CLIMATE TRANSITION RISKS AND THE ENERGY SECTOR [*]

Viral V. Acharya Stefano Giglio Stefano Pastore
Johannes Stroebel Zhenhao Tan Tiffany Yong

Abstract

We build a general equilibrium model to study how climate transition risks affect energy prices and the 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 potentially extract tomorrow. There are also renewable energy firms that produce emission-free energy but cannot currently serve 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 economic sectors; (ii) changes in expected future taxes on carbon emissions; and (iii) restrictions on today's development of additional fossil fuel production capacity. We show that the different transition risk—and, importantly, *uncertainty* about their realizations—have distinct effects on firms' decisions, on their valuations, and on equilibrium energy prices. We provide empirical support for the 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, policy uncertainty, fossil fuel firms, brown firms, carbon tax, drilling restrictions, oil prices

JEL: E31, Q35, Q38, Q43, Q54, Q58.

---

[*] This version: January 20, 2025. Acharya: NYU Stern, CEPR, ECGI and NBER (vva1@stern.nyu.edu). Giglio: Yale SOM, CEPR and NBER (stefano.giglio@yale.edu) Pastore: NYU Stern (spastore@stern.nyu.edu). Stroebel: NYU Stern, CEPR and NBER (johannes.stroebel@nyu.edu). Tan: Yale SOM (zhenhao.tan@yale.edu). Yong: NYU Stern (tiffany.yong@stern.nyu.edu). We thank Richard Berner, Robert Engle, Chitru Fernando (discussant), Chester Spatt (discussant), and seminar participants at various seminars and conferences for helpful suggestions. We are grateful for financial support from the Tobin Center for Economic Policy at Yale University and the Volatility and Risk Institute at NYU Stern.

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 considered and sometimes employed a range of tools, including carbon prices, R&D subsidies for renewable energy, and restrictions on the development of new fossil fuel capacity. This paper explores the effects of these policies, including the effects of *uncertainty* about their future implementation, on the dynamics of prices, inventories, investment, production, and valuations in the energy sector. We find that the different policies—while often jointly referred to as "climate transition risks"—can have meaningfully different implications for these equilibrium outcomes.

We build a two-period general equilibrium model to understand the effects of different climate transition risks on the energy sector (our model periods can be thought of as about a decade apart). We model two types of fossil fuel firms: (i) incumbents with developed reserves that can be extracted at low cost either today or tomorrow, and (ii) new entrants that need to invest today to develop reserves for possible extraction tomorrow.[1] In addition, there are renewable energy firms that invest in capacity today—say by building a wind farm or a solar park—to produce emissions-free energy at zero marginal cost tomorrow. With current technologies, the ability of renewable energy firms to power the economy is limited both by the intermittency of renewable supply—the sun doesn't always shine, and the wind doesn't always blow—and by the fact that many sectors of the economy are hard to electrify. This means that with current technologies, some share of future economy-wide energy demand will need to be supplied by fossil fuel firms, irrespective of the total capacity of renewable firms.

We consider three sources of climate transition risk: (i) restrictions on developing new fossil fuel production capacity; (ii) the possible introduction of future taxes on carbon emissions; and (iii) the possibility of technological breakthroughs in storage and electrification that improve renewable energy firms' ability to meet a larger share of future economy-wide energy demand. Each transition risk has a different effect on energy prices and valuations across the various parts of the energy sector. We first study the various transition risks separately before developing a rich model to consider them jointly.

Key Mechanisms. First, consider the effects of a (time-0) restriction on *new* fossil fuel capacity, which can be analyzed largely by considering only the interaction between incumbent and newly entering fossil fuel firms. Reduced investment in additional fossil fuel capacity today—for example, due to restrictions on the availability of new oil leases—limits the supply of fossil fuels tomorrow and thus puts upward pressure on future (time-1) energy prices. The anticipation of these higher future energy prices leads incumbent fossil fuel producers to delay exploiting some of their existing developed reserves, reducing extraction today and increasing it tomorrow. This inter-temporal inventory management raises today's equilibrium energy prices, leading to what the European Central Bank's Isabel Schnabel (2022) called "fossilflation." This mechanism generates heterogeneous predictions for firm values across the energy sector. Higher energy prices today and tomorrow raise the value of the existing production capacity of incumbent fossil

