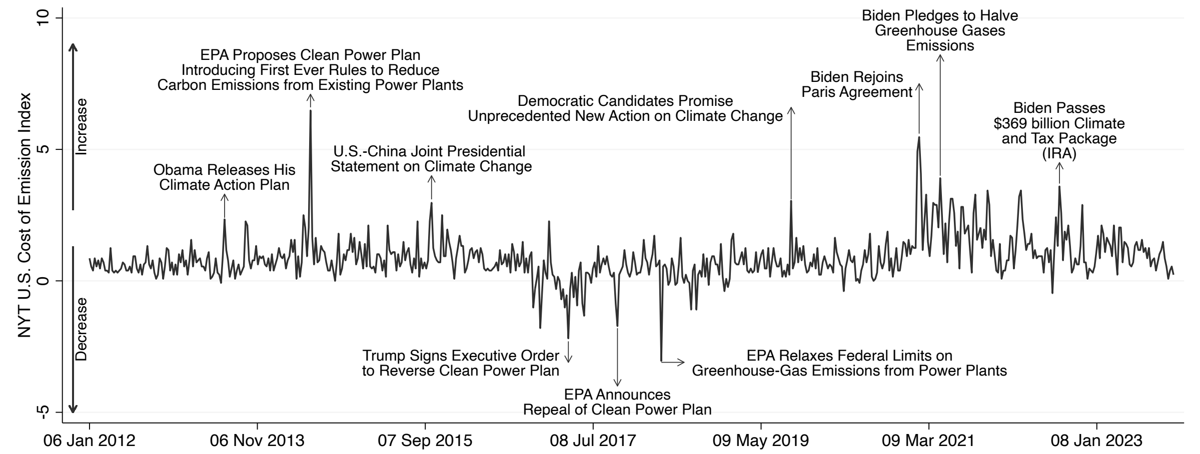
We then study the response of energy prices and stock returns of energy firms to innovations in these news indices. First, consistently with our model, we document that, while noisy, oil futures prices decrease during months with news about possible renewable energy breakthroughs, but they increase in months with news related to increasing cost of carbon emissions (consistent with an expectation that at least some oil capacity will be stranded in the high-tax state of the world). Oil futures prices do not move in a statistically significant manner with news about possible changes in oil capacity.

Next, in line with our model, we identify two groups of firms: fossil fuel firms and renewable firms. For each fossil fuel firm, we measure their "developed ratio", the share of their oil reserves that are already developed. This gives us a continuum, where firms with higher developed ratios—such as Exxon, Chevron, Conoco Phillips, Occidental Petroleum, and Devon Energy—should behave more like the incumbents in our model, and firms with lower developed ratios—such as BPZ Energy, ZaZa Energy, and Lonestar Resources—should behave more like new entrants who will have to decide whether to invest to have oil capacity tomorrow. We identify renewable firms using the holding firms of the Invesco Solar ETF and the First Trust Global Wind Energy ETF, which includes companies in the solar and wind energy industry respectively. Examples of these firms include First Solar, Altus Power, and Arcosa Towers.

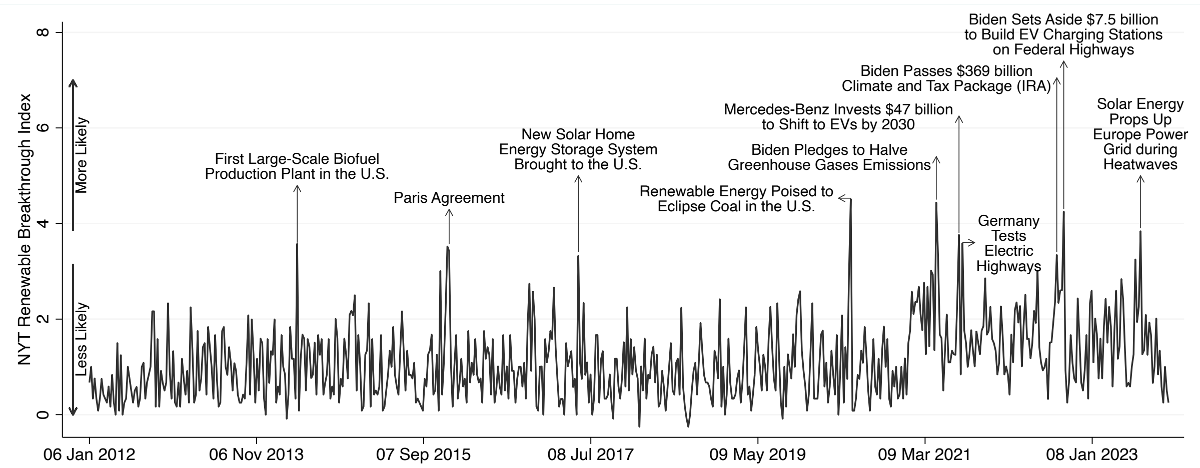
We find that, consistent with the theory, on average renewable energy companies earn positive returns in weeks with each of the three types of transition news, whereas fossil fuel companies on average have negative returns on those days. Consistent with the model predictions, we also observe differential price movements for fossil fuel companies in response to the different types

Figure 1: Time-Series of NYT News Index

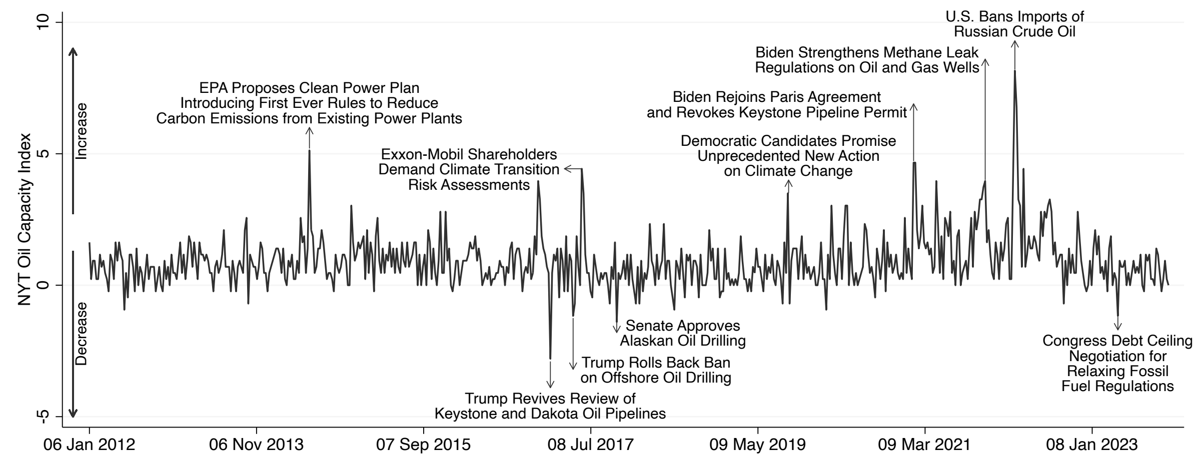
(a) NYT-Emission Cost News



(b) NYT-Renewable Breakthrough News



(c) NYT-Oil Capacity News



Note: Panel (a) shows the weekly NYT-Emission Cost News Index, panel (b) shows the weekly NYT-Renewable Breakthrough News Index, and panel (c) shows the weekly NYT-Oil Capacity News Index from 2012 to 2023, annotated with climate-relevant events that have potential effects on cost of emissions and renewable energy supports. IRA: Inflation Reduction Act.

of news, depending on their developed ratio. News about all three types of transition risks leads to a much larger decline for firms with largely undeveloped reserves, with much smaller effects for firms with largely developed reserves. Overall, these results line up closely with the main predictions of the theoretical model, and highlight how different types of transition risks have very heterogeneous effects on different types of fossil fuel firms.

Related Literature. Our paper belongs to the growing literature on climate finance, recently reviewed by Giglio et al. (2021) and van Benthem et al. (2022). While focus on studying the effects of the climate transition on energy prices from a theoretical perspective, we are motivated by existing empirical evidence. On the energy-price front, Känzig (2023) shows that a carbon policy tightening shock in the Eurozone causes an increase in the price of energy. A similar conclusion is reached by Konradt and Weder di Mauro (2022), who argue that carbon pricing increases the cost of energy. In terms of effects of transition risks on firm valuations, Alekseev et al. (2022) find that energy firm stocks are not generically negatively affected by generic climate transition news. Other papers have also shown that climate transition risk is currently reflected in the stock market (Hong et al., 2019; Bolton and Kacperczyk, 2021; Engle et al., 2020). Connecting these inquiries, our model highlights how the fossil fuel sector might respond differentially to various types of transition risk, and also offers predictions for the stock price of fossil fuel firms in response to climate transition risk and as a function of their existing capacity. Adolfsen et al. (2024) show empirically that firms in the fossil fuel industry with greater exposure to climate change significantly increased their investment in response to the Paris Agreement, arguing that in anticipation of future climate policy, fossil fuel firms might have a short-term incentive to raise production. Our model features such a channel whereby incumbents adjust the timing of the extraction of developed reserves based on expectations of future transition risk realizations.

On the theoretical front, Pisani-Ferry (2021) makes the case that policymakers should adopt a macroeconomic perspective when analyzing the effects of climate policies, and that their general equilibrium effects on the economy should be taken into account. Along these lines, Engle (2023) develops a model of "termination risk" which captures the idea that fossil fuel assets might become stranded at some point in the future, and this might have the effect of reducing energy supply today. We make a related point in our model, and also argue that technological development in the renewable energy sector can instead push down the current price of energy. Barnett (2023) reaches the conclusion that expectations of future restrictions on fossil fuel use might induce oil producers to increase current supply, thus increasing emissions and pushing down energy prices. This possibility has been labeled as the "Green Paradox" (Sinn, 2008; Kellogg, 2024). Our model naturally delivers this result with respect to expectations of breakthroughs in renewable energy technologies, but also highlights how different types of transition risk, such as carbon taxes or restrictions on new drilling, can have different effects on energy prices, firms in the energy sector, and carbon emissions.

A growing theoretical literature also studies the effects of transition risk on the aggregate inflation level, mostly relying on models based on the New Keynesian framework. Ferrari and Nispi Landi (2024) argue that expectations of future carbon taxes can have deflationary effects on the economy, while Del Negro et al. (2023) find that the price level response to the green transition depends on the degree of price stickiness in the various sectors of the economy, and in particular of green and non-green sectors.

Finally, our paper is related to the large macroeconomic literature studying optimal carbon tax and green subsidy policies in the presence of emissions externalities (Acemoglu et al., 2012; Golosov et al., 2014; Lemoine and Traeger, 2014; Acemoglu et al., 2016; Aghion et al., 2016). Another related paper is Acharya et al. (2023), which builds a model to study "Net Zero" carbon commitments by corporations in a model with externalities in renewable sector innovations, and investigates the role of large firms and common ownership in this context. We add to this literature by studying how carbon taxes should depend on the probability of a breakthrough technological development in the renewable energy sector. Furthermore, we also analyze in optimal policy as well as in terms of energy price implications the role of taxes on newly installed fossil fuel production capacity.

1 Two-Period Climate Transition Risk Model

We first start by building and describing a simple model of the energy sector. We gradually introduce each of the various transition risks that we study to clearly isolate their different implications on energy prices and firm valuations. In particular, we start by studying drilling restrictions in a two-period model with no uncertainty about the future, and no renewable energy sector. In the next step, we introduce a carbon tax implemented with some probability in the future. Then, we investigate the possibility of a technological breakthrough that allows green firms to supply energy to the entire economy. Finally, we close this section by studying optimal carbon taxes in our framework. In the subsequent section, we develop a model that incorporates all three climate transition risks jointly while fully endogenizing prices. We solve that model numerically to provide testable implications, and highlight that all intuitions developed in the simpler model in this section carry through.

1.1 Baseline model

Time is discrete and there are two periods, denoted by $t = 0, 1$, with a gross discount rate $R = 1$. We analyze a simple market for energy, where supply is provided by two types of fossil fuel-based energy producers: an incumbent firm and a competitor which will enter in period 1. In this environment, we investigate the effects on energy prices of a tax on the creation of new fossil fuel capacity by the entrant firm, $\bar{\tau}_0$, to be implemented in period 0. This could correspond to a range of actual policies, including increasing the cost of new drilling (or making fewer new oil field leases available).[3] The tax on new production capacity that we study can also capture an increase in the cost of capital for fossil fuel exploration, for instance due to raising banks' cost of lending for such projects.

At time 0, the incumbent fossil fuel producer (superscript I) has an existing capacity of $\bar{f}_0^I$, which can be used immediately to produce energy, or saved for the next period as inventory.

[3] For instance, the Wall Street Journal argues that *"lowering the cost of doing business—say, through less stringent environmental rules—could help smaller, wildcatter-type producers join the drilling party, potentially pinching profitability for the industry overall."* (from "Is Trump Really Better Than Harris for Oil and Gas Investors?", August 2nd 2024) and reports how some energy analysts after the 2024 U.S. elections stated that *"Historically, though, traditional energy has performed slightly better under Democrats [...]. That is because they tend to favor putting roadblocks on new supply, which helps limit capital spending and boost oil prices [...]. And those roadblocks tend to be more damaging to small producers rather than giants."* (from "Why Big Oil Doesn't Mind Big Regulation", November 18th, 2024). These articles crucially highlights how restrictions on new drilling can affect incumbents and new firms differently.

Producing an amount of energy f_t has a cost of $\frac{1}{2\kappa_1}f_t^2$, with $\kappa_1 > 0$. Taking as given the price of energy in the two periods, (P_0, P_1), the incumbent firm chooses production quantities (f_0^I, f_1^I) that solve

$$\max_{0\leq f_0^I \leq \bar{f}_0^I} \quad f_0^I P_0 - \frac{1}{2\kappa_1}(f_0^I)^2 + V_1^I \tag{1}$$

where the period-1 continuation value V_1^I is equal to

$$V_1^I = \max_{0\leq f_1^I \leq \bar{f}_0^I - f_0^I} \quad P_1 f_1^I - \frac{1}{2\kappa_1}(f_1^I)^2 \tag{2}$$

To make the problem interesting, we assume that the initial capacity of the incumbent firm is such that the firm is constrained in period 1, so that it has to choose how to optimally allocate its production capacity across the two periods.

The other producer in the economy is a representative entrant firm (superscript E) that has no existing production capacity, and has to choose how much new capacity to install to be used in period 1.[4] Installing an amount of capacity $\bar{f}_1^E$ has a cost $\frac{1}{2(1-\bar{\tau}_0)\kappa_2}(\bar{f}_1^E)^2$, with $\kappa_2 > 0$. The tax rate $\bar{\tau}_0$ captures the extent of restrictions on capacity expansion. We assume that production costs in period 1 are the same as for the incumbent firm. The fossil fuel entrant firm therefore chooses its capacity investment in period 0 and its production in period 1 $(\bar{f}_1^E, f_1^E)$ by solving:

$$\max_{\bar{f}_1^E \geq 0} \quad -\frac{1}{2(1-\bar{\tau}_0)\kappa_2}(\bar{f}_1^E)^2 + V_1^E \tag{3}$$

where the period-1 continuation value V_1^E is equal to

$$V_1^E = \max_{0\leq f_1^E \leq \bar{f}_1^E} \quad P_1 f_1^E - \frac{1}{2\kappa_1}(f_1^E)^2 \tag{4}$$

We close the model by assuming a simple consumer side of the economy. There is a unit mass of consumers in the economy with strictly concave utility u from energy consumption. In each period T, consumers have exogenous wealth W that can be used to purchase energy. We assume that wealth cannot be stored across periods, so that energy demand in each period is simply equal to $\frac{W}{P_t}$. Therefore, we have the following market clearing conditions

$$\frac{W}{P_0} = f_0^I \tag{5}$$

$$\frac{W}{P_1} = f_1^I + f_1^E \tag{6}$$

The definition of equilibrium in this model is standard. We are interested in studying the effect that drilling restrictions have on the energy price in period 0. We derive the following result.

Proposition 1. *Increases in drilling restrictions cause a reduction in the newly installed production capacity by the entrant firm. In response, the incumbent firm reduces its date-0 energy supply, which increases the price of energy.*

As a consequence, increases in drilling restrictions reduce profits for the entrant but increase them for the incumbent.

[4] In practice, new exploration may also be done by incumbents. By separating the problem of how much to extract from current reserves from the problem of how many new reserves to add, we are able to develop insights into how various transition risks might differentially influence firms with more developed vs. undeveloped reserves.

The intuition is the following. Fossil fuel capacity restrictions only affect the entrant firm in our model. Facing higher costs of installing new capacity, the entrant reduces its investment in period 0. The incumbent firm therefore anticipates that it will face less competition and higher energy prices in period 1, and thus has the incentive to reduce current energy supply to carry production capacity in period 1 as inventory. This has the effect of increasing the current energy price.

The fact that drilling restrictions on new fossil fuel capacity affect only the entrant firm in our model implies that profits for the entrant decrease. The incumbent firm instead benefits from higher future energy prices coming from less competition. Therefore, its profits increase.

In our model, the stochastic discount factor is constant, so that expected profits coincide with stock prices. Therefore, Proposition 1 predicts that, empirically, news about future drilling restrictions should have a negative effect on the stock prices of firms with low existing capacities, while firms with large developed reserves can see their stock market valuations increase. We will test empirically these predictions in the second part of the paper.

1.2 Model with uncertain carbon tax

As a second source of transition risk, we now introduce a carbon tax that is implemented with some uncertainty in the future, and study its effects on the energy sector.

We assume that there are two possible states in period 1, indexed by $s \in \{T, NT\}$. We denote with p_T the probability that state T realizes, and we assume that if this state realizes then a carbon tax on fossil fuel firms' revenues, τ_1, is implemented. Producers face the same demand for energy across the two states, and therefore the only difference is represented by the carbon tax policy. We include in the Appendix more details about the new problem of fossil fuel firms and the solution of this model.

We now show that carbon taxes implemented in the future with uncertainty can have counterintuitive effects on current energy prices. In particular, we have the following result.

Proposition 2. *The effect on the date-0 energy price of future carbon taxes implemented with some probability is ambiguous. In particular:*

- *For low enough values of the tax rate, increases in the carbon tax cause a reduction in the date-0 energy price, that is* $\frac{dP_0}{d\tau_1} < 0$.
- *For high enough values of the tax rate, increases in the carbon tax cause an increase in the date-0 energy price, that is* $\frac{dP_0}{d\tau_1} \geq 0$.

The intuition for this result is the following. If the carbon tax is low, then energy prices are still attractive in both futures states of the world. Therefore, the incumbent firm is expecting to fully sell its fossil fuel inventory both in the T and in the NT state. It then follows that the marginal benefit of carrying an additional unit of inventory in period 1 is given by profits across the two states. Since a higher tax rate reduces expected future profits, increases in the carbon tax induce the incumbent to carry less inventory in period 1 and to increase energy supply in period 0. This has in turn the effect of reducing the period-0 energy price. Our result is therefore a version of the "green paradox" that has been discussed in the literature, as expectations about future climate policies can induce the fossil fuel sector to increase current production, thus increasing carbon emissions.

As the tax rate increases, the difference between profits in the two states increases. Therefore, the incumbent now expects to exhaust its inventory in the NT state only, since post-tax prices in state T are very low and so part of its production capacity will remain unused. It follows that now the *marginal* benefit of carrying inventory into period 1 is given by changes in the price in the NT state only. For the entrant firm, on the other hand, it is more costly to leave unused production capacity, since it has to incur the additional cost of setting it up in period 0. Therefore, its production capacity decisions still take into account the energy price in both states. It follows that as the carbon tax increases, the entrant reduces its investment in new capacity in period 0. But this implies that the incumbent firm is now expecting a higher price in the NT state because of the lower competition by the entrant, and so it has the incentive of carrying more inventory forward into the future. In other words, if the tax rate is high so that assets in the T state are stranded, further increases in the tax rate increase the marginal benefit of carrying inventory in the future. As a consequence, energy supply in period 0 decreases, and the energy price increases. This result therefore suggests that expectations about future carbon taxes do not necessarily need to increase current fossil fuel supply and carbon emissions, thus counteracting the standard intuition behind the green paradox.

In order to understand the possible non-monotone effect of carbon taxes on oil prices more clearly, we can analyze the optimal production quantities by the two firms. If both firms are exhausting their production capacity in both states, then the optimal fossil fuel supply by the incumbent in period 0 is given by

$$f_0 = \frac{\bar{f}_0}{2} + \frac{\kappa_1}{2}\left[P_0 - p_T(1-\tau_1)P_{1,T} - (1-p_T)P_{1,NT}\right]$$

while optimal production capacity by the entrant is given by

$$\hat{f}_1 = \frac{(1-\hat{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\hat{\tau}_0)\kappa_2}\left[p_T(1-\tau_1)P_{1,T} + (1-p_T)P_{1,NT}\right]$$

As the carbon tax increases, profits in the T state decrease for both producers. Therefore, the entrant firm installs less new capacity, and the incumbent firm increases energy supply in period 0, which pushes down the energy price. Note that in equilibrium both prices in period 1 increase due to the lower supply, but this indirect effect is not strong enough to overcome the reduction in future profits due to the higher tax.

Suppose then that the tax in the T state is so high that the incumbent firm optimally decides to leave part of its capacity stranded in that state. Optimal energy supply in period 0 is now given by

$$f_0 = \frac{1-p_T}{2-p_T}\bar{f}_0 + \frac{\kappa_1}{2-p_T}\left[P_0 - (1-p_T)P_{1,NT}\right]$$

Note that now the price in the T state does not affect the supply and inventory decision of the incumbent at the margin, since this firm is expecting to sell all its inventory in the NT state only. Therefore, in this case, increases in the tax rate affect directly only the entrant firm, for which it is still optimal to sell in both states as it has to pay the additional cost of installing the new capacity. A higher tax rate causes lower supply from the entrant firm, which in turn increases the energy price in the NT state. But since this is the only price that is driving the production decisions of the incumbent, this firm reacts to a higher price in the NT state by reducing energy supply in period 0. This, in turn, causes an increase in the energy price in period 0.

We therefore showed that uncertainty about future carbon taxes can have the somewhat counterintuitive effect of pushing up the current price of energy. For low tax rates, a standard intuition holds, so that carbon taxes lower current energy prices. However, our model suggests that this effect can be overturned for high enough tax rates. This result relies crucially on the possibility of a future state of the world where carbon taxes are low and fossil fuel reserves are very valuable. Note that this scenario can occur only if entrant firms are discouraged by the carbon tax from setting up new production capacity. This increases the marginal benefit from fossil fuel production in the NT state, and therefore the incumbent has an incentive to increase its inventory. The fact that in one of the states the incumbent has stranded assets is not sufficient to switch the decision of the incumbent on its own, as if expected profits in the NT state were not increasing, then the incumbent would have an incentive to increase current supply.

Therefore, as investments in new fossil fuel capacity are discouraged by carbon taxes, existing companies with large reserves can potentially have large profits if the state of the world where the tax is not implemented is realized. It follows that it might be optimal to reduce energy supply and carry production capacity into the future, even though this strategy exposes fossil fuel companies to the risk of having their assets stranded in the high-tax state. Our model therefore highlights how carbon taxes can affect firms in the energy sector in different ways, and that these implications should be taken into account when assessing their policy implications.

Empirically, Proposition 2 suggests that firms with large existing production capacities should be less negatively affected by news about carbon taxes, compared to fossil fuel firms with low reserves. This is an additional implication which we test in the data.

1.3 Model with a green energy transition

We now consider a different dimension of uncertainty, related to the possibility of transitioning to an economy where clean producers can reliably satisfy energy demand.

In particular, with probability p_{BT} a breakthrough technology is developed in period 1, which allows renewable energy producers to supply to all sectors of the economy. In this scenario, renewable firms are able to compete with fossil fuel producers in the energy market. We denote the scenario that includes these possible developments as the "Breakthrough Technology" (BT) scenario. If the technological breakthrough does not occur, fossil fuel firms remain the only energy supplier to the economy. This is the "Current Technology" (CT) scenario.[5]

We now describe the renewable firm more in detail. In period 0, this firm has to choose how much production capacity to install, which an then be used in period 1. We assume that installing an amount of production capacity C has a convex cost $\frac{1}{2\delta}C^2$, where $\delta > 0$, and that this capacity can then be used to produce energy in period 1 at zero marginal cost (this captures the fact that wind, solar, and hydro energy production does not require to purchase fuels to operate). Hence, in period 1, the green firm will always choose to activate its full production capacity in the BT state.

The renewable firm maximizes expected profits, taking as given the price of energy in the BT

[5] In the more elaborate model presented below, we allow renewable energy firms to also supply *some* of the oil demand even with current technologies, but few additional insights derive from this complication.

state, $P_{1,BT}$, which is the only market where it is able to sell. The firm's problem is therefore:

$$\max_{C\geq 0} \; -\frac{1}{2\delta}C^2 + p_{BT}CP_{1,BT} \tag{7}$$

which implies that the optimal installed capacity by the renewable firm at time 0 is

$$C = p_{BT}\delta P_{1,BT} \tag{8}$$

The Appendix includes the market clearing conditions, that now include renewable energy supply in the BT state. In this framework, we can then study the effects on energy price of changes in the transition probability. We derive the following result.

Proposition 3. *Increases in the probability of the Breakthrough Technology state cause a reduction in the date-0 energy price. That is,* $\frac{dP_0}{dp_{BT}} < 0$.

The intuition is that the Breakthrough Technology state is characterized by low profits for fossil fuel firms because of the competition from the renewable sector. Therefore, as this state becomes more likely, the incumbent fossil fuel firm anticipates lower profits in the future and therefore increases its current supply. This has the effect of reducing the price of energy in period 0. The valuations of renewable energy firms will increase, while those of fossil fuel firms will decline, with bigger proportional declines for new entrants than for incumbents.

The introduction of the green energy producer introduces an additional transition risk that can create a difference between profits in the two states in period 1 for fossil fuel firms. In particular, if the renewable sector is very efficient (that is the parameter δ is high), then there will be a large supply of green energy in the Breakthrough Technology state, thus driving down the energy price compared to the Current Technology state. The incumbent firm might therefore find it optimal to leave some of its production capacity unused in the Breakthrough Technology state, and to carry more inventory into the future in order to capture higher profits in the Current Technology state, anticipating less competitions by new entrants. We therefore have an analogous result to Proposition 2.

Proposition 4. *The effect on the date-0 energy price of increasing efficiency of the renewable sector is ambiguous. In particular:*

- *If both the carbon tax implemented in the Breakthrough Technology state and renewable efficiency are low enough, increases in renewables efficiency cause a reduction in the date-0 energy price, that is* $\frac{dP_0}{d\delta} < 0$.
- *If either the carbon tax implemented in the Breakthrough Technology state or renewable efficiency are low enough, increases in renewables efficiency cause an increase in the date-0 energy price, that is* $\frac{dP_0}{d\delta} \geq 0$.

Our model therefore provides the following insight. If incumbent fossil fuel firms expect that profits in the state where a green transition occurs will be very low, either because of carbon taxes or because of high competitions from the renewable sector, then they anticipate that some part of their production capacity will not be used in that state. At the margin, their inventory decisions are only affected by expected profits in the state where the green transition does not occur. It then follows that if they anticipate less competition from new entrants in that state, then they can have the incentive to increase their inventory, which they hope to sell at a high price in case the green transition does not occur. This can have the effect of increasing current energy prices due to a lower supply from the fossil fuel sector.

1.4 Optimal carbon tax policy

In the previous section, we separated the discussion of a possible technological breakthrough in green energy production from that related to carbon taxes. We now argue that these two sources of transition risk are closely related. Indeed, the state of the world where a breakthrough in renewable technologies occurs is likely the same state where we can expect to have higher carbon taxes, compared to the state where the green transition does not occur.

Let us expand on this. Suppose that fossil fuel emissions, $f_{1,s}$ in each state $s \in \{BT, CT\}$, entail a social cost $\lambda f_{1,s}^2$, with $\lambda > 0$, and assume that consumers have preferences over energy consumption represented by a CRRA utility function with parameter $\gamma > 1$. Let $e_{1,s}$ denote total energy consumption . We can therefore define social welfare in each state as

$$W_{1,s} = \frac{e_{1,s}^{1-\gamma} - 1}{1-\gamma} - \frac{\lambda}{2} f_{1,s}^2 \tag{9}$$

We then assume that a benevolent social planner chooses a carbon tax in each state in order to maximize social welfare, that is by solving

$$\max_{\tau_{1,s} \in [0,1]} W_{1,s} \tag{10}$$

Two observations are in order. First, in the CT state, energy consumption coincides with carbon emissions, since fossil fuel firms are the only energy providers in the economy. Second, we assume that the planner chooses the tax in period 1, after the state is realized. That is, we do not allow the planner to announce the carbon tax in period 0 in order to maximize expected ex-ante welfare. This is because the optimal ex-ante tax might not necessarily be optimal ex-post, so that the planner might have an incentive to deviate once the uncertainty about the state of the world is resolved. We assume that the agents in the economy anticipate this time-consistency problem, and so consider carbon taxes set optimally in each state. Optimal taxes are thus consistent with a subgame perfect equilibrium.

Having set up the planner's problem, we derive the following result related to the optimal carbon tax policy.

Proposition 5. *It is optimal for the social planner to impose a higher carbon tax in the Breakthrough Technology scenario. That is, $\tau_{1,BT}^* > \tau_{1,CT}^*$. Furthermore, the optimal tax rates are increasing in the social cost of carbon emissions, λ.*

The intuition for this Proposition is that the Breakthrough Technology state is characterized by low energy prices and large supply of clean energy from the renewable sector. Therefore, the marginal utility of energy consumption is lower, and the social planner is willing to reduce fossil fuel production with a high carbon tax in order to reduce emissions. Conversely, in the Current Technology state, the economy still fully relies on fossil fuel producers to satisfy its energy supply. Therefore, large carbon taxes substantially increase prices and are thus harmful to consumers. As a result, the planner is less willing to limit emissions in order to keep energy prices low. It follows that a lower carbon tax is implemented compared to the BT state. Note furthermore that announcing high taxes in the CT state ex-ante would not be an equilibrium in a subgame perfect sense, as agents in the economy would correctly anticipate the high economic costs associated with high taxes in that state, and would therefore not view such announcements as credible.

Note also that the optimal carbon tax rate increases as the social cost of carbon emissions, λ, increases. Intuitively, if the social cost of emissions is higher, then the planner is willing to impose a higher carbon tax and to accept higher energy prices in order to limit fossil fuel production.

Since high carbon taxes are only optimally implemented in the Breakthrough Technology state, then the Current Technology state becomes very attractive to existing fossil fuel companies. Indeed, this is a state of the world where these firms will face lower taxes and lower competition from both green firms and new fossil fuel producers, whose investments have been discouraged by climate policies. The conclusion that can be derived from our model is that uncertainty related to technological breakthroughs in renewable energy, together with the possibility of a high profits state for fossil fuel firms, can potentially generate high energy prices over the transition path to a green economy.

2 Full Model

In this section, we introduce our full model of the energy sector that jointly incorporates all the various transition risks that we discussed before. We argue that the previous results still hold in this more general model, and use numerical examples to illustrate how all equilibrium outcomes change with the various transition risks that we consider.

2.1 Summary of Setup

The model setup is analogous to the one in the previous Section. In particular, we now denote with p the probability that the Breakthrough Technology scenario occurs, which allows renewable energy producers to supply to all sectors of the economy. As in the previous section, we assume that the government can impose a tax on new fossil fuel drilling in period 0, $\bar{\tau}_0$, and a carbon tax in period 1 in case the BT scenario realizes $\tau_{1,BT}$.

The main departure is that we now allow the renewable sector to supply a fraction q of total demand for energy in period 1 in case there is no technological breakthrough. This captures the fact that current renewable technologies can provide clean energy to part of the economy. However, energy use in several key sectors—for example, steel production or maritime and air transportation—cannot be effectively electrified (Williams et al., 2021). Similarly, the lack of large-scale energy storage combined with the intermittency of solar and wind energy production means that, with current technologies, some amount of energy demand can only be met via fossil fuels (see Gowrisankaran et al., 2016; Suberu et al., 2014).

Therefore, the Current Technology scenario is now characterized by an "Electrifiable market" (E), where both fossil fuel producers and renewable firms compete, and a "Non-Electrifiable market" (NE), where all energy supply has to come from fossil fuels. Energy prices can be different across these two markets.

The decision problems of the various firms in the economy are analogous to those in the

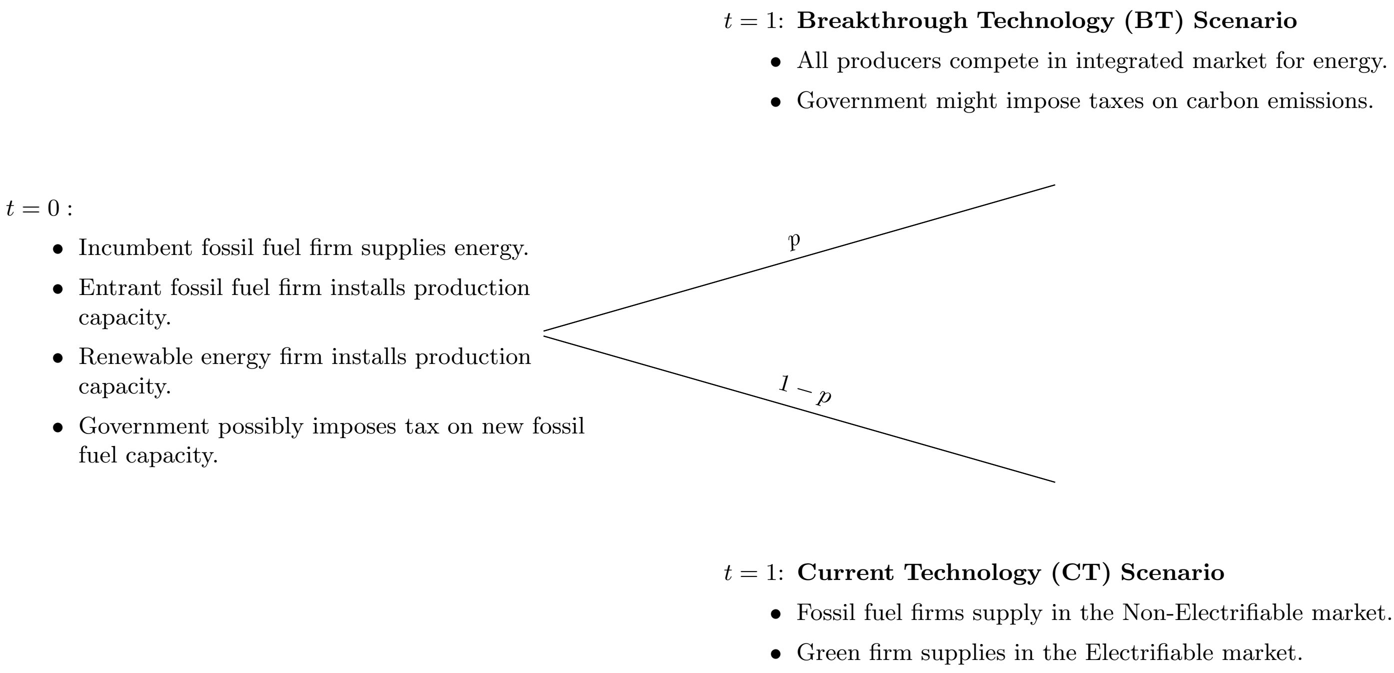


Figure 2: Timeline of the model.

previous section. The main difference is that if the CT state realizes, then renewable firms are allowed to sell in the electrifiable market, and fossil fuel firms can sell in both the electrifiable and non-electrifiable markets. We refer to Appendix A for the details of the full model, where we argue that fossil fuel firms will only sell in the non-electrifiable market of the CT state in equilibrium. The timeline of the model is summarized in Figure 2.

2.2 Main Model Results

We formalize at the outset that the results that we derived in Section 1 continue to hold. In particular, we have the following proposition.

Proposition 6. *In the general model, the price of energy in period 0 is affected by the various transition risks in the following way:*

- *An increase in taxes on new fossil fuel production capacity increases the price of energy in period 0.*
- *An increase in the probability of a technological breakthrough decreases the price of energy in period 0.*
- *For low enough carbon taxes, further increases in the tax rate reduce the energy price in period 0. For high enough carbon taxes, further increases in the tax rate increase the energy price. The same result holds for changes in the production efficiency of the renewable sector.*

We now use the model to illustrate through numerical examples how the various transition risks affect all the endogenous variables, in order to better understand the economic mechanisms that drive the response of energy prices.[6]

2.3 Analysis of Taxes on new Fossil Fuel Production Capacity

The first source of transition risk that we consider in our model is $\bar{\tau}_0$, the tax on new fossil fuel production capacity, which can be interpreted as a policy aimed at restricting new drilling. As we argued before, this could have either the form of an explicit tax imposed by the government, or it could be interpreted as an increase in the cost of raising capital for the creation of new production capacity, as financial markets might decide to allocate capital away from this type of investments.

Figure 3 shows the implications of changes in this policy instrument on energy prices and the other equilibrium quantities in the model. The various panels show (1) the price of energy in period 0 (top left plot), (2) the price of energy in period 1 in various markets and technology scenarios (top right), (3) the supply of fossil fuel in period 0 (middle left), (4) the production capacity of various energy producers in period 1 (middle right), (5) total expected profits for various energy producers (bottom left), and (6) fossil fuel emissions (bottom right).

The first-order effect of this policy is to reduce the amount of capacity that new entrants install today—after all, this is the activity directly taxed by the policy maker. As a result, expected prices in the non-electrifiable segmetn of the market in the no-breakthrough environment increase, since incumbents will face less competition from new entrants. This creates incentives for current incumbents to shift capacity from today to tomorrow, raising energy prices in period 0. Carbon emissions in both periods decrease.

Similarly, renewable energy firms expect to face less competition in period 1 and thus invest in additional renewable capacity. On balance, the reduced supply by new entrants outweighs the additional supply by renewable energy firms, and prices in the breakthrough scenario are higher. On the other hand, the additional capacity of renewable energy providers leads to lower prices in the electrifiable market in the non-breakthrough scenario.

Finally, total expected profits are increasing in the tax rate for the incumbent and renewable firms, but decreasing for the entrant firm.

Our model therefore highlights how restrictions on new drilling can have very different effects on different firms in the energy sector. Fossil fuel producers with large existing production capacity (incumbents in the model) can benefit from such policies, which disproportionately affect their competitors with lower developed production capacity (entrants in the model), allowing them to emerge as the main energy suppliers over the transition path to green energy.

2.4 Analysis of Changes in the Probability of a Technological Breakthrough

We now focus on the effects of changes in the probability of transitioning to a scenario where the renewable sector can reliably supply energy to the entire economy, represented by the parameter p. We can interpret these changes as deriving either from technological breakthroughs in the private sector, or from a policy perspective, we can view these changes as reflecting the size of

[6] All the numerical examples are based on the following calibration: $\bar{f}_0^I = 1.7$, $\kappa_1 = 0.4$, $\kappa_2 = 0.15$, $\delta = 0.3$, $W = 3$, $q = 0.2$, $\tau_{1,BT} = \bar{\tau}_0 = 0$ (unless when we analyzes changes in the tax rate). We choose parameters such that the incumbent fossil fuel firm is not always unconstrained in all states, and is less constrained than the entrant firm in period 1.

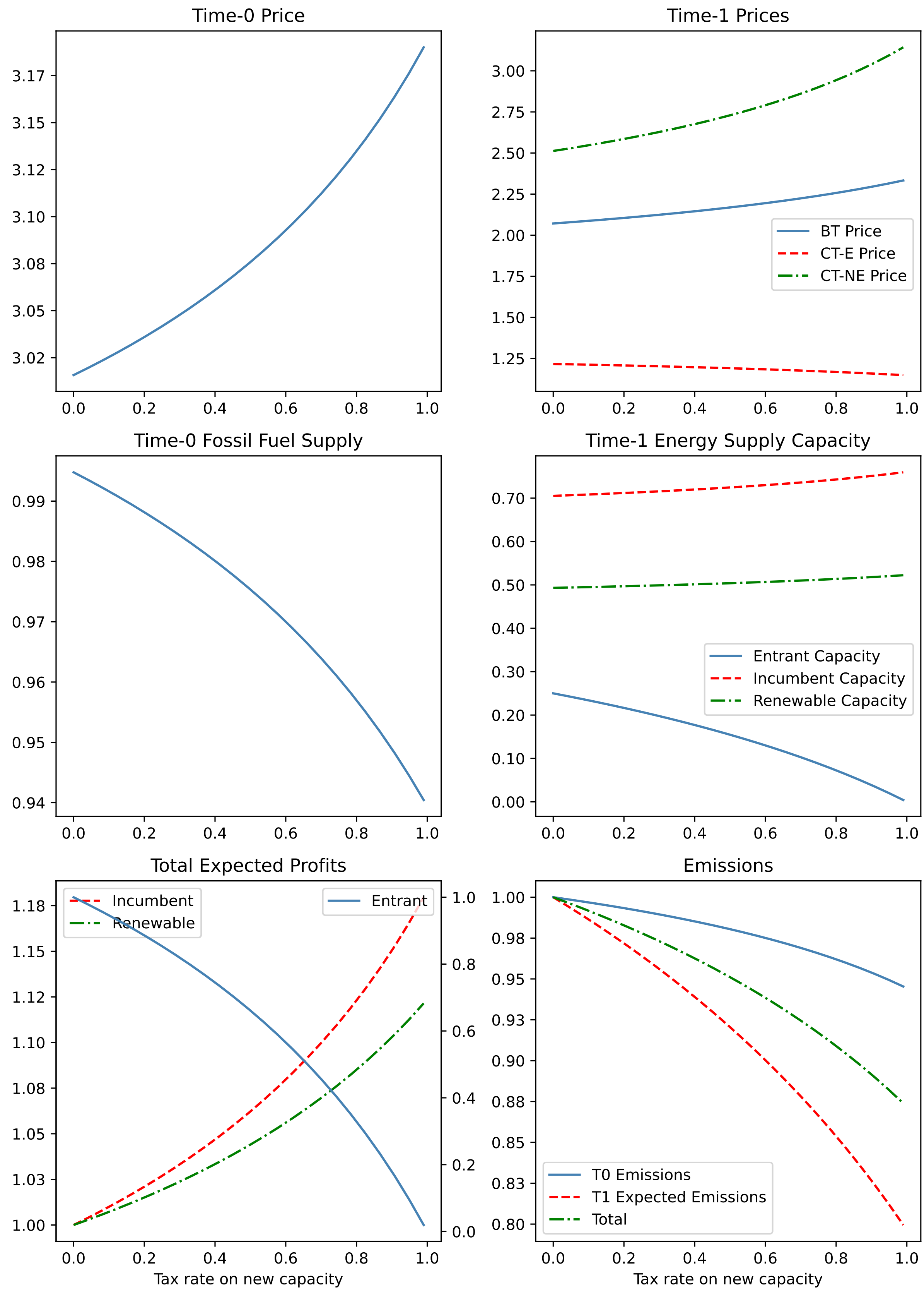


Figure 3: Equilibrium effects of changes in tax rate on new production capacity. Note that profits for each producer are normalized by their profits for $\bar{\tau}_0 = 0$, and emissions are normalized for each period and total by the corresponding value for $\bar{\tau}_0 = 0$. BT scenario probability is fixed at $p = 0.5$.

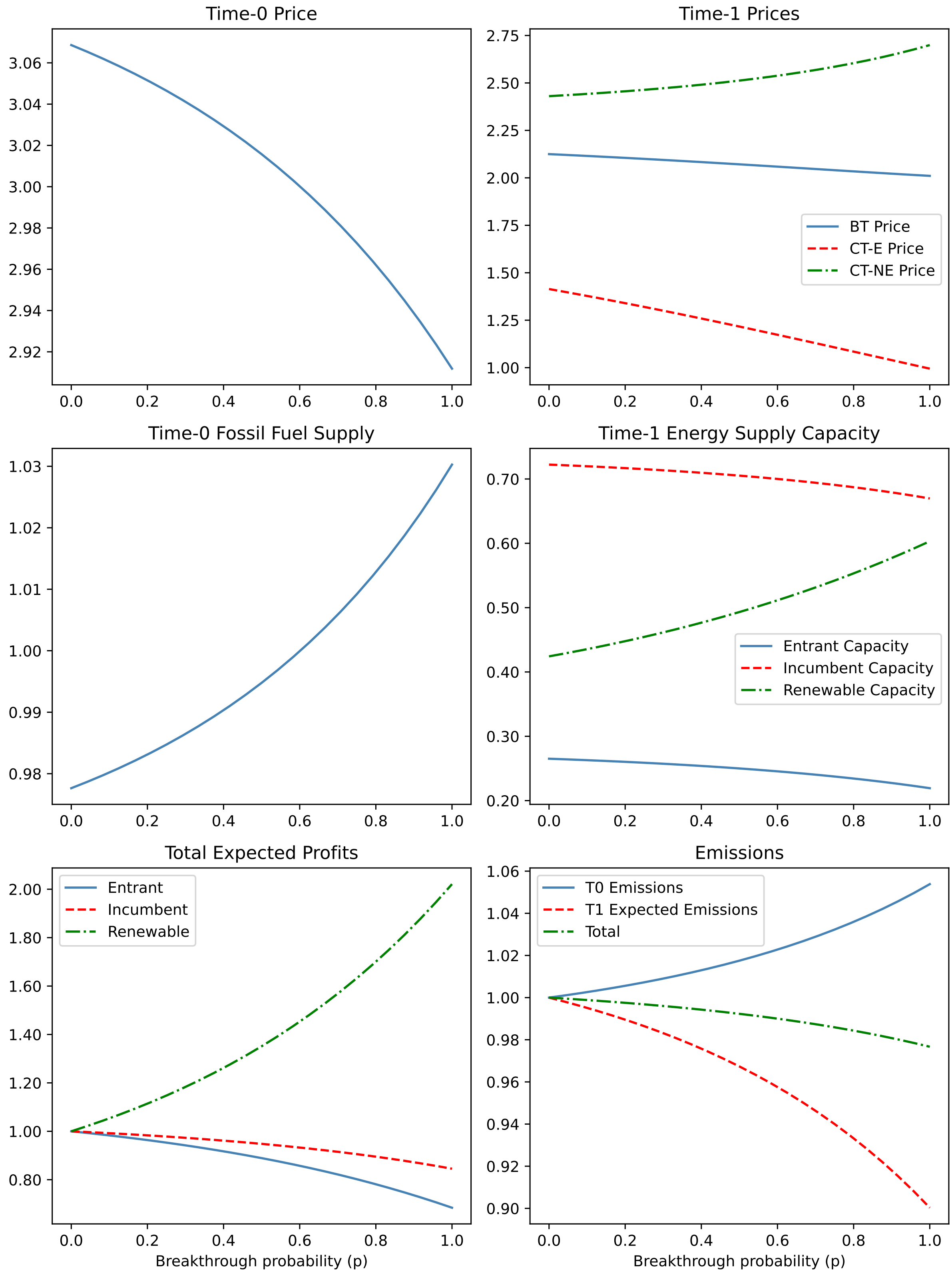


Figure 4: Equilibrium effects of changes in the probability of a technological breakthrough. Note that profits for each producer are normalized by their profits for $p = 0$, and emissions are normalized for each period and total by the corresponding value for $p = 0$.

government subsidies to R&D in the green energy sector. We assume throughout this analysis that carbon taxes ($\tau_{1,BT}$) and production capacity taxes ($\bar{\tau}_0$) are zero.

Figure 4 shows how the model outcomes change as p increases. As the probability of the Breakthrough Technology scenario increases the renewable firm increases its installed capacity. This is due to the fact that the firm is expecting to be able to supply energy to a larger share of the economy in the future, and hence wants to increase its capacity to be able to capture this additional demand.

In contrast, the incumbent fossil fuel incumbent anticipates that, as p increases, it will face higher competition from the renewable sector with a higher probability, and hence wants to produce more in period 0 rather than carrying inventory into period 1–period 0 prices fall, and period 1 emissions rise, consistent with predictions from the "green paradox" literature. Similarly, the expectation of increasing competition from the renewable producer in period 1 induces the fossil fuel entrant to install less production capacity. As a result, as p increases, total emissions in period 0 rise—driven by an increase in the relative attractiveness for incumbents of producing oil today versus in the future—while expected time-1 emissions fall. While overall expected emissions across the two periods decline, the fact that period-0 emissions are more damaging to the climate than period-1 emissions—they contribute to global warming both in period 0 and in period 1—means that the aggregate effect on the climate are uncertain. [CITE]

The production and investment choices of the three firms as p increases have the following effect on period-1 equilibrium prices. First, the increasing supply of green energy pushes the prices down in period 1 in the Breakthrough Technology scenario and in the electrifiable market of the Current Technology scenario. Second, the lower installed capacity from the fossil fuel entrant firm and the lower level of inventory carried by the incumbent firm into period 1, push up the price in period 1 in the non-electrifiable market of the CT scenario. These different dynamics of energy price between the electrifiable and non-electrifiable markets arise due to the fact that, if the technological breakthrough does not realize, the renewable sector will not be able to supply energy to the non-electrifiable sectors of the economy, and the supply of energy from the fossil fuel sector is also lower because of the lower investment in production capacity.

In this context, therefore, government subsidies that increase the probability of technological breakthroughs in period 1 should not translate into a higher price of energy in period zero, but can instead have deflationary effects on the price of energy.

Finally, expected profits are lower as p increases for both fossil fuel firms in our model. Moreover, the stock price of the new fossil fuel entrant firm is affected more negatively than that of the incumbent fossil fuel producer. Renewable firms instead experience an increase in their valuations, as their future expected profits increase with the technological breakthrough becoming more likely.

2.5 Analysis of Changes in the Tax on Fossil Fuel Emissions

Finally, we turn to the analysis of the effects of the introduction of a tax on carbon emissions in case the Breakthrough Technology scenario realizes[7]. Carbon taxes are extensively analyzed both in the literature and in policy discussions, hence understanding their effect on energy prices in our framework is particularly important.