---

[1] In practice, new exploration is often also done by incumbents. Separating the problem of when to extract already developed reserves from the problem of how many new reserves to add allows us to build insights into how various transition risks might differentially influence firms with more developed vs. undeveloped reserves, a distinction that allows us to tie our theory to the data. In particular, in our empirical tests we place energy firms on a continuum between pure entrants and pure incumbents based on the structure of their reserves.

fuel firms, thus raising their valuations. Renewable energy firms also have higher valuations, since they now face less competition from fossil fuel producers tomorrow. At the same time, restrictions on new capacity development reduce valuations of fossil fuel entrants.[2]

The second policy we analyze is the possible introduction of a carbon tax, which we model as a tax on the sale of fossil fuel-based energy. Whereas the drilling restrictions described above take place at time 0 (so there is no uncertainty about them), the possible introduction of a future carbon tax can be uncertain: in our model, we assume that the carbon tax is introduced in period 1 with probability p_T. We call T the state of the world where the carbon tax is introduced, and NT the state of the world with no carbon tax. The effect of changes in the carbon tax rate on energy prices is nonmonotonic, and depends on the initial level of the tax.

Suppose first that the initial expected state-T tax is zero. This, of course, is the same as the baseline case with no carbon tax. Just as in the baseline, it is optimal for the incumbent to always exhaust its full remaining reserves in period 1: if any inventory ended up being "stranded" in period 1—which would happen in both states of the world, since they are identical at zero taxes—the incumbent would prefer extracting and selling it today.

Now consider an increase in the T-state tax from zero to a (small) positive number. This tax results in a decline in expected post-tax state-T energy prices, and the associated reduction in expected profits leads fossil fuel entrants to install less new capacity. This decline in capacity investment actually causes expected prices in the NT state to *increase*, since there is now less supply but, by definition of the NT state, no taxes. Overall, expected post-tax prices in period 1—given by a probability-weighted combination of post-tax prices in the T and NT states—fall after an increase in state-T carbon taxes. Incumbents respond to this decline in expected period-1 post-tax prices by extracting more oil in period 0, so that oil prices today also fall. This is a version of the classic "green paradox", whereby expectations of higher future carbon taxes actually lead to more emissions today (Sinn, 2008). The valuations of both incumbents and new entrants fall as the expected tax increases, while those of renewable firms increase.

But now consider further increases in the expected state-T carbon tax rate, which would lead to further declines in the expected post-tax state-T price. At some point, the tax rate will reach a level τ_{strand} such that the resulting post-tax price is below the marginal cost of extracting the incumbent's full reserves in the T-state (at τ_{strand} it remains profitable for the entrant to extract all reserves, since its marginal cost of extracting the last unit of reserves is lower). What will the incumbent do at this point? It could leave the marginally unprofitable oil "stranded" in state T—simply never extracting that oil—or it could decide to extract more oil at time 0 and thus arrive in period 1 with fewer reserves.

As discussed above, if there was no uncertainty about the implementation of period-1 carbon taxes, it would never be optimal to leave some oil stranded in that period with certainty as long as it could be profitably extracted and sold today. But when carbon tax policy is uncertain, there is also a no-tax state NT in which an incumbent can continue to extract its full inventory. If expected prices in that state are high enough and the state is sufficiently likely, incumbents might be willing to carry more inventory into period 1 than what they might be able to profitably

---

[2] Incidentally, our model highlights how policies aimed at *reducing* restrictions on new oil supply—including policies proposed by the new Trump administration—are not necessarily positive for incumbent producers, as they can put downward pressure on oil prices. Consistent with this conclusion, 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 Morenne and Eaton (2024), "Trump's Oil and Gas Donors Don't Really Want to 'Drill, Baby, Drill'", November 22nd, 2024).

extract in state T. In other words, even if the marginal unit carried into period 1 is stranded in state T, it can still be sold in state NT, giving an expected period-1 revenue of $(1 - p_T)P_{NT}$ for a marginal unit of inventory, which may be more attractive than extracting the unit today.