[7] In Appendix C we show that the results in this section are robust to assuming that carbon taxes are on production quantities of fossil fuel firms rather than on their sales.

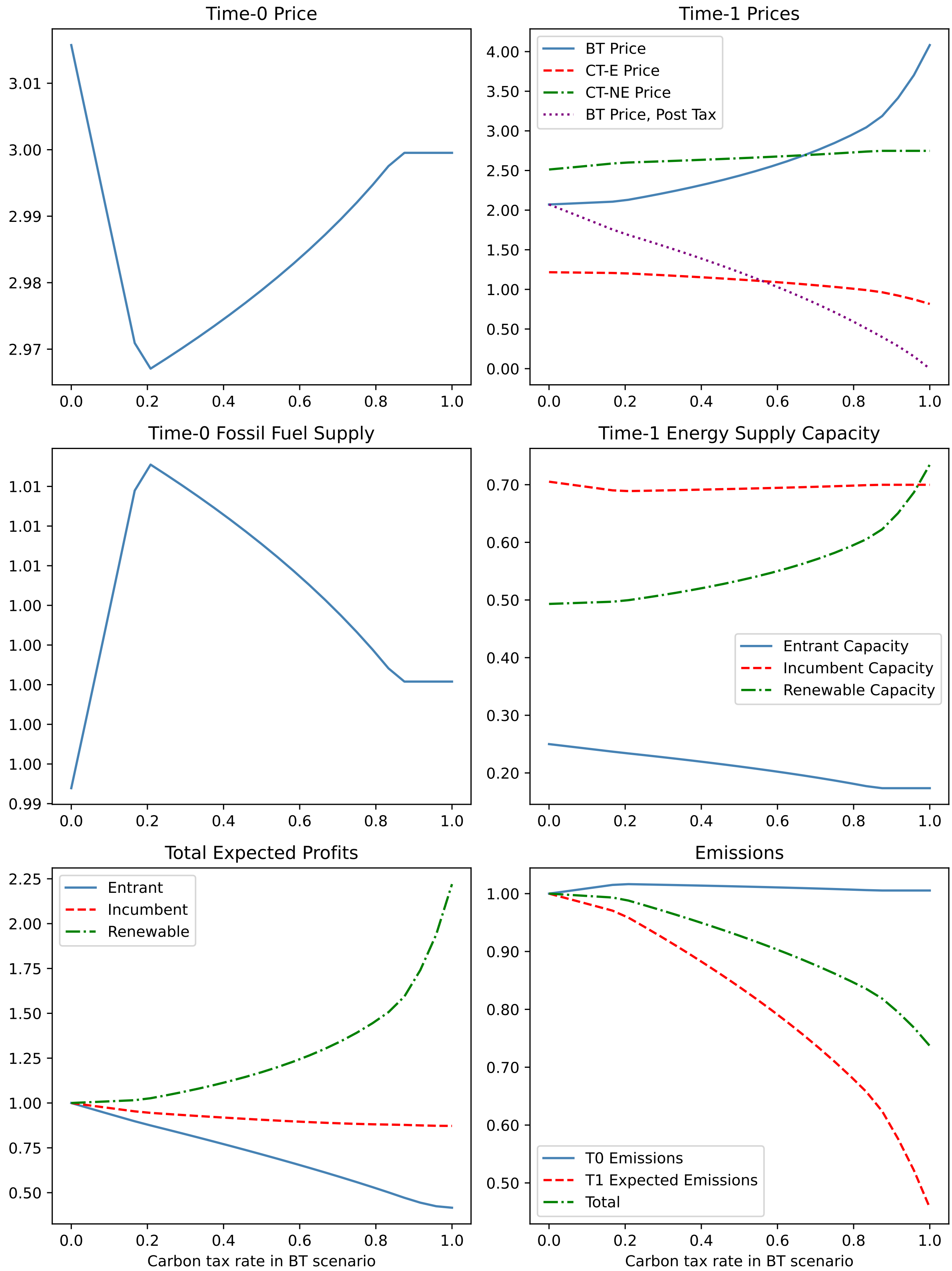


Figure 5: Equilibrium effects of changes in BT tax rate. Note that profits for each producer are normalized by their profits for $\tau_{1,BT} = 0$, and emissions are normalized for each period and total by the corresponding value for $\tau_{1,BT} = 0$. BT scenario probability is fixed at $p = 0.5$.

Figure 5 shows how the endogenous quantities in the model change as the tax rate $\tau_{1,BT}$ on carbon emissions in the BT scenario increases. We fix a value for the breakthrough probability ($p = 0.5$) and abstract from the fact that carbon taxes might endogenously induce firms to invest more in clean technologies, thus accelerating the transition (Acemoglu et al., 2012; Aghion et al., 2016).

We can immediately note the difference compared to the previous case of changes in the transition probability, namely that the effect of the tax rate on the current price of energy is non-monotone. For low levels of the tax rate, tax increases push down the current price of energy; if the tax rate is high enough, however, then further increases will push up the current price of energy. In order to understand this result, it is important to note that a tax on carbon emissions affects *both* the incumbent and the entrant fossil fuel producer. We have therefore two opposite forces affecting the incumbent firm's incentive to supply energy in period 0, which is what drives the potentially counter-intuitive behavior of current price.

The intuition for this result is the same as in the simple model. For low values of the carbon tax, energy prices are relatively high in both future states. Therefore, the incumbent takes into account expected prices both in BT and in CT when making its inventory decisions. Since a higher tax rate lowers the expected future price, it follows that increases in the tax rate lower the incentive of carrying inventory into the future. Therefore, current fossil fuel supply increases, and the price decreases.

For high values of the carbon tax, profits in the BT state are very low, so that it might not be optimal for the incumbent to fully exhaust production capacity in that state, as the marginal benefit from selling an additional energy unit might be lower than the extraction cost. It is therefore optimal to leave stranded assets in the BT state, since the cost of setting up reserves has already been paid. It follows that now the marginal benefit from increasing inventory is represented by the price in the CT state only.

The entrant firm, on the other hand, has to incur an additional cost in order to set up new production capacity. Hence, for them it is more costly to leave stranded assets in the BT state, so they still make their decisions in order to fully exhaust production capacity in both states. It then follows that further increases in the BT tax still affect their investment decisions at the margin, unlike the incumbent which can leave its capacity unused in this state. But then, lower supply from the entrant means that the price in the CT state increases. As this is the state that is driving the incumbent's capacity decisions at the margin, it follows that the firm has an incentive to increase its inventory in order to reap higher profits if the CT state realizes. Therefore, current energy supply decreases, and the energy price increases.

Figure 5 shows that, for low values of the tax rate, the first effect is prevailing. Therefore, the incumbent fossil fuel producer increases the current supply of energy as the tax rate increases, reacting to the expectation of lower future profits. It will only do so, however, up to a certain tax level, after which increasing the current supply of energy is not profitable anymore, as the amount of current energy production is already high. In that case, the incumbent fossil fuel producer optimally reduces current supply of energy, and carries it as inventory in the future in the hope that, if the transition does not realize, then it will be able to sell it for a high margin in the non-electrifiable market, where competition by entrants has been discouraged by the high tax rate.

Our numerical example clearly illustrate this result. For low values of the tax rate, further increases in the tax rate lower the incumbent's future expected profits, hence current energy

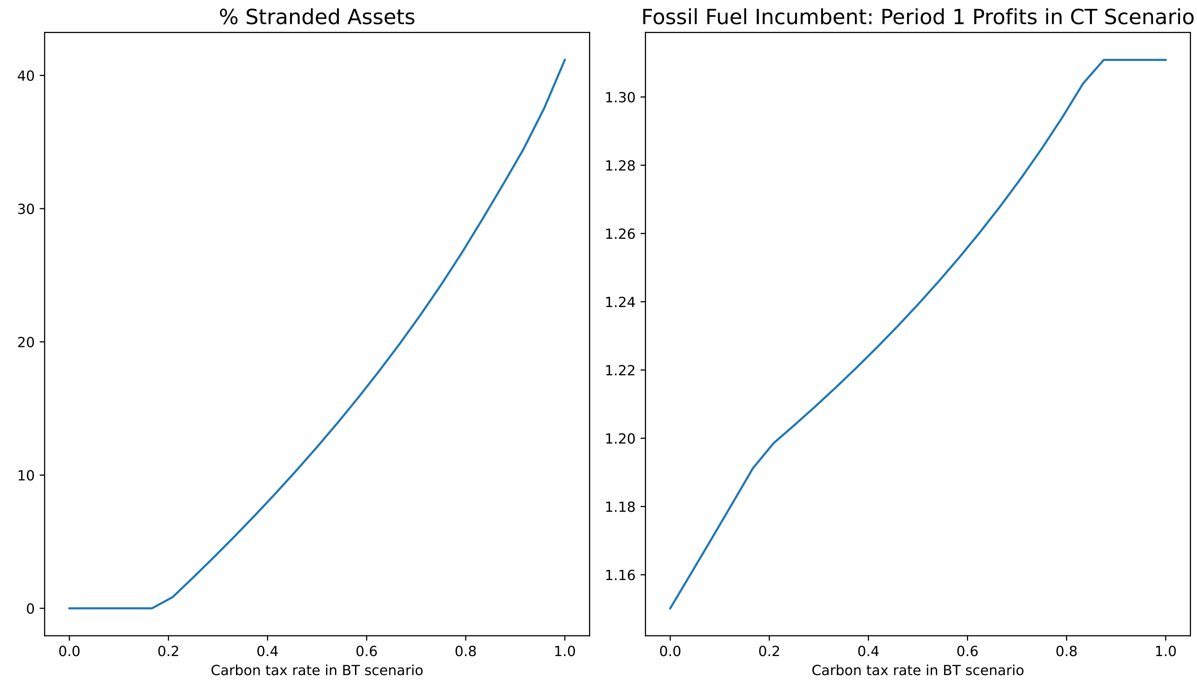


Figure 6: Fossil fuel stranded assets in the BT scenario, and profits in CT scenario, as a function of the tax rate in the BT scenario. BT scenario probability is fixed at $p = 0.5$.

supply increases and energy price decreases. For high values of the tax rate, further increases in the tax rate increase the incumbent's future expected profits in the CT state. Therefore, current energy supply decreases and energy price increases.

Figure 6 clearly shows the mechanism at play. For low values of the carbon tax, the incumbent is fully exhausting its production capacity in the BT state. As the tax rate increases, it becomes optimal for the incumbent to leave its assets stranded in the BT state, as shown in the left panel of the Figure. However, the right panel shows that profits in the CT state are increasing, due to lower supply from the entrant. Therefore, it becomes optimal to increase fossil fuel inventories in period 1, even though more and more assets are getting stranded in the BT state. The higher expected profits in the CT state mean that it becomes optimal to have asset stranded in the BT state, where profits are very low.

Note that, eventually, the tax rate in the BT scenario becomes so so high that for the entrant firm becomes also optimal to leave its assets stranded in the BT state. Therefore, further changes in the tax rate do not change the optimally installed production capacity, and consequently do not affect the price in the CT scenario and the incumbent's incentive to increase its inventory. This corresponds to the rightmost region of the two figures, where the response of period 0 price and CT state profits to carbon tax becomes flat.

Note that we did not obtain this result in the previous section, as increases in the probability p make the realization of the highly profitable CT scenario less likely, thus reducing the incentive of the incumbent fossil fuel sector to carry inventory in period 1. Carbon taxes are therefore an important source of transition risk in our model, which can potentially push up the price of energy over the transition path to a green economy.

Figure 6 also shows that announcements of future carbon emission taxes have a negative effect on profits of fossil fuel producers, with the effect being more negative for the entrant than for the incumbent firm. Renewable firms, on the other hand, experience an increase in their expected profits as the carbon tax increases.

2.6 Empirical Implications

In summary, we have the following empirical implications for the stock prices of the various firms in the energy sector based on the response of energy prices.

Empirical Implications. The various transition risks have the following effects on stock prices of energy producers:

- Announcements of taxes on new fossil fuel production capacity reduce the expected profits and thus the stock price of fossil fuel entrants, but increase the expected profits and valuations for both incumbents and and renewable energy firms.
- Announcements of subsidies to the renewable sector, which make the Breakthrough Technology scenario more likely, have a negative effect on the stock price of fossil fuel firms. Moreover, the stock price of the new fossil fuel entrant firm is affected more negatively than that of the incumbent fossil fuel producer.
- Announcements of future carbon emission taxes have a more negative effect on the stock price of fossil fuel producers with low existing capacity, compared to producers with large unused reserves that are already in place.

In the next section, we test these empirical implications by constructing indexes designed to capture the various transition risks that we study in our model.

3 Empirical Analysis

We now test the main empirical implications of the model, summarized in Table 1.[8] We first study how transition risk affects the valuation of energy companies. A first prediction of the model is that renewable energy companies should gain from an increase in transition risk, no matter its type. A second prediction is that transition risk also affects fossil fuel companies, but the effects on them are more nuanced—they depend on the type of transition risk (whether the transition risk relates to a potential increase of the cost of emissions, or to an increased probability of a renewable breakthrough) and on whether the company has installed capacity or is an entrant. In general, the valuations of new entrants are more negatively affected than the valuations of incumbents with substantial developed capacity.

We then analyze how transition risk affects energy prices. Our model predicts that oil futures prices should decrease with news about renewable energy breakthroughs, and should increase with news about carbon taxes.

To test these hypotheses in the data, we study how stock prices of energy companies and prices of oil futures respond to news about transition risk. Specifically, we build high-frequency transition news indexes that allow us to observe how the stock prices of different companies and oil futures prices move in the days around the news release, and classify firms in groups that mimic the predictions of the model: renewable energy companies, and fossil fuel companies

[8] Step-by-step mechanisms behind these implications are summarized in Table 4 in Appendix D.

positioned on a continuum from entrants to incumbents according to their level of developed reserves.

3.1 Climate Transition News Indexes

We build our high-frequency climate transition measures by analyzing news reported in the New York Times (NYT) using GPT-4o Mini. We next summarize how we construct these climate news indices, and provide additional details in Appendix E. We first obtained all news articles from the NYT via LexisNexis, covering a 12-year period between 2012 and 2023. We then filtered the universe of NYT news articles, isolating those containing at least one of 8 keywords—“carbon,” “renewable,” “drilling,” “fossil,” “oil and gas,” “emissions,” “solar,” or “pipeline”—in order to identify articles related to cost of emissions, probability of breakthroughs in renewable energy technology, or regulation influencing new fossil fuel capacity. This appraoch extracts a very broad set of articles that included many items unrelated to transition risk. We refined our selection and extracted our transition risk measures using a more sophisticated approach, based on GPT-4o Mini.

Specifically, we uploaded each of the articles in that subset to OpenAI’s GPT-4o Mini model, along with a specific prompt aimed to identify whether the article was relevant for climate transition risk, to determine what type of transition risk it referred to, and to quantify the strength and importance of the content of the news for transition risk likelihoods. We analyzed a total of 35,593 news articles, filtered by the above keywords over our 12-year sample period. The prompt to GPT included questions on five topics, which can be broadly characterized into three categories: (1) U.S. carbon pricing policy; (2) the probability of technological breakthroughs in renewable energy or battery storage technology; (3) regulations affecting the expansion of fossil fuel production capacity. The first category captures the introduction of taxes or other policies on carbon emissions, the second category captures the possibility of technological breakthroughs that improve renewable energy firms’ ability to supply energy across all sectors, and the last category captures the the ability of fossil fuel companies to expand their existing production capacity.

The outcome of the GPT processing step yields, for each article, a set of scores on each topic. Positive scores indicate more restrictions on the fossil fuel industry or greater support for renewable energy; negative scores indicate relaxation of these restrictions or lower support for renewable energy. Irrelevant articles get a score of 0. Appendix E provides further details on article filtering, the prompt structure for GPT requests, and example GPT outputs for each topic. We narrow our focus by only including articles from 9 of the top 10 sections of the New York Times by frequency to reduce noise from analyzing non-related sections like “travel”. The 9 sections included were: “business financial”, “national”, “foreign”, “metropolitan”, “science”, “climate”, “us”, “editorial”, “business”. We also choose to exclude the “opinion” section to better capture direct news, like new policy announcements.

We further combine topic-level scores obtained from GPT into scores for our three broad categories, as detailed in Appendix E. Within each of the three categories, we aggregate the scores obtained from each article by taking the sum across all articles at the weekly level.[9] The aggregate score about carbon pricing policy forms the *NYT-Emission Cost News Index*;

[9] We include news from Saturday and Sunday in the following week since this news would only be reflected on Monday prices once the market opens.

the score about probability of renewable technology breakthroughs forms the *NYT-Renewable Breakthrough News Index*; and the score about regulations affecting the expansion of fossil fuel capacity forms the *NYT-Oil Capacity News Index*.

Figure 1 plots the time series of the three news indexes, with labels indicating related events. The cost of emissions and oil capacity news were on average more positive during the Obama and Biden periods, and more negative the Trump administration. The NYT-Emission Cost News Index spikes around significant climate-related events, such as the first proposal of the Clean Power Plan in 2014, its repeal proposal in 2017, and Biden rejoining the Paris Agreement in 2021. The NYT-Oil Capacity News Index spikes around regulations which influence fossil fuel production, like the review of the Keystone XL oil pipeline in 2017, its permit revocation in 2021, and the U.S. import ban on Russian crude oil in 2022. The intensity of the NYT-Renewable Breakthrough News Index has increased in recent years, with spikes around events favoring renewable energy or announcing technological breakthroughs. Notable examples include advancements in industrial-scale biofuel production in the U.S. in 2014, new solar home battery technology introduced to the U.S. in 2017, and investments in expansion of electric vehicle charging networks in 2022.

The correlation between the news indices are as follows: the NYT-Emission Cost News Index and the NYT-Renewable Breakthrough News Index have a correlation of 0.43, the NYT-Emission Cost News Index and the NYT-Oil Capacity News Index have a correlation of 0.49, and the NYT-Renewable Breakthrough News Index and the NYT-Oil Capacity News Index have a correlation of 0.26. This suggests that despite some common events affecting all three indices, they each capture different aspects of climate transition news.

Armed with these high-frequency indices of transition risk, we now move to the empirical tests of the implications of our model.

3.2 Stock Price Reactions of Energy Firms

We start our empirical analysis by studying of the model's predictions for energy firms' price response to transition risk news. Instead of having distinct categories for entrants and incumbents, we choose to place fossil fuel companies on a continuum according to their existing production capacity, allowing us to avoid defining an arbitrary cutoff for an incumbent.

We obtain stock prices from CRSP and industry classification (GICS codes) from Compustat; we use the detailed GICS codes to identify fossil fuel firms: we focus on integrated oil companies engaged in the exploration and production of oil and gas, excluding manufacturers of drilling equipment, drilling contractors, oil marketing, and storage and transportation companies that are not directly involved in oil production (see more details in Appendix E). This helps us identify 152 fossil fuel companies.

Having identified fossil fuel companies, we need to obtain a continuous classification of their existing production capacity. We do so by computing their "developed ratio," which we define as the ratio between the dollar amount of *developed* reserves for oil, natural gas, and natural gas liquids and the dollar amount of *total* proved reserves for these resources, obtained from Compustat.[10] Firms with a higher ratio have developed more of their reserves, suggesting they

[10]Recall that from the model, the key difference was the extent of capital expenditure required to exploit the reserves. The distinction between developed and undeveloped reserves captures this well. As described, from example, by the Chevron 10-k statement: *"Proved developed reserves represent volumes expected to be recovered through existing wells with existing equipment and operating methods. Proved undeveloped reserves are volumes*

can extract this capacity at low cost. Conversely, firms with a lower ratio have not yet built the infrastructure to develop a large fraction of the reserves that they own. The median developed ratio of the fossil fuel firms we have identified is 0.57.

Finally, to identify renewable firms, we use the holding firms of the Invesco Solar ETF and the First Trust Global Wind Energy ETF, which includes companies in the solar and wind energy industry respectively. This helps us identify 19 companies listed on U.S. stock exchanges which we categorize as renewable companies.

Having obtained our classification for energy firms, we based our empirical analysis on the following regression:

$$R_{i,t} = \alpha_k + \gamma_i + \beta_{1,k}\nu_{k,t} + \beta_{2,k}\nu_{k,t}\text{Fos}_i + \beta_{3,k}\nu_{k,t}\text{Fos}_i\text{DevRat}_{i,t} + \beta_{4,k}\nu_{k,t}\text{Ren}_i + \epsilon_{k,i,t},$$

where $R_{i,t}$ is the market-hedged return of stock i at week T,[11] and γ_i represents firm fixed effects. We include the indexes in this regression after estimating an AR(1) model for each using weekly data; we include in the regression the AR(1) innovations $\nu_{k,t}$, where T is the week and k is the index (the NYT-Emission Cost News Index the NYT-Renewable Breakthrough News Index, or the NYT-Oil Capacity News Index); we focus on AR(1) innovations because returns should reflect the unexpected component of the news, though the results are similar if we include the index directly instead of the innovations. We scale the residuals by their standard deviation. We include the interaction of the index with dummies for fossil fuel companies (Fos_i) and renewable companies (Ren_i). Finally, we include in the regression the interaction of the index with the fossil fuel dummy and the developed ratio of firm i at time T ($\text{DevRat}_{i,t}$).

Table 2: Stock Returns and NYT Index

	Emission Cost (1)	Renewable Breakthrough (2)	Oil Capacity (3)
Fossil Fuel Company × Index AR(1) Innovation	-0.0055***	-0.0053***	-0.0050**
	(0.0019)	(0.0015)	(0.0023)
Fossil Fuel Company × Index AR(1) Innovation × Developed Ratio	0.0073**	0.0115***	0.0074*
	(0.0028)	(0.0024)	(0.0039)
Renewable × Index AR(1) Innovation	0.0020**	0.0007**	0.0023*
	(0.0010)	(0.0003)	(0.0012)
Company FE	Yes	Yes	Yes
Remove Market from Stock Returns	Yes	Yes	Yes
R^2	0.512	0.550	0.507
Observations	46805	46805	46805

Note: Regression (1) shows coefficients of regressing stock returns on AR(1) innovations of NYT-Emission Cost News Index interacted with dummies indicating fossil fuel and renewable firms, as well as the interaction between the fossil fuel dummy and the developed ratio, controlling for firm fixed effects. Regression (2) and (3) instead show coefficients of regressing stock returns on AR(1) innovations of the NYT-Renewable Breakthrough News Index and AR(1) innovations of the NYT-Oil Capacity News Index respectively. We removed market influences from stock returns by computing the market beta via a 3-year rolling window for each firm, then subtracting the beta times the market returns from firms' stock returns. We only include 9 of the top 10 most frequent sections: "business financial", "national", "foreign", "metropolitan", "science", "climate", "us", 'editorial", "business". We focus on energy firms in these regressions. Standard errors are in parentheses and are clustered at the company level. Significance levels: * (p<0.10), ** (p<0.05), *** (p<0.01).

Table 2 reports the results of the regression. For readability, the table reports only the coefficients that involve the index term $\nu_{k,t}$. The first and third coefficient captures the stock price

expected to be recovered from new wells on undrilled proved acreage, or from existing wells where a relatively major expenditure is required for recompletion."

[11]We compute rolling 3-year market beta for each firm, and use it to hedge the market exposure of each stock.

reaction to fossil fuel and renewable companies respectively. The second coefficient captures the additional effect to fossil fuel companies based on their developed ratio.

The table directly speaks to the predictions of the theoretical model. First, we find that, consistent with the theory, on average renewable energy companies earn a positive return in weeks with news reporting increases of cost emissions, restrictions in fossil fuel capacity development, or probability of a renewable breakthrough, whereas fossil fuel companies on average have negative returns on those days.

We also find differential price movements according to fossil fuel firms' developed ratios. When news arrives of transition risks, we find that companies with a low developed ratio face a drop in stock price, but the stock prices of companies with a higher developed ratio drop less, and might even increase. This finding is exactly in line with the predictions of the model: entrants are hurt by the increased potential restrictions, whereas incumbents can rely on their inventory to benefit if the transition does not occur.

Overall, these results line up closely with the main predictions of the theoretical model. Appendix E.4 reports a number of robustness tests on this analysis. In particular, the results are robust to reconstructing the indices based on alternative scaling methods. We also show that our results are similar when we run the regression with different specifications; removing section filtering; adding years on our market beta removal; and using the oil developed reserves ratio rather than the total developed reserves ratio.