A key insight from our model is that after the state-T tax reaches τ_{strand}, further increases in the tax rate actually make it desirable for the incumbent to carry *more* inventory into period 1, even if those additional reserves will also be stranded if state T materializes. This is because of the interaction of two forces. First, since for $\tau > \tau_{strand}$ the incumbent's marginal inventory is always stranded in state T, further increases in the tax have no direct effects for the incumbent's decision: on the margin, the incumbent only responds to changes in expected prices in state NT. Second, as described above, higher taxes continue to reduce new entrants' incentive to build capacity, and therefore lead to a higher price in the NT state, thus raising the incentives for the incumbent to carry reserves into period 1. As a result, for $\tau > \tau_{strand}$, equilibrium energy prices today actually increase in τ. Higher taxes continue to reduce the *valuations* of all fossil fuel firms, though this drop in valuations is attenuated for incumbents relative to new entrants.

Another way to think about this mechanism is through the lens of real options. The incumbents' inventory has a real option component in that, if state-T taxes are too high, the incumbent can decide not to extract the oil and let it be stranded; but if state NT occurs, it can make large profits from extracting and selling oil due to less competition from new entrants. For this effect to operate, *uncertainty* in the carbon tax is crucial, since it is that uncertainty that gives value to the optionality. Uncertainty thus affects the "green paradox": whereas higher *certain* carbon taxes always induce more extraction and lower prices today, higher carbon taxes that will be implemented *only with some probability* can have the opposite effect.

Finally, consider the effects of the third type of transition risk, the possibility of a technological breakthrough in renewable energy (assume for simplicity that there are no carbon taxes or restrictions on drilling). To model this transition risk, we introduce renewable energy firms that need to invest in capacity today to provide clean energy in the future. With some probability p_{BT}, a technological breakthrough occurs that allows renewable firms to provide energy to all sectors of the economy at time 1; we denote this scenario as Breakthrough Technology (BT) state. With probability $1 - p_{BT}$ no such breakthrough occurs, and renewable firms can provide energy (together with fossil-fuel firms) to only a share q of total time-1 energy demand, perhaps because renewable supply is intermittent or because many economic sectors are not electrifiable. In this Current Technology (CT) scenario, these non-electrifiable sectors will be entirely served by fossil fuel companies. Without loss of generality, consider the case $q = 0$, such that absent a technological breakthrough, renewable firms cannot supply any energy.

Changes in the possibility of a technological breakthrough p_{BT} are a key source of transition risk. As p_{BT} increases, renewable companies expand their capacity at time 0 to increase their supply in the BT state; this reduces equilibrium BT-state prices. As a result, fossil fuel entrants reduce their own capacity investments, and incumbents extract more of their reserves today, leading to a fall in energy prices today. Valuations of renewable firms increase, while valuations of fossil fuel firms fall, though with smaller declines for incumbents than for new entrants.

Similar to the case of the carbon tax, uncertainty about the technological breakthrough can also induce additional effects through a real options channel. Specifically, if the cost of installing renewable capacity is sufficiently low, there is so much investment from renewable firms that it becomes unprofitable for the fossil fuel incumbent to extract the full inventory in the BT state. Therefore, once again, some of the incumbent's oil reserves can become stranded. At that point, further price changes in the BT state do not influence the marginal inventory decision by the incumbent, which are entirely determined by the price of energy in the CT state. Therefore, for some regions of the parameter space, increases in p_{BT} can lead to higher prices at time 0 (and an increase in time-1 inventories) in anticipation of high profits in the CT state, paralleling our results for the carbon tax.

At a general level, our model therefore highlights that many of standard intuitions about the effects of transition risk (like the "green paradox") become substantially more nuanced when considering the effects of *uncertainty* about risk realizations on the decisions of firms that have the real option to leave some oil capacity stranded in states with negative risk realizations.

Full Model. After exploring the effects of each type of transition risk separately, we develop a model that jointly includes all three sources of transition risk and allows renewable firms to provide energy to parts of the economy in the Current Technology scenario (i.e., we generalize our model to $q > 0$). To reduce the dimensionality of the state space, 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 "technological breakthrough" states of the world in which renewable firms can supply substantial amounts of energy. This is the case since carbon taxes in those states can reduce emissions without substantial negative effects on energy prices and economic activity.