3.3 Oil Futures Price Response to Transition News

We now analyze the model's predictions for energy prices by estimating the following specification:

$$f_t^h = \alpha + \beta_1 \nu_t^{\mathrm{EC}} + \beta_2 \nu_t^{\mathrm{BT}} + \beta_2 \nu_t^{\mathrm{OC}} + Controls_t + \epsilon_t,$$

where f_t^h denotes percentage change in the WTI oil futures price at maturity h from $t-1$ to T, ν_t^{EC} represents the AR(1) innovations of the NYT-Emission Cost News Index, ν_t^{BT} represents the AR(1) innovations of the NYT-Renewable Breakthrough News Index, and ν_t^{OC} represents the AR(1) innovations of the NYT-Oil Capacity News Index. We scale each residual by the total-sample standard deviation to make magnitudes comparable across the three indices. The regression also includes controls for other major determinants of oil prices, described in more detail below. To align with the monthly frequency of these controls and much of the associated analysis of oil price movements, we run this regression at the monthly frequency by aggregating the news indices to a monthly frequency, and then obtain the residuals from an AR(1) model applied to the monthly data.[12]

We obtain daily settlement prices for WTI crude oil futures with various maturities from Bloomberg.[13] We then compute the percentage changes for the closing prices at the end of each month. To further reduce noise, we compute equal-weighted average returns of futures of different maturities: one for short-term maturities averaging all 1-month to 12-month futures, one for longer-term maturities averaging all 13-month to 24-month futures and the 60-month

[12] We also run the same regression at the weekly frequency, obtaining results which are directionally identical to the monthly regression, but generally not statistically significant.

[13] We acquire CL1 to CL24, representing 1-month to 24-month WTI crude oil futures, as well as the 60-month future.

future, and one for all maturities averaging all 1-month to 24-month futures as well as the 60-month future.

We include in the regression controls that help capture other determinants of oil prices (see a discussion of these variables in Alquist et al. (2013)): the U.S. inflation rate, U.S. real GDP growth, percentage change in M1 money supply, percentage change in M2 money supply, Chicago Fed National Activity Index (CFNAI), Kilian's (2009) global real activity index, and percentage change in zero-coupon treasury yields by Liu and Wu (2021).[14] We also control for the stock market excess returns and an additional demand factor OECD liquid fuel consumption change from EIA. The data spans a 11-year period between 2012 and 2022, dropping the final year of our news index. A detailed overview of the data and its sources is provided in Appendix Table 10.

Table 3 shows the results of the regression. Each column of the table reports a different regression using the three average oil futures prices described above.

Across all average maturities, the results we obtain for the NYT-Emission Cost News Index and NYT-Renewable Breakthrough News Index align with the prediction of the model (although the statistical significance is dependent on the regression frequency). Oil futures on average decrease in response to news about a possible renewables breakthrough, as oil companies decide to shift production forward in anticipation of higher competition from the renewable sector in the future. On the other hand, the prices increase on news of higher future emission costs; this is consistent with the model which predicts a lowered incentive to build new capacity, which can lead to a higher equilibrium price along the transition path. The last line shows that the reactions to the two news terms are significantly different from each other. Our model also predicts that oil futures increase on news about restrictions in building new capacity. The results we obtain for the NYT-Oil Capacity News Index are statistically insignificant.

Overall, the table shows that, consistent with the predictions of the model, different types of transition risk can have drastically different effects on oil prices. This highlights the importance of distinguishing different sources of transition risk.

4 Conclusions

We presented a model that can be used to investigate how transition risks can affect the price of energy and the valuation of energy firms. Our model delivers two key insights. First, rather than "transition risks" being a monolithic concept, different transition risks can result in different impacts on energy supply and energy prices across time periods. Second, building on the previous insight, we find that fossil fuel companies are not homogeneous in their response to transition risks, and the effects of transition risk realizations on firm valuations depend on firms' level of existing production capacity. Thus, a full understanding of the impact of transition risks requires differentiating between different types of transition risks and different types of energy firms.

Our current model can be extended in several interesting directions. First, the model can be set into an infinite horizon setting, in order to obtain additional insights and quantitative

[14] The U.S. inflation rate is computed as the percentage change in the U.S. consumer price index (CPI). Both the CFNAI and Kilian's (2009) global real activity index are constructed to be stationary. Treasury yields are matched to the maturity of the oil futures; for instance, we control for 1-month treasury yields when analyzing oil futures with a 1-month maturity.

Table 3: Oil Futures Price and NYT Index

	Monthly Level		
	Avg 1-12m (1)	Avg 13-60m (2)	Avg 1-60m (3)
Index AR(1) Innovation - Emission Cost	0.0122*	0.0080**	0.0104**
	(0.0064)	(0.0040)	(0.0045)
Index AR(1) Innovation - Renewable Breakthrough	-0.0141**	-0.0093**	-0.0140***
	(0.0068)	(0.0047)	(0.0052)
Index AR(1) Innovation - Oil Capacity	-0.0085	-0.0023	-0.0036
	(0.0057)	(0.0035)	(0.0043)
Controls	Yes	Yes	Yes
p-value Emission Cost = Renewable Breakthrough	0.021	0.019	0.0031
p-value Emission Cost = Oil Capacity	0.027	0.062	0.040
p-value Renewable Breakthrough = Oil Capacity	0.55	0.25	0.14
R^2	0.509	0.482	0.540
Observations	131	131	131

Note: Columns (1) to (3) report on three equally weighted averages of WTI oil futures returns: Column (1) covers returns for futures with maturities ranging from 1 to 12 months; Column (2) includes futures with maturities from 13 to 24 months, as well as the 60-month futures returns; and Column (3) uses futures with maturities ranging from 1 to 24 months, and the 60-month futures returns. The regressions control for several macroeconomic factors: the U.S. inflation rate, U.S. real GDP growth, percentage changes in M1 and M2 money supplies, CFNAI, Kilian's (2009) global real activity index, stock market excess returns, and changes in OECD liquid fuel consumption. Additionally, the regressions control for the percentage change in treasury yields matched to the maturity of the oil futures. For instance, for the average oil futures returns across 1 to 12 months, we use 1, 3, 6, and 12-month treasury yields. Similarly, for the average returns of oil futures across 13 to 60 months, 24 and 60-month treasury yields are used. Finally, for average returns of oil futures across 1 to 60 months, we use 1, 3, 6, 12, 24 and 60-month treasury yields. The p-values for testing the difference between the coefficients of each pair of NYT news indices are also reported. Standard errors are in parentheses and are corrected for heteroscedasticity. Significance levels: * (p<0.10), ** (p<0.05), *** (p<0.01).

estimates of the effects that we have described. Second, we could consider subsidies to the renewable sector as an additional policy instrument, in line with what we are currently seeing in the US, and also analyze the effects of technological developments in carbon capture and storage, which would likely help oil and gas firms while hurting renewables. Third, we could make the transition probability endogenous to the tax policy, which would capture the idea that as the fossil fuel sector becomes subject to higher taxes, investors in the economy can reallocate resources to the development of green technologies which would accelerate the transition (Acemoglu et al., 2012; Acharya et al., 2023). Finally, while we focused in our empirical work on energy prices and stock prices of energy subsectors, model implications on inventories, investments and production are also worthy of empirical scrutiny.

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Appendix A Details on Full Model

A.1 Model Setup

A.1.1 Consumers and Demand for Energy

We keep the consumer side of the economy deliberately simple, in order to focus on the sector supplying energy. We assume that in each period there is a uniformly distributed unit mass of competitive consumers of energy, indexed by $i \in [0,1]$. Such consumers include both households and firms that use energy as an intermediate good in their production. Each consumer i is endowed in each period with some exogenous wealth W that can be used to purchase energy. Wealth cannot be stored across periods. In period T, consumers solve the following problem

$$\max_{e_t^i} \frac{(e_t^i)^{1-\gamma} - 1}{1-\gamma}$$

$$s.t.\ P_t e_t^i \leq W,$$

with $\gamma > 1$, where e_t^i denotes consumption of energy, and P_t is the price of energy in the market supplying to them. It follows immediately that each consumer's demand for energy in period 0 is

$$e_0^i = \frac{W}{P_0}$$

In period 1, the price of energy faced by each consumer will differ according to whether the BT or the CT scenario materializes, and, in the latter case, depending on whether the consumer's energy demand is electrifiable or not. Hence, for each scenario $j \in \{BT, CT\}$, we have:

$$e_{1,j}^i = \frac{W}{P_{1,j}^i}$$

In the Breakthrough Technology scenario there is an integrated market for energy. This implies that all the consumers face the same price, that is $P_{1,BT}^i = P_{1,BT}$ for each $i \in [0,1]$. In the Current Technology scenario, on the other hand, we assume without loss of generality that all the consumers in the interval $[0,q]$ can electrify their energy demand, while the rest of the consumers can only purchase energy from the fossil fuel firms. This implies that $P_{1,CT}^i = P_{1,E}$ if $i \in [0,q]$, and $P_{1,CT}^i = P_{1,NE}$ otherwise, where $P_{1,E}$ and $P_{1,NE}$ denote the price of energy in the electrifiable and non-electrifiable markets of the CT scenario respectively.

Integrating across consumers, aggregate demands for energy in each period and scenarios are thus respectively given by

$$D_0 = \frac{W}{P_0},$$

$$D_{1,BT} = \frac{W}{P_{1,BT}}, \qquad D_{1,E} = q\frac{W}{P_{1,E}}, \qquad D_{1,NE} = (1-q)\frac{W}{P_{1,NE}}.$$

A.1.2 Green Firm

In period 0, the green firm has to choose how much production capacity to install, to be potentially used in period 1. We assume that installing an amount of production capacity C

has a convex cost $\frac{1}{2\delta}C^2$, where $\delta > 0$, and that this capacity can then be used to produce energy in period 1 at zero marginal cost, capturing the fact that wind, solar, hydro and tidal energy production does not require to purchase fuels operate. Hence, in period 1, the green firm will always choose to activate its full production capacity. The renewable firm maximizes expected profits, taking as given the price of energy $(P_{1,BT}, P_{1,E})$ in the respective markets at date 1 where it is able to sell. The firm's problem is therefore:

$$\max_{C \geq 0} \; -\frac{1}{2\delta}C^2 + C\Big[pP_{1,BT} + (1-p)P_{1,E}\Big] \tag{11}$$

which implies that the optimal installed capacity by the renewable firm at time 0 is

$$C = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big].$$

A.1.3 Fossil Fuel Firm: Incumbent

At time 0, we assume that an incumbent fossil fuel producer has an existing capacity of $\bar{f}_0^I$, which can be used immediately to produce energy, or saved for the next period as inventory. Producing an amount of energy f_0^I has a cost of $\frac{1}{2\kappa_1}(f_0^I)^2$, $\kappa_1 > 0$. In period 1, if the BT scenario realizes, the firm will always be facing competition of the renewable producer. If the CT scenario realizes, the fossil fuel producer will be the only supplier of energy for a fraction $(1-q)$ of total demand, where it might thus earn high profits. The firm maximizes expected profits by choosing its time- and state-contingent supplies $(f_0^I, f_{1,BT}, f_{1,E}, f_{1,NE})$, taking as given the price of energy at time 0, P_0, and in all the possible states in period 1, $(P_{1,BT}, P_{1,E}, P_{1,NE})$. We also assume that in case of a technological breakthrough in period 1, a social planner imposes a carbon tax on fossil fuel firms at a rate $\tau_{1,BT} \geq 0$ on their sales $P_{1,BT}f_{1,BT}$. As we argued in section 1.4, a social planner would chooses a lower carbon tax in the CT scenario than in the BT scenario: $\tau_{1,CT} < \tau_{1,BT}$. For simplicity, we assume therefore that $\tau_{1,CT} = 0$.

The fossil fuel incumbent producer (superscript I) therefore solves in period 0:

$$\max_{f_0^I} \; f_0^I P_0 - \frac{1}{2\kappa_1}(f_0^I)^2 + E[V_f^I] \tag{12}$$

subject to $0 \leq f_0^I \leq \bar{f}_0^I$. The date-1 continuation value V_f^I is equal to $V_f^{I,BT}$ with probability p, and $V_f^{I,CT}$ with probability $(1-p)$. These continuation values are given by

$$V_f^{I,BT} = \max_{f_{1,BT}^I} \; (1-\tau_{1,BT})P_{1,BT}f_{1,BT}^I - \frac{1}{2\kappa_1}(f_{1,BT}^I)^2, \tag{13}$$

subject to $0 \leq f_{1,BT}^I \leq \bar{f}_0^I - f_0^I$, and

$$V_f^{I,CT} = \max_{f_{1,E}^I, f_{1,NE}^I} \; P_{1,E}f_{1,E}^I + P_{1,NE}f_{1,NE}^I - \frac{1}{2\kappa_1}(f_{1,E}^I + f_{1,NE}^I)^2, \tag{14}$$

subject to $0 \leq f_{1,E}^I + f_{1,NE}^I \leq \bar{f}_0^I - f_0^I$.

A.1.4 Fossil Fuel Firm: Entrant

In order to cleanly model fossil fuel firms with low existing reserves, we also assume that there is a representative entrant firm that has to choose how much new production capacity to install to be potentially produced in period 1. Installing an amount of capacity $\bar{f}_1^E$ has a cost $\frac{1}{2(1-\bar{\tau}_0)\kappa_2}(\bar{f}_1^E)^2$, $\kappa_2 > 0$, and where $\bar{\tau}_0 \geq 0$ represents a tax that might be imposed by the social planner on the construction of new fossil fuel production capacity.The fossil fuel entrant firm (superscript E) therefore chooses its capacity investment in period 0 by solving:

$$\max_{\bar{f}_1^E} \; -\frac{1}{2(1-\bar{\tau}_0)\kappa_2}(\bar{f}_1^E)^2 + E[V_f^E] \tag{15}$$

subject to $\bar{f}_1^E \geq 0$. As for the incumbent fossil fuel firm, the date-1 continuation value for the entrant V_f^E is equal to $V_f^{E,BT}$ with probability p, given by

$$V_f^{E,BT} = \max_{f_{1,BT}^E} \; (1-\tau_{1,BT})P_{1,BT}f_{1,BT}^E - \frac{1}{2\kappa_1}(f_{1,BT}^E)^2, \tag{16}$$

subject to $0 \leq f_{1,BT}^E \leq \bar{f}_1^E$, and to $V_f^{E,CT}$ otherwise, given by

$$V_f^{E,CT} = \max_{f_{1,E}^E, f_{1,NE}^E} \; P_{1,E}f_{1,E}^E + P_{1,NE}f_{1,NE}^E - \frac{1}{2\kappa_1}(f_{1,E}^E + f_{1,NE}^E)^2, \tag{17}$$

subject to $0 \leq f_{1,E}^E + f_{1,NE}^E \leq \bar{f}_1^E$. We describe the solutions to the fossil fuel producers' problems in Appendix A.

A.1.5 Market Clearing and Equilibrium

Given the production choices by the firms in the economy, supplies of energy in each period are given by

$$S_0 = f_0^I,$$
$$S_{1,BT} = C + f_{1,BT}^I + f_{1,BT}^E,$$
$$S_{1,E} = C + f_{1,E}^I + f_{1,E}^E, \text{ and}$$
$$S_{1,NE} = f_{1,NE}^I + f_{1,NE}^E.$$

By imposing market clearing, we obtain the following equilibrium conditions

$$\frac{W}{P_0} = f_0^I, \tag{18}$$

$$\frac{W}{P_{1,BT}} = C + f_{1,BT}^I + f_{1,BT}^E, \tag{19}$$

$$q\frac{W}{P_{1,E}} = C + f_{1,E}^I + f_{1,E}^E, \text{ and} \tag{20}$$

$$(1-q)\frac{W}{P_{1,NE}} = f_{1,NE}^I + f_{1,NE}^E. \tag{21}$$

The previous system can be solved to find an expression for the equilibrium prices and the production choices of the firms as a function of the fundamentals of the economy. Assuming for now that the tax rates are kept fixed, we can provide the following definition of equilibrium in our model.

Definition. *An equilibrium of the two-period model consists of renewable producer installed capacity, C, fossil fuel incumbent producer quantities,* $(f_0^I, f_{1,BT}^I, f_{1,E}^I, f_{1,NE}^I)$*, fossil fuel entrant producer quantities,* $(\bar{f}_1^E, f_{1,BT}^E, f_{1,E}^E, f_{1,NE}^E)$*, and prices,* $(P_0, P_{1,BT}, P_{1,E}, P_{1,NE})$*, such that*

- *Given prices, the renewable capacity C solves the renewable producer problem (1).*
- *Given prices, the fossil fuel producers' quantities solve the fossil fuel producer problems (2)-(7).*
- *Quantities and prices satisfy the market clearing conditions (8)-(11).*

To focus on the more interesting implications of our analysis, we assume that the initial fossil fuel reserves $\bar{f}_0^I$ are not so high that the producer is always unconstrained in all periods. We also assume that in period 1 the incumbent fossil fuel firm is less constrained than the entrant firm.

A.2 Solution to the incumbent fossil fuel producer's problem

Let $\bar{f}_1^I = \bar{f}_0^I - f_0^I$. We can solve the problem of the fossil fuel producer starting from period 1. If the production constraint is binding, then the continuation value in the BT scenario is equal to

$$V_f^{I,BT} = (1 - \tau_{1,BT}) P_{1,BT} \bar{f}_1^I - \frac{1}{2\kappa_1} (\bar{f}_1^I)^2.$$

If instead the constraint is not binding, then the optimal production is given by

$$f_{1,BT}^I = \kappa_1 (1 - \tau_{1,BT}) P_{1,BT},$$

and, consequently,

$$V_f^{I,BT} = \frac{1}{2} \kappa_1 (1 - \tau_{1,BT})^2 (P_{1,BT})^2.$$

Let $P_{1,*} = \max P_{1,E}, P_{1,NE}$. Note that the fossil fuel firm will want to use its entire production capacity in the market where the price for energy is higher. If the production constraint in the CT scenario is binding, we thus have

$$V_f^{I,CT} = (1 - \tau_1^{CT}) P_1^{CT,*} \bar{f}_1^I - \frac{1}{2\kappa_1} (\bar{f}_1^I)^2,$$

and

$$f_{1,E}^I = \begin{cases} \bar{f}_1^I & if\ P_{1,E} > P_{1,NE} \\ \frac{1}{2} \bar{f}_1^I & if\ P_{1,E} = P_{1,NE} \\ 0 & if\ P_{1,E} < P_{1,NE} \end{cases}$$

$$f_{1,NE}^I = \begin{cases} \bar{f}_1^I & if\ P_{1,E} < P_{1,NE} \\ \frac{1}{2} \bar{f}_1^I & if\ P_{1,E} = P_{1,NE} \\ 0 & if\ P_{1,E} > P_{1,NE} \end{cases}$$

where we assumed that in case prices are equal across states, then supply is split equally. Suppose instead that the constraint in the CT scenario is not binding. Then, we have

$$f^I_{1,E} = \begin{cases} \kappa_1(1-\tau_{1,CT})P_{1,NE} & if\ P_{1,E} < P_{1,NE} \\ \frac{1}{2}\kappa_1(1-\tau_{1,CT})P_{1,NE} & if\ P_{1,E} = P_{1,NE} \\ 0 & if\ P_{1,E} > P_{1,NE} \end{cases}$$

which gives

$$V_f^{I,CT} = \frac{1}{2}\kappa_1(1-\tau_{1,CT})^2(P_{1,*})^2.$$

We have therefore different cases to consider.

1. Production constraint in period 1 never binding: this gives

$$\begin{aligned} \max_{0\le f_0^I \le \bar{f}_0^I} \ & f_0^I P_0 - \frac{1}{2\kappa_1}(f_0^I)^2 \\ & + p\frac{\kappa_1}{2}(1-\tau_{1,BT})^2(P_{1,BT})^2 \\ & + (1-p)\frac{\kappa_1}{2}(1-\tau_{1,CT})^2(P_{1,*})^2 \end{aligned}$$

   which gives the following interior solution

$$f_0^I = \kappa_1 P_0.$$

2. Production constraint in period 1 binding in the BT scenario only: this gives

$$\begin{aligned} \max_{0\le f_0^I \le \bar{f}_0^I} \ & f_0^I P_0 - \frac{1}{2\kappa_1}(f_0^I)^2 \\ & + p\left[(1-\tau_{1,BT})P_{1,BT}(\bar{f}_0^I - f_0^I) - \frac{1}{2\kappa_1}(\bar{f}_0^I - f_0^I)^2\right] \\ & + (1-p)\frac{\kappa_1}{2}(1-\tau_{1,CT})^2(P_{1,*})^2 \end{aligned}$$

   which gives the following interior solution

$$f_0^I = \frac{\kappa_1}{1+p}P_0 - \frac{p\kappa_1}{1+p}(1-\tau_{1,BT})P_{1,BT} + \frac{p}{1+p}\bar{f}_0^I.$$

3. Production constraint in period 1 binding in the CT scenario only: this gives

$$\begin{aligned} \max_{0\le f_0^I \le \bar{f}_0^I} \ & f_0^I P_0 - \frac{1}{2\kappa_1}(f_0^I)^2 \\ & + p\frac{\kappa_1}{2}(1-\tau_{1,BT})^2(P_{1,BT})^2 \\ & + (1-p)\left[(1-\tau_{1,CT})P_{1,*}(\bar{f}_0^I - f_0^I) - \frac{1}{2\kappa_1}(\bar{f}_0^I - f_0^I)^2\right] \end{aligned}$$

   which gives the following interior solution

$$f_0^I = \frac{\kappa_1}{2-p}P_0 - \frac{(1-p)\kappa_1}{2-p}(1-\tau_{1,CT})P_{1,*} + \frac{1-p}{2-p}\bar{f}_0^I.$$

4. Production constraint in period 1 always binding: this gives

$$\max_{0\leq f_0^I\leq \bar{f}_0^I} f_0^I P_0 - \frac{1}{2\kappa_1}(f_0^I)^2 + p\Big[(1-\tau_{1,BT})P_{1,BT}(\bar{f}_0^I - f_0^I) - \frac{1}{2\kappa_1}(\bar{f}_0^I - f_0^I)^2\Big] + (1-p)\Big[(1-\tau_{1,CT})P_{1,*}(\bar{f}_0^I - f_0^I) - \frac{1}{2\kappa_1}(\bar{f}_0^I - f_0^I)^2\Big]$$

which gives the following interior solution

$$f_0^I = \frac{1}{2}\bar{f}_0^I + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)(1-\tau_{1,CT})P_{1,*}\Big].$$

A.3 Solution to the entrant fossil fuel producer's problem

In period 1, the problem of the entrant producer is analogous to the one of the incumbent producer, with the only difference being $\bar{f}_1 = \bar{f}_1^E$. We have therefore different cases to consider in period 0.

1. Production constraint binding in the BT scenario only: this gives

$$\max_{\bar{f}_1^E\geq 0} -\frac{1}{2(1-\bar{\tau}_0)\kappa_2}(\bar{f}_1^E)^2 + p\Big[(1-\tau_{1,BT})P_{1,BT}\bar{f}_1^E - \frac{1}{2\kappa_1}\bar{f}_1^E\Big] + (1-p)\frac{\kappa_1}{2}(1-\tau_{1,CT})^2(P_{1,,*})^2$$

which gives the following interior solution

$$\bar{f}_1^E = \frac{p(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + p(1-\bar{\tau}_0)\kappa_2}(1-\tau_1^{BT})P_{1,BT}.$$

2. Production constraint binding in the CT scenario only: this gives

$$\max_{\bar{f}_1^E\geq 0} -\frac{1}{2(1-\bar{\tau}_0)\kappa_2}(\bar{f}_1^E)^2 + p\frac{\kappa_1}{2}(1-\tau_{1,BT})^2(P_{1,BT})^2 + (1-p)\Big[(1-\tau_{1,CT})P_{1,*}\bar{f}_1^E - \frac{1}{2\kappa_1}(\bar{f}_1^E)^2\Big]$$

which gives the following interior solution

$$\bar{f}_1^E = \frac{(1-p)(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-p)(1-\bar{\tau}_0)\kappa_2}(1-\tau_1^{CT})P_{1,*}.$$

3. Production constraint always binding: this gives

$$\max_{\bar{f}_1^E\geq 0} -\frac{1}{2(1-\bar{\tau}_0)\kappa_2}(\bar{f}_1^E)^2 + p\Big[(1-\tau_{1,BT})P_{1,BT}\bar{f}_1^E - \frac{1}{2\kappa_1}(\bar{f}_1^E)^2\Big] + (1-p)\Big[(1-\tau_{1,CT})P_{1,*}\bar{f}_1^E - \frac{1}{2\kappa_1}(\bar{f}_1^E)^2\Big]$$

which gives the following interior solution

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)(1-\tau_{1,CT})P_{1,*}\Big].$$

Appendix B Proofs

Proof of Proposition 1

If the incumbent producer is unconstrained in period 1, we have $f_1^I = \kappa_1 P_1$. Suppose instead that the production constraint in period 1 for the incumbent firm is binding. Optimal production choices for the incumbent are therefore given by

$$f_0^I = \frac{\kappa_1}{2}\Big[P_0 - (1-\tau_1)P_1\Big] + \frac{\bar{f}_0^I}{2} \tag{22}$$

$$f_1^I = \frac{\bar{f}_0^I}{2} - \frac{\kappa_1}{2}\Big[P_0 - (1-\tau_1)P_1\Big] \tag{23}$$

For the entrant firm, it is always optimal to exhaust its production capacity fully in period 1. Optimal installed capacity in period 0 is therefore

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}(1-\tau_1)P_1 \tag{24}$$

Substituting optimal quantities into market clearing conditions, we have

$$\frac{W}{P_0} = \frac{\kappa_1}{2}\Big[P_0 - (1-\tau_1)P_1\Big] + \frac{\bar{f}_0^I}{2} \tag{25}$$

$$\frac{W}{P_1} = \frac{\bar{f}_0^I}{2} - \frac{\kappa_1}{2}\Big[P_0 - (1-\tau_1)P_1\Big] + \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}(1-\tau_1)P_1 \tag{26}$$

Let us consider how equilibrium outcomes change with the derivative with respect to the tax on new drilling. Optimal quantities change according to

$$\frac{df_0^I}{d\bar{\tau}_0} = \frac{\kappa_1}{2}\Big[\frac{dP_0}{d\bar{\tau}_0} - (1-\tau_1)\frac{dP_1}{d\bar{\tau}_0}\Big] \tag{27}$$

$$\frac{df_1^I}{d\bar{\tau}_0} = -\frac{df_0^I}{d\bar{\tau}_0} \tag{28}$$

$$\frac{d\bar{f}_1^E}{d\bar{\tau}_0} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}(1-\tau_1)\frac{dP_1}{d\bar{\tau}_0} - \frac{\kappa_1^2\kappa_2}{[\kappa_1 + (1-\bar{\tau}_0)\kappa_2]^2}(1-\tau_1)P_1 \tag{29}$$

and from market clearing conditions we have that

$$-\frac{W}{P_0^2}\frac{dP_0}{d\bar{\tau}_0} = \frac{df_0^I}{d\bar{\tau}_0} \tag{30}$$

$$-\frac{W}{P_1^2}\frac{dP_1}{d\bar{\tau}_0} = -\frac{df_0^I}{d\bar{\tau}_0} + \frac{d\bar{f}_1^E}{d\bar{\tau}_0} \tag{31}$$

We proceed again by contradiction. Suppose that $\frac{dP_0}{d\bar{\tau}_0} < 0$. Then (30) implies that $\frac{df_0^I}{d\bar{\tau}_0} > 0$. From (27) we then get $\frac{dP_1}{d\bar{\tau}_0} < 0$ which implies, using (29), that $\frac{d\bar{f}_1^E}{d\bar{\tau}_0} < 0$, and using (31) that $\frac{d\bar{f}_1^E}{d\bar{\tau}_0} > 0$, which is a contradiction. Therefore, it must be that $\frac{dP_0}{d\bar{\tau}_0} \geq 0$. But $\frac{dP_0}{d\bar{\tau}_0} = 0$ implies, following the same steps, that $P_1 = 0$, which cannot be an equilibrium. Therefore, it must be $\frac{dP_0}{d\bar{\tau}_0} > 0$.

We now prove the result on firms' profits and drilling restrictions. Starting from the incumbent, we have

After some algebra, we find

$$\frac{d\Pi^E}{d\bar{\tau}_0} = \frac{1-\tau_1}{2}\left[\frac{d\bar{f}_1^E}{d\bar{\tau}_0}P_1 + \bar{f}_1^E \frac{dP_1}{d\bar{\tau}_0}\right] \tag{32}$$

Using (31), we have

$$\frac{W}{P_1^2}\frac{dP_1}{d\bar{\tau}_0} + \frac{d\bar{f}_1^E}{d\bar{\tau}_0} < 0 \tag{33}$$

but the market clearing condition implies that $\frac{W}{P_1^2} > \frac{\bar{f}_1^E}{P_1}$, from which it follows immediately that $\frac{d\Pi^E}{d\bar{\tau}_0} < 0$.

Finally, after some algebra we obtain

$$\frac{d\Pi^I}{d\bar{\tau}_0} = \frac{dP_0}{d\bar{\tau}_0}\left[\frac{\kappa_1}{2}(P_0 - (1-\tau_1)P_1) + \frac{1}{2}\bar{f}_0^I\right] + \frac{1-\tau_1}{2}\frac{dP_1}{d\bar{\tau}_0}\left[\bar{f}_0^I - \kappa_1(P_0 - (1-\tau_1)P_1)\right] \tag{34}$$

which is positive as both prices are increasing in the tax rate, and it follows immediately from the expressions for the equilibrium quantities that both terms in brackets are positive.

□

Proof of Proposition 2

Let $P_{1,T}$ and $P_{1,NT}$ denote the price of energy in the two possible states in period 1. We first describe the solutions for the two producers' problems and then prove our proposition.

Consider the incumbent fossil fuel firm first. Now it has to choose production quantities in each period and state, $(f_0^I, f_{1,T}^I, f_{1,NT}^I)$, in order to solve

$$\max_{0 \le f_0^I \le \bar{f}_0^I} \; f_0^I P_0 - \frac{1}{2\kappa_1}(f_0^I)^2 + E[V_1^I] \tag{35}$$

where now the date-1 continuation value V_1^I is equal to $V_{1,T}^I$ with probability p_T, and $V_{1,NT}^I$ with probability $(1-p_T)$. These continuation values are given by

$$V_{1,T}^I = \max_{0 \le f_{1,T}^I \le \bar{f}_0^I - f_0^I} (1-\tau_1)P_{1,T}f_{1,T}^I - \frac{1}{2\kappa_1}(f_{1,T}^I)^2, \tag{36}$$

and

$$V_{1,NT}^I = \max_{0 \le f_{1,NT}^I \le \bar{f}_0^I - f_0^I} P_{1,NT}f_{1,NT}^I - \frac{1}{2\kappa_1}(f_{1,NT}^I)^2, \tag{37}$$

We have therefore two cases to consider. If the production constraint in period 1 is binding in both states, then we have

$$f_0^I = \frac{\bar{f}_0^I}{2} + \frac{\kappa_1}{2}\left[P_0 - p_T(1-\tau_1)P_{1,T} - (1-p_T)P_{1,NT}\right] \tag{38}$$

Suppose instead that the production constraint is only binding in state NT, so that $f_{1,T}^I = (1-\tau_1)\kappa_1 P_{1,T} < \bar{f}_0^I - f_0^I$. In this case, we have

$$f_0^I = \frac{1-p_T}{2-p_T}\bar{f}_0^I + \frac{\kappa_1}{2-p_T}\left[P_0 - (1-p_T)P_{1,NT}\right] \tag{39}$$

Note that since demand for energy is the same in both states, in equilibrium we always have $(1-\tau_1)P_{1,T} \le P_{1,NT}$, so that the production constraint can never be binding in the T state only.

The entrant firm now has to choose production capacity and quantities in each state, namely $(\bar{f}_1^E, f_{1,T}^E, f_{1,NT}^E)$. Proceeding in the same way, if the production constraint in period 1 for the entrant firm is binding in both states, then we have

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[p_T(1-\tau_1)P_{1,T} + (1-p_T)P_{1,NT}\right] \tag{40}$$

If instead the production constraint is binding in state NT only, then we have

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-p_T)(1-\bar{\tau}_0)\kappa_2}(1-p_T)P_{1,NT} \tag{41}$$

Finally, market clearing conditions are now given by

$$\frac{W}{P_0} = f_0^I \tag{42}$$

$$\frac{W}{P_{1,T}} = f_{1,T}^I + f_{1,T}^E \tag{43}$$

$$\frac{W}{P_{1,NT}} = f_{1,NT}^I + f_{1,NT}^E \tag{44}$$

We now turn to the proof of the proposition. If the tax rate is low enough, then production capacity is binding in both states for both producers. Therefore, we have

$$\frac{df_0^I}{d\tau_1} = \frac{\kappa_1}{2}\left[\frac{dP_0}{d\tau_1} - p_T(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} + pP_{1,T} - (1-p_T)\frac{dP_{1,NT}}{d\tau_1}\right] \tag{45}$$

$$\frac{d\bar{f}_1^E}{d\tau_1} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[p_T(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} - pP_{1,T} + (1-p_T)\frac{dP_{1,NT}}{d\tau_1}\right] \tag{46}$$

and

$$-\frac{W}{P_0^2}\frac{dP_0}{d\tau_1} = \frac{df_0^I}{d\tau_1} \tag{47}$$

$$-\frac{W}{P_{1,T}^2}\frac{dP_{1,T}}{d\tau_1} = -\frac{df_0^I}{d\tau_1} + \frac{d\bar{f}_1^E}{d\tau_1} \tag{48}$$

$$-\frac{W}{P_{1,NT}^2}\frac{dP_{1,NT}}{d\tau_1} = -\frac{df_0^I}{d\tau_1} + \frac{d\bar{f}_1^E}{d\tau_1} \tag{49}$$

Suppose by contradiction that $\frac{dP_0}{d\tau_1} > 0$. Then, using (47), we have $\frac{df_0^I}{d\tau_1} < 0$. It follows from (45) that

$$-p_T(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} + pP_{1,T} - (1-p_T)\frac{dP_{1,NT}}{d\tau_1} < 0 \tag{50}$$

which in turn implies, using (46), that $\frac{d\bar{f}_1^E}{d\tau_1} > 0$. But then it follows from (48) and (49) that $\frac{dP_{1,T}}{d\tau_1} < 0$ and $\frac{dP_{1,NT}}{d\tau_1} < 0$, which contradicts (50). Therefore, it must be $\frac{dP_0}{d\tau_1} \leq 0$. Following the same steps, we find immediately that $\frac{dP_0}{d\tau_1} = 0$ implies that $P_{1,T} = 0$, which cannot be an equilibrium. Therefore, it must be $\frac{dP_0}{d\tau_1} > 0$.

Suppose now that the tax rate increases so that the production constraint for the incumbent fossil fuel firm becomes not binding in the T state. We assume that the initial production capacity of the incumbent is large enough so that it is less constrained than the entrant firm. We now have

$$\frac{df_0^I}{d\tau_1} = \frac{\kappa_1}{2-p_T}\left[\frac{dP_0}{d\tau_1} - (1-p_T)\frac{dP_{1,NT}}{d\tau_1}\right] \tag{51}$$

$$\frac{df_{1,T}^I}{d\tau_1} = \kappa_1\left[(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} - P_{1,T}\right] \tag{52}$$

and using market clearing in the T state

$$-\frac{W}{P_{1,T}^2}\frac{dP_{1,T}}{d\tau_1} = \frac{df_{1,T}^I}{d\tau_1} + \frac{d\bar{f}_1^E}{d\tau_1} \tag{53}$$

Suppose now that $\frac{dP_0}{d\tau_1} < 0$. Using (47), we have $\frac{df_0^I}{d\tau_1} > 0$ which implies, using (51), that $\frac{dP_{1,NT}}{d\tau_1} < 0$. But then, using (49), we have that $\frac{d\bar{f}_1^E}{d\tau_1} > 0$ which implies, using (46), that $\frac{dP_{1,T}}{d\tau_1} > 0$. From (53) we then get $\frac{df_{1,T}^I}{d\tau_1} < 0$ which implies, using (52), that

$$(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} - P_{1,T} < 0 \tag{54}$$

But this, using (46), implies that $\frac{d\bar{f}_1^E}{d\tau_1} < 0$, which is a contradiction. Therefore, we must have $\frac{dP_0}{d\tau_1} \geq 0$. Following the same steps, we can see immediately that $\frac{dP_0}{d\tau_1} = 0$ implies $\frac{df_{1,T}^I}{d\tau_1} < 0$ from (53) and $\frac{df_{1,T}^I}{d\tau_1} = 0$ from (52), which is a contradiction. Therefore, it must be $\frac{dP_0}{d\tau_1} > 0$.

Note that as the tax rate increases even further, then the production constraint becomes binding in state NT only for the entrant firm as well, which implies that further changes in the tax rate don't affect the decisions of any of the two firms. Therefore, as $\tau_1 \to 1$ we get $\frac{dP_0}{d\tau_1} = 0$.

□

Proof of Proposition 3

Optimal quantities of the two fossil fuel producers are the same as in the previous section, with the two states now being $T = BT$ and $NT = CT$. We allow for a carbon tax in the BT state, but set it equal to zero for now. Market clearing conditions in the two states in period 1 are now given by

$$\frac{W}{P_0} = f_0^I \tag{55}$$

$$\frac{W}{P_{1,BT}} = C + f_{1,BT}^I + f_{1,BT}^E \tag{56}$$

$$\frac{W}{P_{1,CT}} = f_{1,CT}^I + f_{1,CT}^E \tag{57}$$

Consider first the case where the production capacity is binding in both states for both fossil fuel producers. Therefore, we have

$$\frac{df_0^I}{dp} = \frac{\kappa_1}{2}\left[\frac{dP_0}{dp} - (1-\tau_{1,BT})\left(P_{1,BT} + p_{BT}\frac{dP_{1,BT}}{dp}\right) - (1-p_{BT})\frac{dP_{1,CT}}{dp} + P_{1,CT}\right] \tag{58}$$

$$\frac{d\bar{f}_1^E}{dp} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[(1-\tau_{1,BT})\left(P_{1,BT} + p_{BT}\frac{dP_{1,BT}}{dp}\right) + (1-p_{BT})\frac{dP_{1,CT}}{dp} - P_{1,CT}\right] \tag{59}$$

$$\frac{dC}{dp} = \delta\left(P_{1,BT} + p_{BT}\frac{dP_{1,BT}}{dp}\right) \tag{60}$$

and

$$-\frac{W}{P_0^2}\frac{dP_0}{dp} = \frac{df_0^I}{dp} \tag{61}$$

$$-\frac{W}{P_{1,BT}^2}\frac{dP_{1,BT}}{dp} = \frac{dC}{dp} - \frac{df_0^I}{dp} + \frac{d\bar{f}_1^E}{dp} \tag{62}$$

$$-\frac{W}{P_{1,CT}^2}\frac{dP_{1,CT}}{dp} = -\frac{df_0^I}{dp} + \frac{d\bar{f}_1^E}{dp} \tag{63}$$

As usual, we prove the proposition by contradiction. Suppose that $\frac{dP_0}{dp} > 0$. Using (61), this implies that $\frac{df_0^I}{dp} < 0$. It then follows from (58) that

$$-(1-\tau_{1,BT})\left(P_{1,BT} + p_{BT}\frac{dP_{1,BT}}{dp}\right) - (1-p_{BT})\frac{dP_{1,CT}}{dp} + P_{1,CT} < 0 \tag{64}$$

which immediately implies, using (59), that $\frac{d\bar{f}_1^E}{dp} > 0$. Using (63), we then have $\frac{dP_{1,CT}}{dp} < 0$, which implies, using (64), that

$$P_{1,BT} + p_{BT}\frac{dP_{1,BT}}{dp} > 0 \tag{65}$$

which immediately implies, using (60) and (62), that $\frac{dC}{dp} > 0$ and $\frac{dP_{1,BT}}{dp} < 0$. Now, note that since in this case fossil fuel firms are supplying the same quantity in both states, using market clearing conditions we have $P_{1,BT} < P_{1,CT}$. But then this implies, using (58), that $\frac{df_0^I}{dp} > 0$, which is a contradiction. Therefore, it must be $\frac{dP_0}{dp} \leq 0$. Following the same steps, we get the same contradiction if $\frac{dP_0}{dp} = 0$, so that it must be $\frac{dP_0}{dp} < 0$.

Consider now the case where the production constraint for the incumbent fossil fuel producer is only binding in the CT state. We now have

$$\frac{df_0^I}{dp} = \frac{\kappa_1}{2-p_{BT}}\left[\frac{dP_0}{dp} - (1-p_{BT})\frac{dP_{1,CT}}{dp} + P_{1,CT}\right] \tag{66}$$

$$\frac{df_{1,BT}^I}{dp} = (1-\tau_{1,BT})\kappa_1\frac{dP_{1,BT}}{dp} \tag{67}$$

and

$$-\frac{W}{P_{1,BT}^2}\frac{dP_{1,BT}}{dp} = \frac{dC}{dp} + \frac{df_{1,BT}^I}{dp} + \frac{d\bar{f}_1^E}{dp} \tag{68}$$

We first show that $\frac{dC}{dp} \geq 0$. Suppose that the opposite holds, which immediately implies from (60) that

$$P_{1,BT} + p_{BT}\frac{dP_{1,BT}}{dp} < 0 \tag{69}$$

and consequently $\frac{dP_{1,BT}}{dp} < 0$. It then follows from (67) that $\frac{df_{1,BT}^I}{dp} < 0$, and using (68) it follows that $\frac{d\bar{f}_1^E}{dp} > 0$. Then, from (69) and (59) we get

$$(1-p_{BT})\frac{dP_{1,CT}}{dp} - P_{1,CT} > 0 \tag{70}$$

and consequently $\frac{dP_{1,CT}}{dp} > 0$. It then follows from (63) that $\frac{df_0^I}{dp} > 0$ and from (61) that $\frac{dP_0}{dp} < 0$. But then, (66) implies that $-(1-p_{BT})\frac{dP_{1,CT}}{dp} + P_{1,CT} > 0$, which contradicts (70). Therefore, it must be $\frac{dC}{dp} \geq 0$, which immediately implies that

$$P_{1,BT} + p_{BT}\frac{dP_{1,BT}}{dp} \geq 0 \tag{71}$$

Suppose now that $\frac{dP_0}{dp} > 0$, which immediately implies from (61) that $\frac{df_0^I}{dp} < 0$. It then follows from (66) that

$$-(1-p_{BT})\frac{dP_{1,CT}}{dp} + P_{1,CT} < 0 \tag{72}$$

which immediately implies $\frac{dP_{1,CT}}{dp} > 0$ and consequently, using (63), that $\frac{d\bar{f}_1^E}{dp} < 0$. But then, (71) and (59) imply that $(1-p_{BT})\frac{dP_{1,CT}}{dp} - P_{1,CT} < 0$, which contradicts (72). Therefore, it must be $\frac{dP_0}{dp} \leq 0$. Following the same steps, we find that if $\frac{dP_0}{dp} = 0$ then (59) implies that $\frac{d\bar{f}_1^E}{dp} \geq 0$ and (63) implies $\frac{d\bar{f}_1^E}{dp} > 0$, which is a contradiction. Therefore, it must be $\frac{dP_0}{dp} < 0$.

□

Proof of Proposition 4

Consider first the case where the production capacity is binding in both states for both fossil fuel producers. Therefore, we have

$$\frac{df_0^I}{d\delta} = \frac{\kappa_1}{2}\left[\frac{dP_0}{d\delta} - p_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\delta} - (1-p_{BT})\frac{dP_{1,CT}}{d\delta}\right] \tag{73}$$

$$\frac{d\bar{f}_1^E}{d\delta} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1+(1-\bar{\tau}_0)\kappa_2}\left[p_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\delta} + (1-p_{BT})\frac{dP_{1,CT}}{d\delta}\right] \tag{74}$$

$$\frac{dC}{d\delta} = p_{BT}\left(P_{1,BT} + \delta\frac{dP_{1,BT}}{d\delta}\right) \tag{75}$$

and

$$-\frac{W}{P_0^2}\frac{dP_0}{d\delta} = \frac{df_0^I}{d\delta} \tag{76}$$

$$-\frac{W}{P_{1,BT}^2}\frac{dP_{1,BT}}{d\delta} = \frac{dC}{d\delta} - \frac{df_0^I}{d\delta} + \frac{d\bar{f}_1^E}{d\delta} \tag{77}$$

$$-\frac{W}{P_{1,CT}^2}\frac{dP_{1,CT}}{d\delta} = -\frac{df_0^I}{d\delta} + \frac{d\bar{f}_1^E}{d\delta} \tag{78}$$

We prove the proposition by contradiction. Suppose that $\frac{dP_0}{d\delta} > 0$. Using (76), this implies that $\frac{df_0^I}{d\delta} < 0$. It then follows from (73) that

$$-p_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\delta} - (1-p_{BT})\frac{dP_{1,CT}}{d\delta} < 0 \tag{79}$$

which immediately implies, using (74), that $\frac{d\bar{f}_1^E}{d\delta} > 0$. Using (78), we then have $\frac{dP_{1,CT}}{d\delta} < 0$, which implies, using (79), that $\frac{dP_{1,BT}}{d\delta} > 0$, which immediately implies, using (75) that $\frac{dC}{d\delta} > 0$. But them (77) implies $\frac{dP_{1,BT}}{d\delta} < 0$, which is a contradiction. Therefore, it must be $\frac{dP_0}{d\delta} \leq 0$. Assuming $\frac{dP_0}{d\delta} = 0$ and following the same steps, it is immediate to find $\frac{dP_0}{d\delta} < 0$.

Consider now the case where the production constraint for the incumbent fossil fuel producer is only binding in the CT state. We now have

$$\frac{df_0^I}{d\delta} = \frac{\kappa_1}{2-p_{BT}}\left[\frac{dP_0}{d\delta} - (1-p_{BT})\frac{dP_{1,CT}}{d\delta}\right] \tag{80}$$

$$\frac{df_{1,BT}^I}{d\delta} = (1-\tau_{1,BT})\kappa_1\frac{dP_{1,BT}}{d\delta} \tag{81}$$

and

$$-\frac{W}{P_{1,BT}^2}\frac{dP_{1,BT}}{d\delta} = \frac{dC}{d\delta} + \frac{df_{1,BT}^I}{d\delta} + \frac{d\bar{f}_1^E}{d\delta} \tag{82}$$

Suppose now that $\frac{dP_0}{d\delta} < 0$, from which it follows immediately from (76) that $\frac{df_0^I}{d\delta} > 0$. Using (80) this implies $\frac{dP_{1,CT}}{d\delta} < 0$, which implies using (78) that $\frac{d\bar{f}_1^E}{d\delta} > 0$. It then follows from (74) that $\frac{dP_{1,BT}}{d\delta} > 0$, which implies using (81) that $\frac{df_{1,BT}^I}{d\delta} > 0$ and using (75) that $\frac{dC}{d\delta} > 0$. But then (82) implies $\frac{dP_{1,BT}}{d\delta} < 0$, which is a contradiction. Hence, it must be $\frac{dP_0}{d\delta} \geq 0$.

Finally, if the production constraint in the BT state becomes not binding from the entrant also, then none of the two firms is reacting to the price in that state, and so they are not modifying their optimal decisions. It then follows that $\frac{dP_0}{d\delta} = 0$.

□

Proof of Proposition 5

We consider the planner's problem to set the optimal tax in each state, taking as given the production capacities of each producer. Let us consider the CT state first. Considering interior solutions for both fossil fuel producers, optimal quantities are given by

$$f^I_{1,CT} = f^E_{1,CT} = (1 - \tau_{1,CT})\kappa_1 P_{1,CT} \tag{83}$$

Plugging these quantities into the market clearing condition (57) we obtain the following expression for the equilibrium price

$$P_{1,CT} = \sqrt{\frac{W}{2\kappa_1(1 - \tau_{1,CT})}} \tag{84}$$

The first order condition for the planner's problem is

$$\left[2\kappa_1(1 - \tau_{1,CT})P_{1,CT}\right]^{-\gamma} = \lambda 2\kappa_1(1 - \tau_{1,CT})P_{1,CT} \tag{85}$$

Plugging in the expression for the equilibrium price and rearranging, we obtain

$$\tau^*_{1,CT} = 1 - \frac{1}{\lambda^{\frac{2}{1+\gamma}} 2W\kappa_1} \tag{86}$$

where we assume that $\lambda > \left[\frac{1}{2W\kappa_1}\right]^{\frac{1+\gamma}{2}}$. Note that it is immediate to see that $\tau^*_{1,CT}$ is increasing in λ.