We therefore simplify the full model by considering two states of the world: one in which the technological breakthrough occurs and carbon taxes are high, and one in which 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; it also allows us to analyze how the various transition risks affect the difference between energy prices for firms who can use renewable energy in the Current Technology scenario, and those that have to rely on fossil fuels for their energy demand. We find that all types of transition risk amplify the difference between prices across the two markets, by encouraging investments in renewable energy production capacity and reducing fossil fuel supply.

Our model provides several testable implications for how oil prices and the stock prices of different energy-sector firms should move in response to news about different climate transition risks, as summarized in Table 1. 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. The valuations of renewable energy firms should increase. 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 ('entrants') but may even raise the valuation of companies with large existing reserves ('incumbents').

Finally, our model highlights uncertain and complex effects of news about carbon prices and breakthrough probabilities on energy prices, while suggesting that energy prices would rise upon the imposition of restrictions on new capacity development.

Empirical Results. We empirically test these implications by studying the reactions of oil futures prices and of equity valuations in different energy sub-sectors to news about different climate transition risks. To achieve this, we construct high-frequency transition news indices by analyzing news reported in the New York Times (NYT) using GPT-4o Mini, an advanced large language model (LLM) developed by OpenAI. 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

Table 1: Summary of model predictions.

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

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, and actual technological advancements in these fields; 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 indices. In Panel A, 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. In Panel B, 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, the unveiling of affordable zinc air batteries in 2018, and China scaling up production of sodium batteries in 2023. In Panel C, the NYT-Oil Capacity News Index spikes around regulations related to fossil fuel production, like the review of the Keystone XL oil pipeline in 2017 (negative spike indicating fewer restrictions) and its permit revocation in 2021 (positive spike indicating more restrictions).

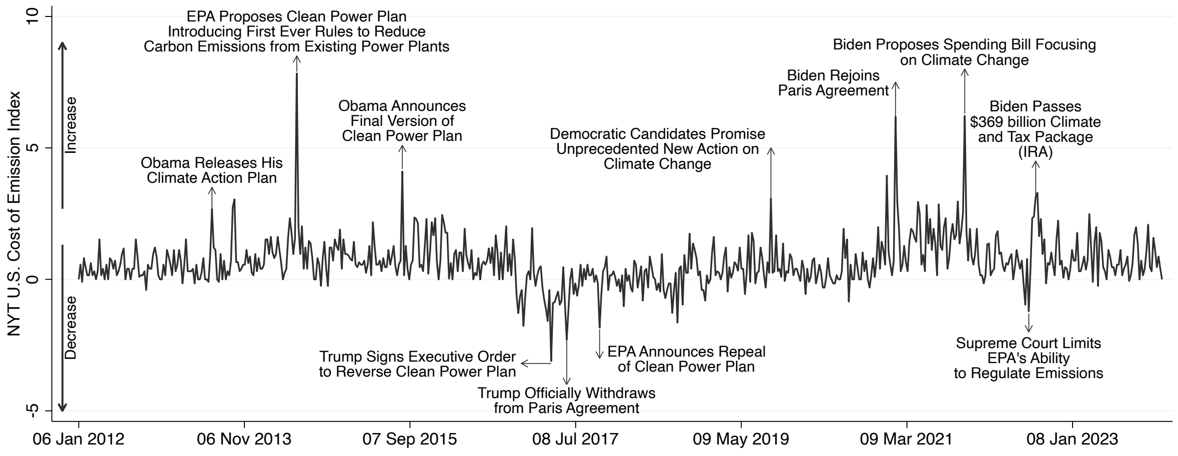
We then study the response of energy prices and stock returns of energy firms to innovations in these news indices. For our stock-price analysis, we identify two groups of firms: fossil fuel firms and renewable energy firms. For each fossil fuel firm, we measure its "developed ratio", the share of its oil reserves that are already developed.[3] 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.