Consider now the BT state. optimal fossil fuel quantities are as before

$$f^I_{1,BT} = f^E_{1,BT} = (1 - \tau_{1,BT})\kappa_1 P_{1,BT} \tag{87}$$

Using market clearing condition (56), the equilibrium price is now given by

$$P_{1,BT} = \frac{\sqrt{C^2 + 8\kappa_1(1 - \tau_{1,BT})W} - C}{4\kappa_1(1 - \tau_{1,BT})} \tag{88}$$

The optimality condition for the planner is now

$$\left[C + 2\kappa_1(1 - \tau_{1,BT})P_{1,BT}\right]^{-\gamma} = \lambda 2\kappa_1(1 - \tau_{1,BT})P_{1,BT} \tag{89}$$

Plugging in the expression for the equilibrium price and rearranging, we can rewrite the previous expression as

$$\left[2\lambda\kappa_1(1 - \tau_{1,BT})W\right]^{\frac{1}{1-\gamma}} - \left[\frac{1}{\lambda(2\kappa_1 W)^\gamma(1 - \tau_{1,BT})^\gamma}\right]^{\frac{1}{1-\gamma}} = C > 0 \tag{90}$$

which implies after rearranging, since $\gamma > 1$, that

$$\tau^*_{1,BT} > 1 - \frac{1}{\lambda^{\frac{2}{1+\gamma}} 2W\kappa_1} = \tau^*_{1,CT} \tag{91}$$

Finally, note that the left-hand side of (90) is decreasing in λ and increasing in $\tau_{1,BT}$. Therefore, as λ increases, the optimal tax rate that satisfies (90) also has to increase. □

B.1 Proof of Proposition 6: effects of drilling restrictions

Suppose that the period-1 production constraint is binding for both fossil fuel producers. Differentiating both sides of the market clearing conditions with respect to $\bar{\tau}_0$, we obtain

$$-\frac{W}{(P_0)^2}\frac{dP_0}{\bar{\tau}_0} = \frac{df_0^I}{d\bar{\tau}_0} \tag{92}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\bar{\tau}_0} = \frac{dC}{d\bar{\tau}_0} - \frac{df_0^I}{d\bar{\tau}_0} + \frac{d\bar{f}_1^E}{d\bar{\tau}_0} \tag{93}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\bar{\tau}_0} = \frac{dC}{d\bar{\tau}_0} \tag{94}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\bar{\tau}_0} = -\frac{df_0^I}{d\bar{\tau}_0} + \frac{d\bar{f}_1^E}{d\bar{\tau}_0} \tag{95}$$

For simplicity, let us set $\tau_{1,BT} = 0$, as this has no consequences for the proof. Optimal quantities are given by

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\Big[pP_{1,BT} + (1-p)P_{1,NE}\Big] \tag{96}$$

$$f_0^I = \frac{1}{2}\bar{f}_0^I + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\Big[pP_{1,BT} + (1-p)P_{1,NE}\Big] \tag{97}$$

$$C = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big] \tag{98}$$

which implies

$$\begin{aligned}\frac{d\bar{f}_1^E}{d\bar{\tau}_0} = &-\frac{\kappa_1^2\kappa_2}{[\kappa_1 + (1-\bar{\tau}_0)\kappa_2]^2}\Big[pP_{1,BT} + (1-p)P_{1,NE}\Big] \\ &+ \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\Big[p\frac{dP_{1,BT}}{d\bar{\tau}_0} + (1-p)\frac{dP_{1,NE}}{d\bar{\tau}_0}\Big]\end{aligned} \tag{99}$$

$$\frac{df_0^I}{d\bar{\tau}_0} = \frac{\kappa_1}{2}\frac{dP_0}{d\bar{\tau}_0} - \frac{\kappa_1}{2}\Big[p\frac{dP_{1,BT}}{d\bar{\tau}_0} + (1-p)\frac{dP_{1,NE}}{d\bar{\tau}_0}\Big] \tag{100}$$

$$\frac{dC}{d\bar{\tau}_0} = \delta\Big[p\frac{dP_{1,BT}}{d\bar{\tau}_0} + (1-p)\frac{dP_{1,E}}{d\bar{\tau}_0}\Big] \tag{101}$$

We want to show that $\frac{dP_0}{d\bar{\tau}_0} \geq 0$. We proceed again by contradiction, and suppose that the opposite holds. From (92), this implies $\frac{df_0^I}{d\bar{\tau}_0} > 0$. It follows from (100) that

$$p\frac{dP_{1,BT}}{d\bar{\tau}_0} + (1-p)\frac{dP_{1,NE}}{d\bar{\tau}_0} < 0 \tag{102}$$

which implies, using (99) that $\frac{d\bar{f}_1^E}{d\bar{\tau}_0} < 0$. From (95), it then follows that $\frac{dP_{1,NE}}{d\bar{\tau}_0} > 0$, which implies, using (102), that $\frac{dP_{1,BT}}{d\bar{\tau}_0} < 0$. From (93), we then have $\frac{dC}{d\bar{\tau}_0} > 0$, which implies, from (94), that $\frac{dP_{1,E}}{d\bar{\tau}_0} < 0$. But then, (101) implies $\frac{dC}{d\bar{\tau}_0} < 0$, which is a contradiction. Therefore, we must have $\frac{dP_0}{d\bar{\tau}_0} \geq 0$.

□

B.2 Proof of Proposition 6: effects of changes in the transition probability

First, note that from the market clearing conditions (8) – (11), we must always have $P_{1,E} \leq P_{1,NE}$. Indeed, suppose not. Then, both fossil fuel producers would choose to sell in the electrifiable market only. Therefore, there would be zero supply of energy in the non-electrifiable market, which would imply $P_{1,NE} \to \infty$, causing a contradiction.

Let us focus on the case where the period-1 production constraint is binding for both fossil fuel producers. Market clearing conditions in this case are therefore

$$\frac{W}{P_0} = f_0^I \tag{103}$$

$$\frac{W}{P_{1,BT}} = C + \bar{f}_0^I - f_0^I + \bar{f}_1^E \tag{104}$$

$$q\frac{W}{P_{1,E}} = C \tag{105}$$

$$(1-q)\frac{W}{P_{1,NE}} = \bar{f}_0^I - f_0^I + \bar{f}_1^E \tag{106}$$

Differentiating both sides of the previous equations with respect to p, we obtain

$$-\frac{W}{(P_0)^2}\frac{dP_0}{dp} = \frac{df_0^I}{dp} \tag{107}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{dp} = \frac{dC}{dp} - \frac{df_0^I}{dp} + \frac{d\bar{f}_1^E}{dp} \tag{108}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{dp} = \frac{dC}{dp} \tag{109}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{dp} = -\frac{df_0^I}{dp} + \frac{d\bar{f}_1^E}{dp} \tag{110}$$

Moreover, optimal quantities are given by

$$\bar{f}_1^E = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[pP_{1,BT} + (1-p)P_{1,NE}\Big] \tag{111}$$

$$f_0^I = \frac{1}{2}\bar{f}_0^I + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\Big[pP_{1,BT} + (1-p)P_{1,NE}\Big] \tag{112}$$

$$C = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big] \tag{113}$$

which implies

$$\frac{d\bar{f}_1^E}{dp} = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[P_{1,BT} - P_{1,NE} + p\frac{dP_{1,BT}}{dp} + (1-p)\frac{dP_{1,NE}}{dp}\Big] \tag{114}$$

$$\frac{df_0^I}{dp} = \frac{\kappa_1}{2}\frac{dP_0}{dp} - \frac{\kappa_1}{2}\Big[P_{1,BT} - P_{1,NE} + p\frac{dP_{1,BT}}{dp} + (1-p)\frac{dP_{1,NE}}{dp}\Big] \tag{115}$$

$$\frac{dC}{dp} = \delta\Big[P_{1,BT} - P_{1,E} + p\frac{dP_{1,BT}}{dp} + (1-p)\frac{dP_{1,E}}{dp}\Big] \tag{116}$$

Let us first show that we have $\frac{dP_0}{dp} \leq 0$. By contradiction, suppose $\frac{dP_0}{dp} > 0$. Then, (20) implies $\frac{df_0^I}{dp} < 0$. But then, using (28), we have

$$P_{1,BT} - P_{1,NE} + p\frac{dP_{1,BT}}{dp} + (1-p)\frac{dP_{1,NE}}{dp} > 0 \tag{117}$$

It then follows from (27) that $\frac{d\bar{f}_1^E}{dp} > 0$, which implies, using (23), that $\frac{dP_{1,NE}}{dp} < 0$. Now, note that market clearing conditions (17)-(19) imply that $P_{1,E} < P_{1,BT} < P_{1,NE}$. Using (30), It follows that $\frac{dP_{1,BT}}{dp} > 0$, which in turn implies, using (21), that $\frac{dC}{dp} < 0$. But then, (22) implies that $\frac{dP_{1,E}}{dp} > 0$, which in turn implies, using (29), that $\frac{dC}{dp} > 0$. This is a contradiction, so we must have $\frac{dP_0}{dp} \leq 0$.

Since $\frac{dP_0}{dp} \leq 0$, we can repeat the previous steps to show that $\frac{df_0^I}{dp} \geq 0$, $\frac{d\bar{f}_1^E}{dp} \leq 0$, $\frac{dP_{1,NE}}{dp} \geq 0$, and

$\frac{dP_{1,BT}}{dp} \leq 0$. Then, suppose again by contradiction that $\frac{dC}{dp} < 0$. From (22), it follows that $\frac{dP_{1,E}}{dp} > 0$, and using (21), we have $\frac{dP_{1,BT}}{dp} > 0$. This is a contradiction, so we must have $\frac{dC}{dp} \geq 0$, and then from (22) it follows immediately that $\frac{dP_{1,E}}{dp} \leq 0$.

□

B.3 Proof of Proposition 6: effects of carbon tax

First, consider the case where $\tau_{1,BT} \to 0$. It follows that the fossil fuel production constraint is binding in both scenarios in period 1. Differentiating both sides of the market clearing conditions with respect to $\tau_{1,BT}$, we obtain

$$-\frac{W}{(P_0)^2}\frac{dP_0}{\tau_{1,BT}} = \frac{df_0^I}{d\tau_{1,BT}} \tag{118}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} - \frac{df_0^I}{d\tau_{1,BT}} + \frac{d\bar{f}_1^E}{d\tau_{1,BT}} \tag{119}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} \tag{120}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\tau_{1,BT}} = -\frac{df_0^I}{d\tau_{1,BT}} + \frac{d\bar{f}_1^E}{d\tau_{1,BT}} \tag{121}$$

For simplicity, let us set $\bar{\tau}_0 = 0$, as this has no consequences for the proof. Optimal quantities are now given by

$$\bar{f}_1^E = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\Big] \tag{122}$$

$$f_0^I = \frac{1}{2}\bar{f}_0^I + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\Big] \tag{123}$$

$$C = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big] \tag{124}$$

which implies that we have

$$\frac{d\bar{f}_1^E}{d\tau_{1,BT}} = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[-pP_{1,BT} + p(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,NE}}{d\tau_{1,BT}}\Big] \tag{125}$$

$$\frac{df_0^I}{d\tau_{1,BT}} = \frac{\kappa_1}{2}\frac{dP_0}{d\tau_{1,BT}} - \frac{\kappa_1}{2}\Big[-pP_{1,BT} + p(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,NE}}{d\tau_{1,BT}}\Big] \tag{126}$$

$$\frac{dC}{d\tau_{1,BT}} = \delta\Big[p\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,E}}{d\tau_{1,BT}}\Big] \tag{127}$$

We can proceed as in the proof for Proposition 1 to show that $\frac{dP_0}{d\tau_{1,BT}} \leq 0$. Suppose by contradiction that $\frac{dP_0}{d\tau_{1,BT}} > 0$. Then, by (118), $\frac{df_0^I}{d\tau_{1,BT}} < 0$. It follows from (126) that

$$-pP_{1,BT} + p(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0 \tag{128}$$

which in turn implies, using (125), that $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} > 0$. Using (121), it follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$, which implies, using (128), that $\frac{dP_{1,BT}}{d\tau_{1,BT}} > 0$. It then follows from (119) that $\frac{dC}{d\tau_{1,BT}} < 0$ which in turn implies from (33) that $\frac{dP_{1,E}}{d\tau_{1,BT}} > 0$. But then, (127) implies that $\frac{dC}{d\tau_{1,BT}} > 0$, a contradiction. Therefore, it must be that $\frac{dP_0}{d\tau_{1,BT}} \leq 0$.

Consider now the case where $\tau_{1,BT} \to 1$. This implies that the production constraint of the fossil fuel firms becomes binding in the Current Technology scenario only. Assume that the initial capacity of the incumbent firm is large enough so that it is less constrained that the entrant firm. We therefore have two cases to consider:

Case 1: Production constraint of the entrant firm binding in both technology scenarios; production constraint of the incumbent firm binding in the CT scenario only. Market clearing conditions are

$$\frac{W}{P_0} = f_0^I \tag{129}$$

$$\frac{W}{P_{1,BT}} = C + f_{1,BT}^I + \bar{f}_1^E \tag{130}$$

$$q\frac{W}{P_{1,E}} = C \tag{131}$$

$$(1-q)\frac{W}{P_{1,NE}} = \bar{f}_0^I - f_0^I + \bar{f}_1^E \tag{132}$$

Differentiating both sides of the previous equations with respect to the tax rate, we obtain

$$-\frac{W}{(P_0)^2}\frac{dP_0}{d\tau_{1,BT}} = \frac{df_0^I}{d\tau_{1,BT}} \tag{133}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} + \frac{df_{1,BT}^I}{d\tau_{1,BT}} + \frac{d\bar{f}_1^E}{d\tau_{1,BT}} \tag{134}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} \tag{135}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\tau_{1,BT}} = -\frac{df_0^I}{d\tau_{1,BT}} + \frac{d\bar{f}_1^E}{d\tau_{1,BT}} \tag{136}$$

Optimal quantities are given by

$$f_0^I = \frac{\kappa_1}{2-p}P_0 - \frac{(1-p)\kappa_1}{2-p}P_{1,NE} + \frac{1-p}{2-p}\bar{f}_0^I \tag{137}$$

$$\bar{f}_1^E = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\Big] \tag{138}$$

$$f_{1,BT}^I = \kappa_1(1-\tau_{1,BT})P_{1,BT} \tag{139}$$

$$C = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big] \tag{140}$$

which implies

$$\frac{df_0^I}{d\tau_{1,BT}} = \frac{\kappa_1}{2-p}\frac{dP_0}{d\tau_{1,BT}} - \frac{(1-p)\kappa_1}{2-p}\frac{dP_{1,NE}}{d\tau_{1,BT}} \tag{141}$$

$$\frac{d\bar{f}_1^E}{d\tau_{1,BT}} = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[-pP_{1,BT} + p(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,NE}}{d\tau_{1,BT}}\Big] \tag{142}$$

$$\frac{df_{1,BT}^I}{d\tau_{1,BT}} = \kappa_1\Big[-P_{1,BT} + (1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}}\Big] \tag{143}$$

$$\frac{dC}{d\tau_{1,BT}} = \delta\Big[p\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,E}}{d\tau_{1,BT}}\Big] \tag{144}$$

To show that $\frac{dP_0}{d\tau_{1,BT}} \geq 0$, we proceed in various steps. First, we show that $\frac{dC}{d\tau_{1,BT}} \geq 0$. Suppose that the opposite holds. Then, by (135) we have $\frac{dP_{1,E}}{d\tau_{1,BT}} > 0$. This implies, using (144), that $\frac{dP_{1,BT}}{d\tau_{1,BT}} < 0$. Using (143) we then have $\frac{df_{1,BT}^I}{d\tau_{1,BT}} < 0$, and using (134) we have $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} > 0$. Then, from (142) we find $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, which implies using (136) that $\frac{df_0^I}{d\tau_{1,BT}} > 0$. But then (133) implies $\frac{dP_0}{d\tau_{1,BT}} < 0$ and (141) gives $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$, which is a contradiction. Therefore, it must be $\frac{dC}{d\tau_{1,BT}} \geq 0$, which in turn implies $\frac{dP_{1,E}}{d\tau_{1,BT}} \leq 0$

and $\frac{dP_{1,BT}}{d\tau_{1,BT}} \geq 0$ following the same steps.

We now show that $\frac{df^I_{1,BT}}{d\tau_{1,BT}} \leq 0$. Suppose that the opposite holds. Then, (134) implies $\frac{d\bar{f}^E_1}{d\tau_{1,BT}} < 0$, and using (55) we get $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$. But then (136) implies $\frac{df^I_0}{d\tau_{1,BT}} < 0$, (133) implies $\frac{dP_0}{d\tau_{1,BT}} > 0$, and (141) implies $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, a contradiction. Hence, $\frac{df^I_{1,BT}}{d\tau_{1,BT}} \leq 0$.

Then, suppose that $\frac{d\bar{f}^E_1}{d\tau_{1,BT}} > 0$. From (142) we have $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, from (136) we have $\frac{df^I_0}{d\tau_{1,BT}} > 0$, from (133) we have $\frac{dP_0}{d\tau_{1,BT}} < 0$ and from (141) we have $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$, a contradiction. Therefore, $\frac{d\bar{f}^E_1}{d\tau_{1,BT}} \leq 0$

For the next step, suppose that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$. Then, using (136) we have $\frac{df^I_0}{d\tau_{1,BT}} < 0$, using (133) we have $\frac{dP_0}{d\tau_{1,BT}} > 0$, and using (141) we get $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, a contradiction. Therefore, $\frac{dP_{1,NE}}{d\tau_{1,BT}} \geq 0$.

Finally, suppose that $\frac{dP_0}{d\tau_{1,BT}} < 0$. Using (133), this implies that $\frac{df^I_0}{d\tau_{1,BT}} > 0$. From (141), it then follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$, a contradiction. This proves that we must have $\frac{dP_0}{d\tau_{1,BT}} \geq 0$.

Case 2: Production constraint of both firms binding in the CT scenario only. In this case, we have $\frac{dP_0}{d\tau_{1,BT}} = 0$. Market clearing conditions are now

$$\frac{W}{P_0} = f^I_0 \tag{145}$$

$$\frac{W}{P_{1,BT}} = C + f^I_{1,BT} + f^E_{1,BT} \tag{146}$$

$$q\frac{W}{P_{1,E}} = C \tag{147}$$

$$(1-q)\frac{W}{P_{1,NE}} = \bar{f}^I_0 - f^I_0 + \bar{f}^E_1 \tag{148}$$

Differentiating both sides of the previous equations with respect to the tax rate, we obtain

$$-\frac{W}{(P_0)^2}\frac{dP_0}{d\tau_{1,BT}} = \frac{df^I_0}{d\tau_{1,BT}} \tag{149}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} + \frac{df^I_{1,BT}}{d\tau_{1,BT}} + \frac{df^E_{1,BT}}{d\tau_{1,BT}} \tag{150}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} \tag{151}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\tau_{1,BT}} = -\frac{df^I_0}{d\tau_{1,BT}} + \frac{d\bar{f}^E_1}{d\tau_{1,BT}} \tag{152}$$

Optimal quantities are now given by

$$f^I_0 = \frac{\kappa_1}{2-p}P_0 - \frac{(1-p)\kappa_1}{2-p}P_{1,NE} + \frac{1-p}{2-p}\bar{f}^I_0 \tag{153}$$

$$\bar{f}^E_1 = \frac{(1-p)\kappa_1\kappa_2}{\kappa_1 + (1-p)\kappa_2}P_{1,NE} \tag{154}$$

$$f^I_{1,BT} = f^E_{1,BT} = \kappa_1(1-\tau_{1,BT})P_{1,BT} \tag{155}$$

$$C = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big] \tag{156}$$

which implies

$$\frac{df^I_0}{d\tau_{1,BT}} = \frac{\kappa_1}{2-p}\frac{dP_0}{d\tau_{1,BT}} - \frac{(1-p)\kappa_1}{2-p}\frac{dP_{1,NE}}{d\tau_{1,BT}} \tag{157}$$

$$\frac{d\bar{f}_1^E}{d\tau_{1,BT}} = \frac{(1-p)\kappa_1\kappa_2}{\kappa_1+(1-p)\kappa_2}\frac{dP_{1,NE}}{d\tau_{1,BT}} \tag{158}$$

$$\frac{df^I_{1,BT}}{dd\tau_{1,BT}} = \frac{df^E_{1,BT}}{dd\tau_{1,BT}} = \kappa_1\Big[-P_{1,BT}+(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}}\Big] \tag{159}$$

$$\frac{dC}{d\tau_{1,BT}} = \delta\Big[p\frac{dP_{1,BT}}{d\tau_{1,BT}}+(1-p)\frac{dP_{1,E}}{d\tau_{1,BT}}\Big] \tag{160}$$

Suppose first that $\frac{dP_0}{d\tau_{1,BT}} < 0$. Using (149), this implies that $\frac{df_0^I}{d\tau_{1,BT}} > 0$. From (157), it then follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$. This implies, from (152), that $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} > 0$. But then, from (158), it follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$. This is a contradiction, hence it must be $\frac{dP_0}{d\tau_{1,BT}} \geq 0$. Assume now that $\frac{dP_0}{d\tau_{1,BT}} > 0$. Using (149), this implies that $\frac{df_0^I}{d\tau_{1,BT}} < 0$. From (157), it then follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$. Then, from (152), this $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} < 0$. But it then follows from (158) that $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, which is a contradiction. It must therefore be $\frac{dP_0}{d\tau_{1,BT}} = 0$. Following the same reasoning, this also implies $\frac{df_0^I}{d\tau_{1,BT}} = \frac{d\bar{f}_1^E}{d\tau_{1,BT}} = \frac{dP_{1,NE}}{d\tau_{1,BT}} = 0$

□

B.4 Proof for results on Firm Profits and drilling restrictions

For simplicity, suppose that the tax on carbon emissions is set to zero. Let us start from the entrant fossil fuel firm. Assuming that the production constraint is always binding, we have

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1+(1-\bar{\tau}_0)\kappa_2}\Big[pP_{1,BT}+(1-p)P_{1,NE}\Big]$$

which implies that total expected profits in period 0 are

$$\Pi_0^E = \frac{1}{2}\frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1+(1-\bar{\tau}_0)\kappa_2}\Big[pP_{1,BT}+(1-p)P_{1,NE}\Big]^2$$

It follows that

$$\begin{aligned}\frac{d\Pi_0^E}{d\bar{\tau}_0} = \frac{1}{2}\Big(pP_{1,BT}+(1-p)P_{1,NE}\Big)\Big[-\frac{\kappa_1^2\kappa_2}{[\kappa_1+(1-\bar{\tau}_0)\kappa_2]^2}\Big(pP_{1,BT}+(1-p)P_{1,NE}\Big)\\ +\frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1+(1-\bar{\tau}_0)\kappa_2}\frac{1}{2}\Big(p\frac{dP_{1,BT}}{d\bar{\tau}_0}+(1-p)\frac{dP_{1,NE}}{d\bar{\tau}_0}\Big)\Big]\end{aligned}$$

Therefore, we want to show that

$$\frac{(1-\bar{\tau}_0)}{2}\Big(p\frac{dP_{1,BT}}{d\bar{\tau}_0}+(1-p)\frac{dP_{1,NE}}{d\bar{\tau}_0}\Big) \leq \frac{\kappa_1}{\kappa_1+(1-\bar{\tau}_0)\kappa_2}\Big(pP_{1,BT}+(1-p)P_{1,NE}\Big)$$

Recall that in section B.3 we showed that

$$\frac{dP_0}{d\bar{\tau}_0} \geq 0,\ \frac{df_0^I}{d\bar{\tau}_0} \leq 0$$

It follows then immediately, using (100), that

$$p\frac{dP_{1,BT}}{d\bar{\tau}_0}+(1-p)\frac{dP_{1,NE}}{d\bar{\tau}_0} \geq 0$$

We now want to show that $\frac{dC}{d\bar{\tau}_0} \geq 0$. By contradiction, suppose that the opposite holds. Then, using (94), we have $\frac{dP_{1,E}}{d\bar{\tau}_0} > 0$ which in turn implies, using (101), that $\frac{dP_{1,BT}}{d\bar{\tau}_0} < 0$. But then, subtracting (94) from (93), we find that $\frac{d\bar{f}_1^E}{d\bar{\tau}_0} - \frac{df_0^I}{d\bar{\tau}_0} > 0$, which in turn implies, using (95), that $\frac{dP_{1,NE}}{d\bar{\tau}_0} < 0$. But then it follows that

$$p\frac{dP_{1,BT}}{d\bar{\tau}_0}+(1-p)\frac{dP_{1,NE}}{d\bar{\tau}_0}<0$$

which is a contradiction, hence it must be $\frac{dC}{d\bar{\tau}_0}\geq 0$. Then, using (94) we find $\frac{dP_{1,E}}{d\bar{\tau}_0}\leq 0$ which in turn implies, using (101), that $\frac{dP_{1,BT}}{d\bar{\tau}_0}\geq 0$. It then follows, using (93), that $\frac{d\bar{f}_1^E}{d\bar{\tau}_0}\leq 0$. Finally, using (99), we obtain

$$(1-\bar{\tau}_0)\left(p\frac{dP_{1,BT}}{d\bar{\tau}_0}+(1-p)\frac{dP_{1,NE}}{d\bar{\tau}_0}\right)\leq\frac{\kappa_1}{\kappa_1+(1-\bar{\tau}_0)\kappa_2}\left(pP_{1,BT}+(1-p)P_{1,NE}\right)$$

which implies directly that $\frac{d\Pi_0^E}{d\bar{\tau}_0}\leq 0$.

Turning to the incumbent fossil fuel firm, and considering again the case where the production constraint is always binding, we have

$$f_0^I=\frac{1}{2}\bar{f}_0^I+\frac{\kappa_1}{2}P_0-\frac{\kappa_1}{2}\left(pP_{1,BT}+(1-p)P_{1,NE}\right)$$

and total expected profits in period 0 are

$$\begin{aligned}\Pi_0^I=\ & f_0^IP_0-\frac{1}{2\kappa_1}(f_0^I)^2\\&+\Big[pP_{1,BT}+(1-p)P_{1,NE}\Big](\bar{f}_0^I-f_0^I)\\&-\frac{1}{2\kappa_1}(\bar{f}_0^I-f_0^I)^2\end{aligned}$$

To ease notation, let $P_1:=pP_{1,BT}+(1-p)P_{1,NE}$. If we plug the value for f_0^I into the previous expression, it follows that

$$\Pi_0^I=\ \frac{1}{2}\bar{f}_0^I(P_0+P_1)+\frac{1}{4}\kappa_1(P_0-P_1)^2-\frac{1}{4\kappa_1}(\bar{f}_0^I)^2$$

Hence, it follows that

$$\frac{d\Pi_0^I}{d\bar{\tau}_0}=\ \frac{1}{2}\bar{f}_0^I\left(\frac{dP_0}{d\bar{\tau}_0}+\frac{dP_1}{d\bar{\tau}_0}\right)+\frac{1}{2}\kappa_1(P_0-P_1)\left(\frac{dP_0}{d\bar{\tau}_0}-\frac{dP_1}{d\bar{\tau}_0}\right)$$

Using (97), $P_0-P_1=\frac{2}{\kappa_1}\left(f_0^I-\frac{1}{2}\bar{f}_0^I\right)$, hence

$$\begin{aligned}\frac{d\Pi_0^I}{d\bar{\tau}_0}&=\ \frac{1}{2}\bar{f}_0^I\left(\frac{dP_0}{d\bar{\tau}_0}+\frac{dP_1}{d\bar{\tau}_0}\right)+\left(f_0^I-\frac{1}{2}\bar{f}_0^I\right)\left(\frac{dP_0}{d\bar{\tau}_0}-\frac{dP_1}{d\bar{\tau}_0}\right)\\&=(\bar{f}_0^I-f_0^I)\frac{dP_1}{d\bar{\tau}_0}+f_0^I\frac{dP_0}{d\bar{\tau}_0}\geq 0\end{aligned}$$

where the last inequality follows from the production constraint $f_0^I\leq\bar{f}_0^I$ and from the fact that both prices are increasing in $\bar{\tau}_0$, as shown before and in section B.3.

Finally, consider the renewable energy producer. Its profits are given by

$$\Pi_0^R=C\Big[pP_{1,BT}+(1-p)P_{1,E}\Big]-\frac{1}{2\delta}C^2$$

using

$$C=\delta\Big[pP_{1,BT}+(1-p)P_{1,E}\Big]$$

we have

$$\Pi_0^R = \frac{\delta}{2}\Big[pP_{1,BT} + (1-p)P_{1,E}\Big]^2$$

Therefore, this implies

$$\frac{d\Pi_0^R}{d\bar{\tau}_0} = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big]\Big[p\frac{dP_{1,BT}}{d\bar{\tau}_0} + (1-p)\frac{dP_{1,E}}{d\bar{\tau}_0}\Big] \geq 0$$

where the results follows from $\frac{dC}{d\bar{\tau}_0} \geq 0$ and (101).

□

B.5 Proof for results on Firm Profits and probability of Breakthrough Technology State

For simplicity, suppose that the taxes on carbon emissions and new production capacity are set to zero. Let us start from the entrant fossil fuel firm. Assuming that the production constraint is always binding, we have

$$\bar{f}_1^E = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[pP_{1,BT} + (1-p)P_{1,NE}\Big]$$

which implies that total expected profits in period 0 are

$$\Pi_0^E = \frac{1}{2}\frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[pP_{1,BT} + (1-p)P_{1,NE}\Big]^2$$

It follows that

$$\frac{d\Pi_0^E}{dp} = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[pP_{1,BT} + (1-p)P_{1,NE}\Big]\Big[P_{1,BT} - P_{1,NE} + p\frac{dP_{1,BT}}{dp} + (1-p)\frac{dP_{1,NE}}{dp}\Big]$$

In section B.1, we showed that $\frac{d\bar{f}_1^E}{dp} \leq 0$. But then, using (27), it follows immediately that $\frac{d\Pi_0^E}{dp} \leq 0$.

Turning to the incumbent fossil fuel firm, and considering again the case where the production constraint is always binding, total expected profits in period 0 are

$$\Pi_0^I = \frac{1}{2}\bar{f}_0^I(P_0+P_1) + \frac{1}{4}\kappa_1(P_0-P_1)^2 - \frac{1}{4\kappa_1}(\bar{f}_0^I)^2$$

where $P_1 := pP_{1,BT} + (1-p)P_{1,NE}$. Hence, it follows that

$$\begin{aligned}\frac{d\Pi_0^I}{dp} = & \frac{1}{2}\Big[\bar{f}_0^I + \kappa_1(P_0-P_1)\Big]\frac{dP_0}{dp} \\ & + \frac{1}{2}\Big[\bar{f}_0^I - \kappa_1(P_0-P_1)\Big]\Big[P_{1,BT} - P_{1,NE} + p\frac{dP_{1,BT}}{dp} + (1-p)\frac{dP_{1,NE}}{dp}\Big]\end{aligned}$$

In section B.1 we showed that $\frac{dP_0}{dp} \leq 0$. Moreover, we argued before that the last term in square brackets in the previous expression is negative, and we also have $\bar{f}_0^I - \kappa_1(P_0-P_1) \geq 0$, which follows immediately from (25) and $f_0^I \leq \bar{f}_0^I$. For the last step, we also have $\bar{f}_0^I + \kappa_1(P_0-P_1) \geq 0$, which follows from $P_0 - P_1 = \frac{2}{\kappa_1}\left(f_0^I - \frac{1}{2}\bar{f}_0^I\right)$ and $f_0^I \geq 0$.

Finally, consider the renewable energy producer. Its profits are given by

$$\Pi_0^R = C\Big[pP_{1,BT} + (1-p)P_{1,E}\Big] - \frac{1}{2\delta}C^2$$

using

$$C = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big]$$

we have

$$\Pi_0^R = \frac{\delta}{2}\Big[pP_{1,BT} + (1-p)P_{1,E}\Big]^2$$

Therefore, this implies

$$\frac{d\Pi_0^R}{dp} = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big]\Big[P_{1,BT} - P_{1,E} + p\frac{dP_{1,BT}}{dp} + (1-p)\frac{dP_{1,E}}{dp}\Big] \geq 0$$

where the results follows from $\frac{dC}{dp} \geq 0$ and (29).

□

B.6 Proof for results on Firm Profits and carbon tax in BT scenario

For simplicity, suppose that the tax on new production capacity is set to zero, as this has no consequences for the proof. Let us start from the entrant fossil fuel firm. For small tax on carbon emissions, the production constraint is binding in both technology scenarios. This implies that new capacity is given by

$$\bar{f}_1^E = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\Big]$$

and, consequently, profits are

$$\Pi_0^E = \frac{1}{2}\frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\Big]^2$$

It follows that

$$\frac{d\Pi_0^E}{d\tau_{1,BT}} = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\Big]\Big[p\Big((1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} - P_{1,BT}\Big) + (1-p)\frac{dP_{1,NE}}{d\tau_{1,BT}}\Big]$$

Recall that in section B.2 we showed that, when the carbon tax rate is low, $\frac{dP_0}{d\tau_{1,BT}} \leq 0$. This in turn implies, using (118), that $\frac{df_0^I}{d\tau_{1,BT}} \geq 0$. Therefore, using (126) it follows immediately that

$$p\Big((1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} - P_{1,BT}\Big) + (1-p)\frac{dP_{1,NE}}{d\tau_{1,BT}} \leq 0$$

which implies that $\frac{d\Pi_0^E}{d\tau_{1,BT}} \leq 0$.

Consider now the incumbent fossil fuel producer. Optimal quantity produced in period 0 is

$$f_0^I = \frac{1}{2}\bar{f}_0^I + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\Big]$$

and, consequently, profits are

$$\begin{aligned}\Pi_0^I = &\ \frac{1}{2}\bar{f}_0^I(P_0+P_1) + \frac{1}{4}\kappa_1(P_0-P_1)^2 \\ &- \frac{1}{4\kappa_1}(\bar{f}_0^I)^2\end{aligned}$$

where $P_1 := p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}$. It follows that

$$\begin{aligned}\frac{d\Pi_0^I}{d\tau_{1,BT}} = &\ \frac{1}{2}\bar{f}_0^I\Big[\frac{dP_0}{d\tau_{1,BT}} + \frac{dP_1}{d\tau_{1,BT}}\Big] \\ &+ \frac{1}{2}\kappa_1(P_0-P_1)\Big[\frac{dP_0}{d\tau_{1,BT}} - \frac{dP_1}{d\tau_{1,BT}}\Big]\end{aligned}$$

Note that

$$\frac{dP_1}{d\tau_{1,BT}} = p\bigg((1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} - P_{1,BT}\bigg) + (1-p)\frac{dP_{1,NE}}{d\tau_{1,BT}} \leq 0$$

and, using (123), $P_0 - P_1 = \frac{2}{\kappa_1}(f_0^I - \bar{f}_0^I)$. It then follows that

$$\frac{d\Pi_0^I}{d\tau_{1,BT}} = (\bar{f}_0^I - f_0^I)\frac{dP_1}{d\tau_{1,BT}} + f_0^I\frac{dP_0}{d\tau_{1,BT}} \leq 0$$

since both prices are decreasing in the tax rate, and $f_0^I \leq \bar{f}_0^I$.

Finally, consider the renewable energy producer firm. Its profits are given by

$$\Pi_0^R = C\Big[pP_{1,BT} + (1-p)P_{1,E}\Big] - \frac{1}{2\delta}C^2$$

using

$$C = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big]$$

we have

$$\Pi_0^R = \frac{\delta}{2}\Big[pP_{1,BT} + (1-p)P_{1,E}\Big]^2$$

Therefore, this implies

$$\frac{d\Pi_0^R}{d\tau_{1,BT}} = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big]\Big[p\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,E}}{d\tau_{1,BT}}\Big]$$

We now argue that $\frac{dC}{d\tau_{1,BT}} \geq 0$. Suppose that the opposite holds. Then, using (120), $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, which in turn implies, using (127), that $\frac{dP_{1,BT}}{d\tau_{1,BT}} < 0$. But then, it follows from (119) that $\frac{dC}{d\tau_{1,BT}} > 0$, which is a contradiction. Therefore, it must be $\frac{dC}{d\tau_{1,BT}} \geq 0$. But then, using (127), it immediately follows that $\frac{d\Pi_0^R}{d\tau_{1,BT}} \geq 0$.

We now turn to the case where $\tau_{1,BT} \to 1$, and we consider two separate cases as before.

Case 1: Production constraint of the entrant firm binding in both technology scenarios; production constraint of the incumbent firm binding in the CT scenario only. Let us start from the entrant fossil fuel firm. New production capacity is given by

$$\bar{f}_1^E = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\Big]$$

and profits are

$$\Pi_0^E = \frac{\kappa_1\kappa_2}{2(\kappa_1+\kappa_2)}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\Big]^2$$

It then follows that

$$\frac{d\Pi_0^E}{d\tau_{1,BT}} = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\Big] \times \Big[p\bigg((1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} - P_{1,BT}\bigg) + (1-p)\frac{dP_{1,NE}}{d\tau_{1,BT}}\Big]$$

Recall that in section B.2 we showed that $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} \leq 0$, which immediately implies, using (142), that $\frac{d\Pi_0^E}{d\tau_{1,BT}} \leq 0$. We now turn to the incumbent firm. Optimal quantities are

$$f_0^I = \frac{\kappa_1}{2-p}P_0 - \frac{(1-p)\kappa_1}{2-p}P_{1,NE} + \frac{1-p}{2-p}\bar{f}_0^I$$

$$f^I_{1,BT} = \kappa_1(1-\tau_{1,BT})P_{1,BT}$$

and profits are

$$\begin{aligned}\Pi^I_0 &= f^I_0 P_0 - \frac{1}{2\kappa_1}(f^I_0)^2 \\ &+ p\frac{\kappa_1}{2}(1-\tau_{1,BT})^2(P_{1,BT})^2 \\ &+ (1-p)\left[P_{1,NE}(\bar{f}^I_0 - f^I_0) - \frac{1}{2\kappa_1}(\bar{f}^I_0 - f^I_0)^2\right]\end{aligned}$$

It then follows that

$$\begin{aligned}\frac{d\Pi^I_0}{d\tau_{1,BT}} &= \frac{df^I_0}{d\tau_{1,BT}}P_0 + f^I_0\frac{dP_0}{d\tau_{1,BT}} - \frac{1}{\kappa_1}f^I_0\frac{df^I_0}{d\tau_{1,BT}} \\ &+ p\kappa_1(1-\tau_{1,BT})\left[(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} - P_{1,BT}\right]P_{1,BT} \\ &+ (1-p)\left[\frac{dP_{1,NE}}{d\tau_{1,BT}}(\bar{f}^I_0 - f^I_0) - P_{1,NE}\frac{df^I_0}{d\tau_{1,BT}} + \frac{1}{\kappa_1}(\bar{f}^I_0 - f^I_0)\frac{df^I_0}{d\tau_{1,BT}}\right]\end{aligned}$$

which can be rewritten as

$$\begin{aligned}\frac{d\Pi^I_0}{d\tau_{1,BT}} &= p\kappa_1(1-\tau_{1,BT})\left[(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} - P_{1,BT}\right]P_{1,BT} \\ &+ f^I_0\frac{dP_0}{d\tau_{1,BT}} + (1-p)(\bar{f}^I_0 - f^I_0)\frac{dP_{1,NE}}{d\tau_{1,BT}}\end{aligned}$$

Note that the first term of the previous expression is negative, as it reflects reduced profits from the carbon tax in the BT scenario. The terms in the second line are instead positive, as they reflect increasing profits from moving fossil fuel production from time 0 to the CT scenario in time 1. In all our numerical experiments, the first effect always prevail so that profits of the incumbent fossil fuel firm decrease with the carbon tax rate.

For the renewable firm, it is easy to show that its profits increase with the carbon tax rate by repeating the same steps as before.

Case 2: Production constraint of both firms binding in the CT scenario only. Let us start from the entrant fossil fuel firm. New production capacity is given by

$$\bar{f}^E_1 = \frac{\kappa_1\kappa_2}{\kappa_1 + (1-p)\kappa_2}(1-p)P_{1,NE}$$

and profits are

$$\begin{aligned}\Pi^E_0 &= \frac{\kappa_1\kappa_2}{2[\kappa_1 + (1-p)\kappa_2]}(1-p)^2(P_{1,NE})^2 \\ &+ p\frac{1}{2}\kappa_1(1-\tau_{1,BT})^2(P_{1,BT})^2\end{aligned}$$

It then follows that

$$\begin{aligned}\frac{d\Pi^E_0}{d\tau_{1,BT}} &= \frac{\kappa_1\kappa_2}{\kappa_1 + (1-p)\kappa_2}(1-p)^2 P_{1,NE}\frac{dP_{1,NE}}{d\tau_{1,BT}} \\ &+ p\kappa_1(1-\tau_{1,BT})P_{1,BT}\left[(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} - P_{1,BT}\right]\end{aligned}$$

Using the results from section B.2, the first term of the previous expression is equal to zero, while the second term is negative. Overall, profits of the entrant fossil fuel firm therefore decrease with the carbon tax.

Turning to the incumbent fossil fuel firm, profits have the same expressions as in the previous case. However, since now both P_0 and $P_{1,NE}$ do not change with the tax rate, now profits are unambiguously decreasing in $\tau_{1,BT}$. Similarly, for the renewable firm, profits have the same expression as before, and it follows immediately from the results in section B.2 that they are increasing in the carbon tax rate.

Appendix C Carbon tax on production rather than on sales

In the main text, we assumed that taxes in the BT scenario are imposed on sales of fossil fuels, rather than directly on units produced. Under this alternative specification, the period 1 problems of the incumbent fossil fuel producer in the BT scenario would be

$$\max_{f^I_{1,BT}} (P_{1,BT} - \tau_{1,BT}) f^I_{1,BT} - \frac{1}{2\kappa_1}(f^I_{1,BT})^2,$$

subject to $0 \leq f^I_{1,BT} \leq \bar{f}^I_0 - f^I_0$, while the problem of the entrant firm would be

$$\max_{f^E_{1,BT}} (P_{1,BT} - \tau_{1,BT}) f^E_{1,BT} - \frac{1}{2\kappa_1}(f^E_{1,BT})^2,$$

subject to $0 \leq f^E_{1,BT} \leq \bar{f}^E_1$.

Note that this formulation of the model is equivalent to our main specification, as if the government where to set a tax on fossil fuel emissions higher than the equilibrium price, then both firms would choose not to produce in that scenario. Indeed, Figure 7 shows the same exercise as in the previous section, and we can see that the results are qualitatively the same. We therefore maintain the initial model formulation.

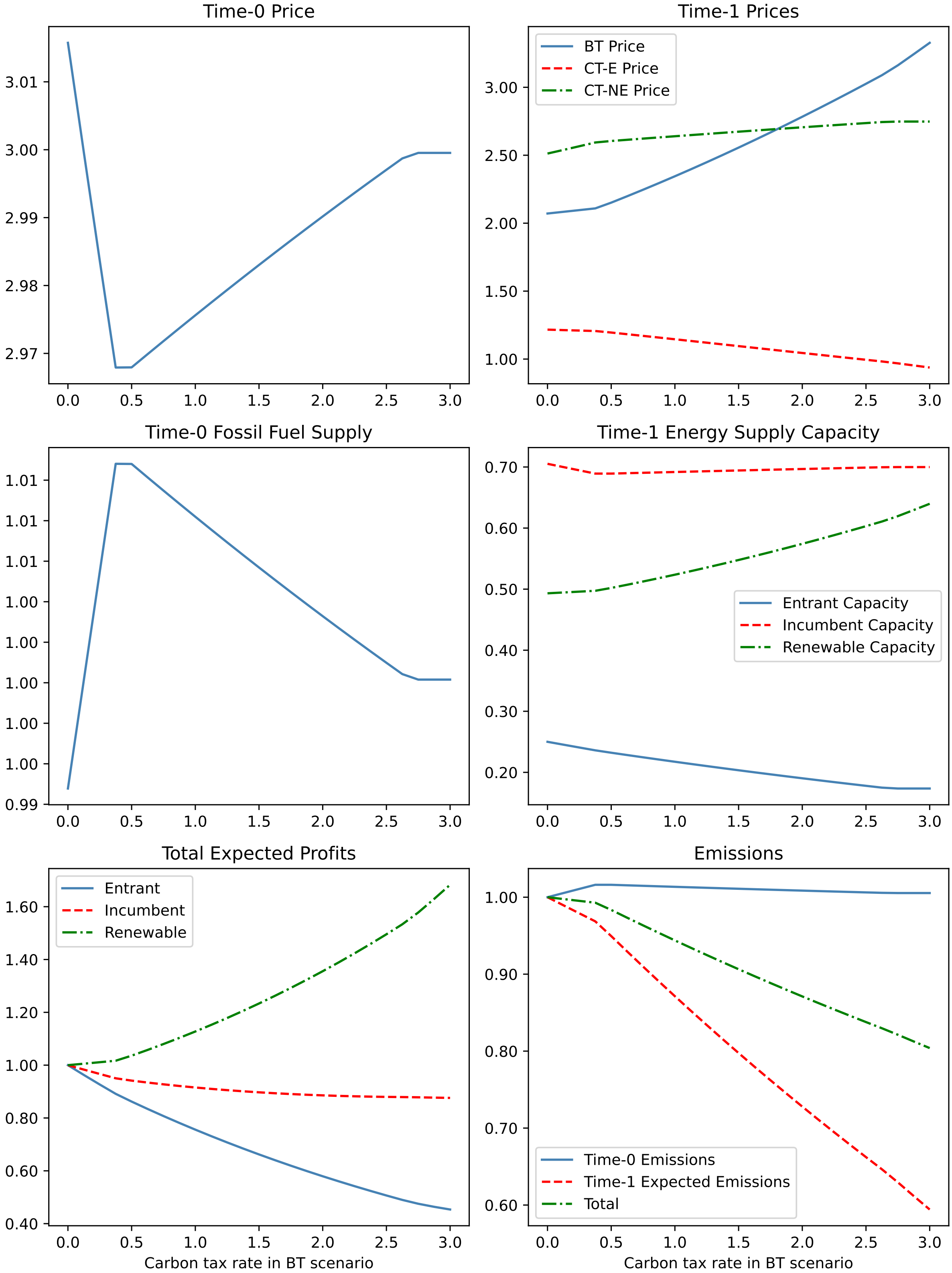


Figure 7: Equilibrium effects of changes in BT tax rate. Note that profits for each producer are normalized by their profits for $p = 0$, whereas emissions are normalized for each period and total by the corresponding value for $p = 1$. BT scenario probability is fixed at $p = 0.5$.

Appendix D Summary of Mechanisms at Work

Table 4: Step-by-step mechanisms at work underlying Table 1.

Increase in:	Transition probability (p)	Carbon tax in BT state ($\tau_{1,BT}$)	Drilling restrictions ($\bar{\tau}_0$)
Energy price in BT state ($P_{1,BT}$)	Decreases	Increases	Increases
Post-tax price	-	Decreases	-
Energy price in CT-NE state ($P_{1,NE}$)	Increases	Increases	Increases
Fossil fuel emissions			
Time-0	Increase	Uncertain	Decrease
Time-1 (expected)	Decrease	Decrease	Decrease
Total	Decrease	Decrease	Decrease

Appendix E Additional Data Details

E.1 Measuring Climate Transition Risks By GPT

We construct several indices to measure the climate transition risks we mentioned in the model applying the state-of-the-art large language models (LLMs) on news reported in the New York Times (NYT). LLMs are a type of artificial intelligence (AI) model designed to understand, generate, and interact with human-like text. LLMs are leading in performance across a range of natural language processing (NLP) tasks, largely due to their extensive scale. We utilize GPT-4o Mini, one of the most advanced LLMs pre-trained by OpenAI.[15]

E.1.1 Pre-processing

We obtained historical news articles from the NYT through LexisNexis, covering a 12-year period from 2012 to 2023. We first need to identify news articles that cover the climate transition risks we are measuring, which are the cost of emissions and the possibility of a technological breakthrough that improves renewable energy firms' ability to provide energy to all sectors. We filtered all NYT articles that contain at least one of the following terms: "carbon," "renewable," "drilling," "fossil," "oil and gas," "emissions," "solar," or "pipeline." We believe these terms provide a comprehensive dataset, capturing most articles relevant to our topics. For instance, articles discussing carbon emissions pricing likely mentioned the term "carbon" at least once. While this approach might also include some irrelevant articles, such as those about drilling on Mars, the capability of the GPT model to filter out irrelevant information, as demonstrated in Table 5, ensures these articles do not compromise our index construction.

The LexisNexis dataset includes both electronic (online) and printed versions of news articles, which sometimes feature different titles and slight sentence adjustments. For example, the article titled "Seismic Survey of Alaskan Arctic Refuge Won't Move Forward" appeared online in the New York Times on February 22, 2021, and the same article was published in the printed version under the headline "A Deadline Missed Kills An Oil Survey In the Arctic" on February 23, 2021. Similarly, the online article "Obama Climate Plan, Now in Court, May Hinge on Error in 1990 Law" from September 25, 2016, corresponds to the printed article "Obama's Climate Change Plan May Hinge on a Clerical Error in a 1990 Law" from September 26, 2016. We eliminated such "duplicates", retaining only the one that appeared first.[16]

[15] The OpenAI model we used is `gpt-4o-mini-2024-07-18`.

[16] We use TF-IDF to embed documents into a 256-dimensional vector and compute cosine similarity for all pairs of articles. For those very similar articles (i.e., cosine similarity > 0.98), we only keep the one that appeared first. TF-IDF, which stands for term frequency-inverse document frequency, is a numerical representation used in information retrieval and NLP. It measures the importance of a term in a collection of documents by considering its frequency within a document (TF) and its rarity across the entire collection (IDF).

E.1.2 Article-level Analysis by GPT

Beyond the initial filtering and cleaning, we made queries to OpenAI's GPT-4o Mini model instance with each query for one NYT news article. We report the prompt format used to query GPT below. Overall, this prompt has three parts: 1) news article input, where "%s" indicates the inserted location of the news article we want to analyze; 2) guidence of the output structure; 3) questions. For each risk measure, we pose four questions. The first question assesses the relevance of the article to the targeted topic, guiding the model toward the specific transition risk we are measuring. The second question determines the direction indicated by the news article concerning the topic, such as whether it suggests a tightening or loosening of U.S. carbon pricing policy. The third question evaluates the strength of this direction, and the fourth question estimates the potential impact of the news on market prices and operational strategies of fossil fuel companies.

Here is a news article:

"%s"

Please answer the following questions and present your findings as a single JSON object, conforming to the following structure:

{'Question1': '(choice id)'};
{'Question2': '(choice id)'};
{'Question3': '(choice id)'};
{'Question4': '(choice id)'};
{'Question5': Provide detailed explanations on Question1 to Question4, identifying specific parts of the article or exact policies discussed that contribute to this score. The explanation should be concise and precise, directly relating to the aspects mentioned in the article. (less than 150 words)};

- - -

Question1: Does this article discuss U.S. carbon pricing policy, or factors related to U.S. carbon pricing policy?
(a) Yes
(b) No

Question2: Does this article indicate a tightening or loosening U.S. carbon pricing policy?
(a) Tightening
(b) Loosening
(c) Neutral - The article does not provide specific details or evidence regarding changes in U.S. carbon pricing policy.

Question3: How likely is the change you indicated in Question2?
(a) Extremely Likely
(b) Very Likely
(c) Somewhat Likely
(d) Slightly Likely
(e) Neutral - if answered Neutral in Question2.