---

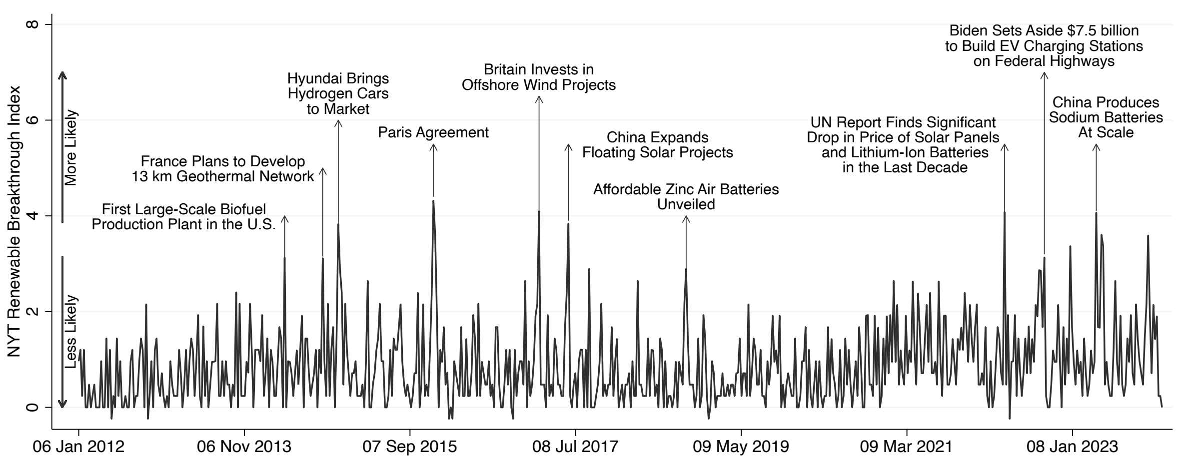
[3] Chevron's 10-K statement provides the following definitions: *"Proved developed reserves represent volumes expected to be recovered through existing wells with existing equipment and operating methods. Proved undeveloped reserves are volumes expected to be recovered from new wells on undrilled proved acreage, or from existing wells where a relatively major expenditure is required for recompletion."*

Figure 1: Time-Series of NYT News Index

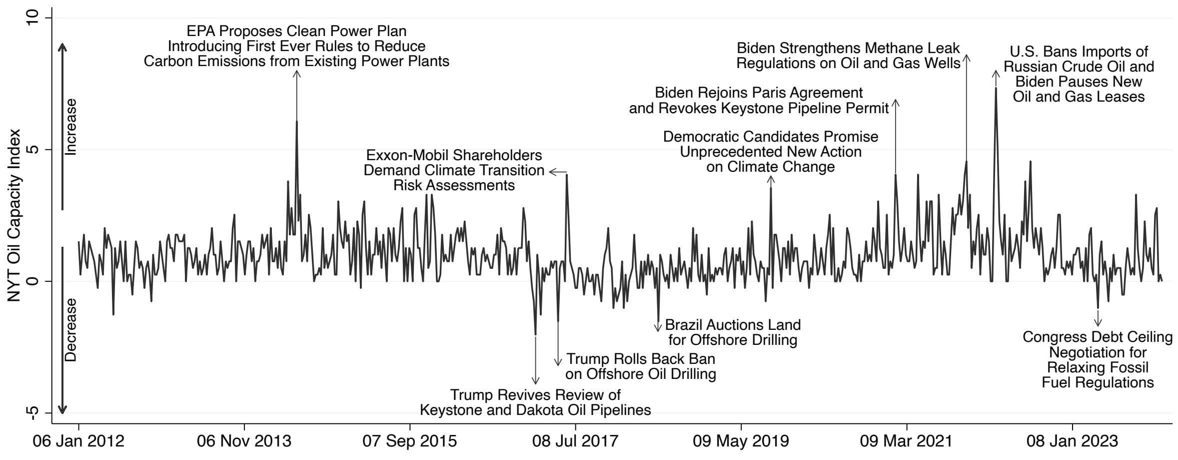
(a) NYT-Emission Cost News



(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.

We find that, consistent with the theory, renewable energy companies earn positive returns in weeks with news about each of the three types of transition risks, whereas fossil fuel companies generally have negative returns in those weeks. Consistent with the model predictions, we also observe differential price movements for fossil fuel firms depending on their developed ratios: news about all three types of transition risks leads to larger price declines for firms with more undeveloped vs. developed reserves. Overall, these results highlight how transition risk realizations have heterogeneous effects on different types of fossil fuel firms.

Oil future prices are more noisy and driven by macroeconomic factors besides transition risk news. Nevertheless, we find that, consistent with our model, oil futures prices decrease during months with news about possible renewable energy breakthroughs. They increase in months with news related to increasing cost of carbon emissions (consistent with an expectation that some oil capacity will be stranded in the high-tax state of the world). Oil futures prices do not generally move in a statistically significant manner with news about changes in oil capacity.