Question4: How significant do you anticipate the impact of this news about U.S. carbon pricing policy will be on the market prices and operational strategies of companies in oil/gas industry?
(a) Most Significant Impact[17]
(b) Highly Significant Impact[18]
(c) Moderate Impact[19]
(d) Minimal Impact[20]
(e) No Impact[21]

We analyzed a total of 35,593 news articles, filtered by the above keywords over our 10-year sample period. We analyzed each article in five topics:

- U.S. carbon pricing policy
- U.S. regulatory or financial cost of carbon emissions
- Renewable energy or battery storage technology breakthroughs probability
- Actual technology breakthroughs on renewable energy or battery storage
- Regulations that affect the production capacity of fossil fuels

Table 5 to 9 present sample responses from GPT-4 along with explanations. The model successfully identifies irrelevant news articles and assigns them neutral scores, which are mapped as zero in subsequent aggregations and do not affect the construction of the index. It also effectively analyzes the direction each article takes on the topics, demonstrating its capability for news analysis tasks.

[17] We also provide detailed instructions to the GPT model to identify articles that should be considered of most significant impact. This news is amongst the most impactful on the fossil fuel industry in a given year. It's likely to lead to extreme fluctuations in market prices and will force companies to alter their long-term operational strategies and investment plans.

[18] This news will have a large impact on fossil fuel industry. It's likely to lead to considerable fluctuations in market prices and may prompt these companies to re-evaluate and alter their long-term operational strategies.

[19] There might be some short-term volatility in market prices, but the long-term operational strategies of these companies are likely to remain largely unchanged.

[20] This news is unlikely to have a substantial impact on the fossil fuel industry. There might be slight and temporary fluctuations in market prices, but the overall business operations and strategies of these companies are expected to remain stable and largely unaffected by this development.

[21] The article has negligible impact on both the prices and operational strategies of fossil fuel firms.

Table 5: Responses From GPT - U.S. Carbon Pricing Policy

	Responses from GPT-4				
Headline	Relevance	Direction	Strength	Importance	Explanation
Using Executive Powers, Obama Begins His Last Big Push on Climate Policy	Yes	Tightening	Extremely Likely	Most Significant Impact	The article discusses President Obama's plan to implement regulations that will force power plants to reduce carbon emissions, indicating a tightening of U.S. carbon pricing policy. This is significant as it could lead to the closure of coal-fired plants, impacting the fossil fuel industry. The anticipated impact on market prices and operational strategies is high due to the potential for job losses and increased energy costs, as highlighted by critics like Senator Enzi.
Divide at the White House Over the Paris Climate Agreement	Yes	Loosening	Extremely Likely	Most Significant Impact	The article discusses the potential withdrawal from the Paris Agreement, indicating a loosening of U.S. carbon pricing policy. This is significant as it suggests a shift away from regulatory frameworks aimed at reducing carbon emissions, which could lead to increased carbon emissions and a lack of accountability for fossil fuel companies. The proposed cuts to the EPA and the elimination of regulations like the Clean Power Plan further emphasize this loosening, impacting the fossil fuel industry's operational strategies.
A Peek for Disney Fans	No	Neutral	Neutral	No Impact	The article does not discuss U.S. carbon pricing policy or related factors, focusing instead on Disney's movie pipeline and fan reactions. Therefore, it is marked as having no impact on carbon pricing policy.

Note: Sample responses from GPT-4 on the topic of U.S. Carbon Pricing Policy.

Table 6: Responses From GPT - U.S. Regulatory or Financial Cost of Carbon Emissions

Headline	Responses from GPT-4				
	Relevance	Direction	Strength	Importance	Explanation
Administration to Press Ahead With Carbon Limits	Yes	Increase	Extremely Likely	Highly Significant Impact	The article indicates an increase in regulatory costs due to the new carbon limits imposed by the EPA. The requirement for coal plants to implement carbon capture and sequestration technology will likely raise operational costs. This increase in regulatory costs is expected to significantly impact the fossil fuel industry, prompting companies to reassess their strategies and potentially leading to fluctuations in market prices.
Trump to Undo Vehicle Rules That Curb Global Warming	Yes	Decrease	Extremely Likely	Highly Significant Impact	The article indicates a decrease in regulatory costs associated with carbon emissions due to the rollback of stringent vehicle emissions standards. This change is likely to be significant for the fossil fuel industry, as it may reduce compliance costs and encourage continued reliance on fossil fuels, thus impacting market prices positively. The likelihood of this change is high, given the direct actions being taken by the Trump administration.
In Liguria's Coastal Hills, A Storm's Fury Brings A Struggle for Restoration	No	Neutral	Neutral	No Impact	The article does not address the regulatory or financial cost of carbon emissions in the U.S. It is centered on local recovery efforts in a specific Italian region following severe weather damage.

Note: Sample responses from GPT-4 on the topic of U.S. regulatory or financial cost of carbon emissions.

Table 7: Responses From GPT - Renewable Energy or Battery Storage Technology Breakthrough Probability

	Responses from GPT-4				
Headline	Relevance	Direction	Strength	Importance	Explanation
New Solar Process Gets More Out of Natural Gas	Yes	Increase	Extremely Likely	Highly Significant Impact	The article discusses a breakthrough in renewable energy technology, specifically the solar augmentation of natural gas. This indicates an increase in the probability of renewable energy breakthroughs. The significance of this news on fossil fuel companies is high, as it could lead to shifts in energy production strategies and market dynamics, especially in regions with high natural gas prices.
Japanese Cabinet Proposes Energy Sector Overhauls	Yes	Increase	Extremely Likely	Moderate Impact	The article discusses renewable energy breakthroughs, particularly the photovoltaic panels on the Bullitt Center, indicating an increase in renewable energy technology. This could significantly impact fossil fuel companies as they adapt to changing energy landscapes.
Offshore Wind Firm Cancels N.J. Projects, as Industry's Prospects Dim	Yes	Decrease	Very Likely	Highly Significant Impact	The article indicates a decrease in the likelihood of breakthroughs in renewable energy technology due to the financial challenges faced by companies like Orsted. The mention of equipment shortages and high financing costs suggests that innovation may be stifled, impacting the overall market for fossil fuels.

Note: Sample responses from GPT-4 on the topic of renewable energy or battery storage technology breakthroughs probability.

Table 8: Responses From GPT - Actual Breakthroughs on Renewable Energy or Battery Storage

	Responses from GPT-4		
Headline	Discussed Actual BT?	Importance	Explanation
Batteries That Make Use of Solar Power, Even in the Dark	Yes	Most Significant Impact	The article highlights actual technology breakthroughs in battery storage, which can significantly impact the fossil fuel industry by providing alternatives to traditional energy sources, thus marked as 'Yes'.
Wind Farms See Promise in Platforms That Float	Yes	Highly Significant Impact	The article discusses actual technology breakthroughs in renewable energy, specifically the successful testing of floating wind platforms. This success is likely to influence market dynamics and operational strategies in the fossil fuel industry as renewable energy becomes more competitive.
Soap, Detergent and Even Laxatives Could Turbocharge a Battery Alternative	Yes	Highly Significant Impact	The article highlights actual technology breakthroughs in supercapacitor development, which could lead to significant impacts on the fossil fuel industry. The advancements in energy storage technology are likely to influence market dynamics and operational strategies.

Note: Sample responses from GPT-4 on the topic of actual technology breakthroughs on renewable energy or battery storage.

Table 9: Responses From GPT - Regulations that Affect the Production Capacity of Fossil Fuels

	Responses from GPT-4				
Headline	Relevance	Direction	Strength	Importance	Explanation
Trump Revives Keystone Pipeline Rejected by Obama	Yes	Expansion	Extremely Likely	Most Significant Impact	The article discusses President Trump's actions to expedite the Keystone XL and Dakota Access pipelines, which directly affect fossil fuel companies' ability to expand production capacity. By reviving these projects and reducing regulatory hurdles, the administration is facilitating increased fossil fuel extraction and transportation, indicating a clear policy shift towards expansion. Trump's directive to streamline environmental reviews further supports this expansionist approach.
Biden Administration Moves to Limit Methane, a Potent Greenhouse Gas	Yes	Restriction	Extremely Likely	Highly Significant Impact	The article discusses the Biden administration's new rule to regulate methane emissions from existing oil and gas rigs, which directly affects fossil fuel companies' production capacity. This regulation aims to limit methane leaks, which could restrict the operational capabilities of these companies. The emphasis on stricter regulations indicates a clear shift towards limiting fossil fuel production expansion.
The Bank of England adds green criteria to its corporate bond purchases	Yes	Restriction	Extremely Likely	Highly Significant Impact	The article discusses the Bank of England's decision to exclude bonds from coal mining companies, which directly restricts fossil fuel companies' ability to expand production capacity. The new rules require companies to phase out coal by 2025 and use renewable energy, indicating a significant shift in policy that limits fossil fuel expansion.

Note: Sample responses from GPT-4 on the topic of regulations that affect the production capacity of fossil fuels.

E.1.3 Aggregation

To measure the overall views of climate transition news in a given week, we construct news indices by aggregating article-level scores to a weekly level. Compared with daily scores, weekly scores are more likely to capture discussions around the event date. They also better capture reflections in the stock market in the days following the event when we connect these indices to stock returns later. We include news from Saturday and Sunday in the following week since this news would only be reflected on Monday when the market opens. Before aggregation, we map textual responses into numerical scores. For direction responses, tightening carbon policies, more drilling restrictions, and increased renewable technology breakthrough probability are mapped to "+1". Loosening carbon policies, fewer drilling restrictions, and decreased renewable technology breakthrough probability are mapped to "-1". For the question measuring the strength of direction, responses range from neutral to extremely likely. We code "Extremely Likely" and "Very Likely" as 1; and "Somewhat Likely," "Slightly Likely," and "Neutral" as 0. This coding scheme accounts for the GPT's noisy yet broadly accurate characterizations, allowing for the detection of overarching patterns while acknowledging the unreliability of fine-grained distinctions in magnitude. For the question measuring the potential impact of the news on market prices and operational strategies of fossil fuel companies, responses range from no impact to highly significant impact. Similarly to the question measuring strength, we code "Most Significant Impact" and "Highly Significant Impact" as 1; and "Moderate Impact," "Minimal Impact," and "No Impact" as 0.

We build the indices by multiplying direction scores with strength and importance scores, which measure the magnitude and direction of the news' effect on stock prices of fossil fuel firms.

$$\text{Idx}_{k,t} = \sum_{j=1}^{N} D_{k,j,t} S_{k,j,t} I_{k,j,t},$$

where $D_{k,j,t}$ is the direction score for index k of article j at week T, $S_{k,j,t}$ is the strength score for index k of article j at week T, and $I_{k,j,t}$ is the importance score for index k of article j at week T. N is the total number of article within each week. We build an index for each of the topics mentioned in Section E.1.2.

Among the five indices we measured, the index measuring U.S. carbon pricing policy and the index measuring U.S. regulatory or financial cost of carbon emissions both assess the cost of emissions but with different focuses. The U.S. carbon pricing policy index focuses more on policy announcements, while the other index covers events like changes in fuel efficiency standards. To better comprehend the index measuring the cost of emissions and eliminate potential noise from model running, we combine these two indices into a single NYT-Emission Cost News Index. Similarly, the renewable energy technology breakthrough probability index and the actual technology breakthroughs in renewable energy index are combined into the NYT-Renewable Breakthrough News Index. We combine these indices by taking the arithmetic mean of each index divided by their standard deviation. Figure 1 plots the time series of these two news indices, with labels indicating related events.

E.2 Oil Futures Price

Table 10 reports the data description and sources of the variables utilized in our study of oil futures prices.

E.3 Correlation with Stock Returns

We next examine how news is reflected in the stock returns of energy firms and how these reflections differ among three types of firms in our model: entrants, incumbents, and renewable firms. Rather than having distinct categories for entrants and incumbents, we choose to place fossil fuel companies on a continuum according to their existing production capacity—to avoid defining an arbitrary cutoff for an incumbent. We merge the constructed NYT news indices with individual stock data from the Center

Table 10: Data Description and Sources

Variable	Description	Source	Frequency	Processing
CL.hh	WTI crude oil futures *hh*-month contract (settlement price)	Bloomberg	Daily	End of week/month % change
CPIAUCSL	U.S. CPI for all urban consumers: all items	FRED	Monthly	% change
GDPC1	U.S. Real Gross Domestic Product	FRED	Quarterly	% change
M1SL	M1 money supply	FRED	Monthly	% change
M2SL	M2 money supply	FRED	Monthly	% change
CFNAI	Chicago Fed National Activity Index	Chicago FED	Monthly	constructed to be stationary
IGREA	Kilian's (2009) index of global real economic activity	Dallas FED	Monthly	constructed to be stationary
LW.hh	*hh*-month zero-coupon treasury yields by Liu and Wu (2021)	Wu's webpage	Daily	End of week/month % change
OECD ConsChg	OECD liquid fuel consumption change	EIA	Quarterly	

Note: Table provides descriptions, sources, and the frequency of the variables utilized in our study of oil futures prices (Section 3.3). The last column details the processing methods applied to convert raw data into the variables used in our analysis.

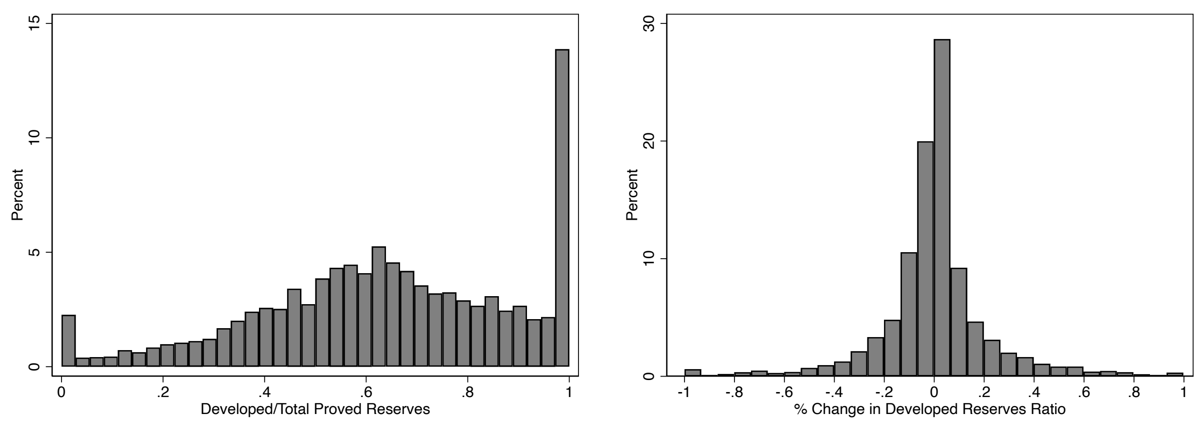
for Research in Security Prices (CRSP) and Global Industry Classification Standard (GICS) industry codes for firms from Compustat. For fossil fuel firms, we focus on integrated oil companies engaged in the exploration and production of oil and gas (GICS codes 10102010 and 10102020), excluding manufacturers of drilling equipment (GICS code 10101020), drilling contractors (GICS code 10101010), oil marketing (GICS code 10102030), and storage and transportation companies (GICS code 10102040) that are not directly involved in oil production.

To obtain our continuous classification of existing production capacity, we compute a proved developed reserves ratio by dividing the dollar amount of proved developed reserves for oil, natural gas, and natural gas liquids by the dollar amount of total proved reserves for these resources. We obtain the proved developed reserves and total proved reserves from the Industry Specific Annual section of Compustat. This ratio indicates the extent to which a firm has capitalized on its reserves: firms with a higher ratio have developed more of theirs, suggesting they have established operations and are more similar to incumbents in our model. Conversely, firms with a lower ratio have not yet build the infrasturcture to develop a large fraction of the reserves that they own, and are more similar to entrants in our model. Figure 8 shows the histogram of developed reserves ratio.

Figure 8: Distribution of Developed Reserves Ratio

(a) Developed Reserves Ratio

(b) % Change in Developed Reserves Ratio



Note: The left panels show the distribution of ratios of developed/total reserves (reported annually). The right panels instead report the distribution of annual percentage change in the developed reserves ratio by firms. Rare extreme changes (i.e., above 100% and below -100%) are excluded.

For renewable firms, we use the holding firms of the Invesco Solar ETF and the First Trust Global Wind Energy ETF, which includes companies in the solar and wind energy industry respectively. We use these ETFs to categorize 19 companies listed on U.S. stock exchanges as renewable companies.

To implement the test, we measure innovations in each of the emission cost, renewable technology breakthrough probability, and oil capacity news by constructing values of each as residuals from the following weekly AR(1) model:

$$\text{Idx}_{k,t} = \alpha_k + \varphi_k \text{Idx}_{k,t-1} + \nu_{k,t},$$

where $\text{Idx}_{k,t}$ is index k at week T and $\nu_{k,t}$ represents the AR(1) innovations of index k at week T. We scale the residuals by their standard deviation. We then run the following regressions to observe the stock prices reactions of different types of firms on each news index:

$$R_{i,t} = \alpha_k + \gamma_i + \beta_{1,k}\nu_{k,t} + \beta_{2,k}\nu_{k,t}\text{Fos}_i + \beta_{3,k}\nu_{k,t}\text{Fos}_i\text{DevRat}_{i,t} + \beta_{4,k}\nu_{k,t}\text{Ren}_i + \epsilon_{k,i,t},$$

where $R_{i,t}$ is the market-hedged return of stock i at week T, and γ_i represents firm fixed effects. We hedge the market exposure of each stock by computing a rolling 3-year market beta for each firm. $\nu_{k,t}$ is the AR(1) innovations of index k (the NYT-Emission Cost News Index the NYT-Renewable Breakthrough News Index, or the NYT-Oil Capacity News Index) at week T. We focus on AR(1) innovations because returns should reflect the unexpected component of the news, though the results are similar if we include the index directly instead of the innovations. We scale the residuals by their standard deviation. We include the interaction of the index with dummies for fossil fuel companies (Fos_i) and renewable companies (Ren_i). Finally, we include in the regression the interaction of the index with the fossil fuel dummy and the developed ratio of firm i at time T ($\text{DevRat}_{i,t}$). Table 2 reports the results from the regression.

E.4 Robustness

In this section, we include several robustness tests on filtering articles, aggregating article-level GPT responses to the weekly level, and regression specifications. We constructed the news indices by summing the products of direction and importance responses. Table 11 presents versions for other scaling methods: direction only, direction scaled by signal strength, and direction scaled only by importance. We also include a version using the first principal component while combining indices instead of taking the arithmetic average. The results are consistent across scaling methods.

We obtained our results in Table 2 by adding section filtering for 9 of the 10 most frequent sections in the New York Times, using a 3-year rolling window for each firm to remove market influences, and using the total developed ratio of fossil fuel firms. Table 12 presents versions of our regression without section filtering, using a 5-year rolling window to remove market beta, and using the oil developed ratio, defined as the ratio between the dollar amount of developed reserves for oil and the dollar amount of total proved reserves for oil, obtained from Compustat. We find that our results are directionally consistent across all regression specifications, with varying levels of statistical significance.

Table 11: Stock Returns and NYT Index - Robustness (Scaling Methods)

	Cost of Emission				Renewable BT				Oil Capacity		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Fossil Fuel Company × Index AR(1) Innovation	-0.0059***	-0.0055***	-0.0053***	-0.0055***	-0.0049***	-0.0052***	-0.0053***	-0.0053***	-0.0050**	-0.0050**	-0.0050**
	(0.0020)	(0.0019)	(0.0020)	(0.0019)	(0.0014)	(0.0014)	(0.0015)	(0.0015)	(0.0023)	(0.0023)	(0.0023)
Developed Ratio × Index AR(1) Innovation	0.0068**	0.0072**	0.0068**	0.0073**	0.0111***	0.0114***	0.0115***	0.0115***	0.0074*	0.0074*	0.0074*
	(0.0029)	(0.0028)	(0.0029)	(0.0028)	(0.0023)	(0.0023)	(0.0024)	(0.0024)	(0.0038)	(0.0039)	(0.0039)
Renewable × Index AR(1) Innovation	0.0021**	0.0021**	0.0019*	0.0020**	0.0006*	0.0007*	0.0007**	0.0007**	0.0023*	0.0023*	0.0023*
	(0.0010)	(0.0010)	(0.0009)	(0.0010)	(0.0003)	(0.0004)	(0.0003)	(0.0003)	(0.0012)	(0.0012)	(0.0012)
Company FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Section Filtering	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Remove Market from Stock Returns	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Specification	Dir	Dir×Str	Dir×Imp	Dir×Str×Imp, PCA	Dir	Dir×Str	Dir×Imp	Dir×Str×Imp, PCA	Dir	Dir×Str	Dir×Imp
R^2	0.525	0.512	0.510	0.512	0.553	0.551	0.551	0.550	0.507	0.507	0.507
Observations	46805	46805	46805	46805	46805	46805	46805	46805	46805	46805	46805

Note: This is a robustness table of Table 2. Regressions (1)-(4) show coefficients of regressing stock returns on AR(1) innovations of NYT-Emission Cost News Index interacted with dummies indicating fossil fuel and renewable firms, as well as the interaction between the fossil fuel dummy and the developed ratio, controlling for firm fixed effects. Regressions (5)-(8) instead show coefficients of regressing stock returns on AR(1) innovations of NYT-Renewable Breakthrough News Index, and regressions (9)-(11) show coefficients of regressing stock returns on AR(1) innovations of NYT-Oil Capacity Index. We removed market influences from stock returns by computing the market beta via a 3-year rolling window for each firm, then subtracting the beta times the market returns from firms' stock returns. We only include 9 of the top 10 most frequent sections: "business financial", "national", "foreign", "metropolitan", "science", "climate", "us", 'editorial", "business". We focus on energy firms in these regressions. The news indices were constructed by scaling direction based on the news's importance to market prices and oil industry operation strategies. This table includes several scaling methods: direction only ((1), (5) and (9)); direction scaling by signal strength ((2), (6) and (10)); and direction scaling by importance ((3), (7) and (11)). In the main table, we combined multiple indices by taking their arithmetic average to obtain our indices. In this robustness table, versions using the first principal component are included in (4) and (8). Standard errors are in parentheses and are clustered at the company level. Significance levels: * (p<0.10), ** (p<0.05), *** (p<0.01).

Table 12: Stock Returns and NYT Index - Robustness (Regression Specifications)

	Cost of Emission			Renewable BT			Oil Capacity		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Fossil Fuel Company × Index AR(1) Innovation	-0.0052***	-0.0068***	-0.0053**	-0.0055***	-0.0068***	-0.0058***	-0.0044***	-0.0042*	-0.0040*
	(0.0019)	(0.0022)	(0.0022)	(0.0016)	(0.0017)	(0.0019)	(0.0013)	(0.0024)	(0.0024)
Developed Ratio × Index AR(1) Innovation	0.0076**	0.0082***	0.0069**	0.0072***	0.0114***	0.0122***	0.0099***	0.0065	0.0060
	(0.0032)	(0.0031)	(0.0032)	(0.0023)	(0.0026)	(0.0028)	(0.0021)	(0.0040)	(0.0041)
Renewable × Index AR(1) Innovation	0.0023*	0.0025**	0.0022*	0.0020**	0.0005	0.0007	0.0007**	0.0023**	0.0019
	(0.0012)	(0.0010)	(0.0012)	(0.0010)	(0.0005)	(0.0005)	(0.0003)	(0.0011)	(0.0012)
Company FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Section Filtering	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Market Removal from Stock Returns	3y	5y	3y	3y	5y	3y	3y	5y	3y
Developed Ratio Type	Total	Total	Oil	Total	Total	Oil	Total	Total	Oil
R^2	0.504	0.535	0.472	0.507	0.524	0.520	0.537	0.501	0.459
Observations	46328	46805	41591	46328	46805	41591	46328	46805	41591

Note: This is a robustness table of Table 2. Regressions (1) and (2) show coefficients of regressing stock returns on AR(1) innovations of NYT-Emission Cost News Index interacted with dummies indicating fossil fuel and renewable firms, as well as the interaction between the fossil fuel dummy and the total developed reserves ratio, controlling for firm fixed effects. Regression (3) shows coefficients of the same regression specifications, instead using the oil developed reserves ratio. Regressions (4)-(6), and Regressions (7)-(9) follow a similar pattern, instead showing coefficients of regressing stock returns on AR(1) innovations of NYT-Renewable Breakthrough News Index and on AR(1) innovations of NYT-Oil Capacity Index respectively. Except for in Regressions (2), (5) and (8), we removed market influences from stock returns by computing the market beta via a 3-year rolling window for each firm, then subtracting the beta times the market returns from firms' stock returns. Except for in Regressions (1), (4) and (7), we only include 9 of the top 10 most frequent sections: "business financial", "national", "foreign", "metropolitan", "science", "climate", "us", 'editorial", "business". We focus on energy firms in these regressions. In Regressions (1), (4) and (7) no section filter is applied before running the empirical analysis. In Regressions (2), (5) and (8) we computed the market beta via a 5-year rolling window for each firm, and then subtracted the beta times the market returns from firms' stock returns. In Regressions (3), (6) and (9), we used the oil developed ratio as the regressor, defined as the ratio between the dollar amount of developed reserves for oil and the dollar amount of total proved reserves for oil. Standard errors are in parentheses and are clustered at the company level. Significance levels: * (p<0.10), ** (p<0.05), *** (p<0.01).