Related Literature. Our paper belongs to the growing literature on climate finance, recently reviewed by Giglio et al. (2021), with a particular focus on the implication for energy firms (see van Benthem et al., 2022). While we focus on studying the effects of climate transition risks on the energy sector 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 the effects of transition risks on firm valuations, Alekseev et al. (2022) find that energy firm stocks are not consistently negatively affected by generic climate transition news (see also Hong et al., 2019; Bolton and Kacperczyk, 2021; Engle et al., 2020, for related work studying the stock price effects of climate risks). Connecting these lines of research, 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. We also relate to empirical work by Adolfsen et al. (2024), who show that fossil fuel firms 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) highlight that policymakers should adopt a macroeconomic perspective that takes general equilibrium effects into account when analyzing the effects of climate policies. 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, which might have the effect of reducing energy supply today. Our model features similar forces, but also shows that technological developments in the renewable energy sector can instead push down the current price of energy. Barnett (2023) reaches the related 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 provides a nuanced view on the possible relationship between changes in expected transition risk realizations and energy prices, and highlights the importance of transition uncertainty in driving these effects.

A growing theoretical literature also studies the effects of climate transition risks 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 optimal carbon taxes should depend on the extent of a breakthrough technological development in the renewable energy sector. Furthermore, we also analyze the energy price implications of taxes on newly installed fossil fuel production capacity.

1 Two-Period Climate Transition Risk Model

We start by building and describing a simple two-period general-equilibrium model of the energy sector. We gradually introduce each of the three transition risks that we study to clearly isolate their implications on energy prices and firm valuations. In particular, we start by studying drilling restrictions in a model with no renewable energy sector and no uncertainty about the future. In the next step, we introduce the possibility of future carbon taxes. We first study the effects of such taxes that will be implemented with certainty, before introducing uncertainty about their future implementation. Then, we investigate the effects of a possible technological breakthrough that allows green firms to supply energy to the entire economy. We close this section by studying optimal carbon taxes in our framework. In the subsequent section, we present 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 Without Renewable Energy Firms

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 with developed reserves that can be extracted today or tomorrow, and a new entrant that needs to invest today to build capacity to extract tomorrow. We investigate the effects on energy prices of a time-0 tax on the creation of new fossil fuel capacity by the entrant firm, $\bar{\tau}_0$. This tax could correspond to a range of actual policies, including increasing the cost of new drilling or making fewer new oil leases available; it can also capture an increase in the cost of capital for fossil fuel exploration.

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

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

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

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

The other producer in the economy is a representative fossil-fuel 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 new 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. Production costs in period 1 are the same as for the incumbent firm. The fossil fuel entrant therefore chooses its capacity investment in period 0 and its production in period 1 $(\bar{f}_1^E, f_1^E)$ by solving:

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

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

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

We close the model by introducing a unit mass of consumers with strictly concave utility u from energy consumption. In each period, 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 equal to $\frac{W}{P_t}$, giving us 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. Throughout the paper, we make the following assumption.

Assumption 1. *The initial production capacity of the incumbent fossil fuel firm, $\bar{f}_0^I$, is not so large that the firm is unconstrained in both periods.*

This assumption suggests that, absent any transition risk realizations, the incumbent firm expects to extract its full remaining reserves at the period-1 equilibrium price, setting up an interesting trade-off between the choice of extracting today or tomorrow.

1.2 Effects of Drilling Restrictions

In this section, we are interested in studying the effect that drilling restrictions have on firm valuations and energy prices. We derive the following result.

---

[4] In practice, new oil 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.

Proposition 1. *Increases in drilling restrictions (higher $\bar{\tau}_0$) 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 date-0 price of energy. Increases in drilling restrictions reduce profits for the entrant but increase them for the incumbent.*

The intuition is the following. Restrictions on the development of new fossil fuel capacity only affect the entrant firm directly: given higher costs of installing new capacity, it reduces its investment in period 0. The incumbent firm 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 shift production capacity to period 1. This increases the period-0 energy price.

Drilling restrictions reduce expected profits for the entrant who has to pay $\bar{\tau}_0$. The incumbent instead benefits from the reduced future competition by the entrant in period 1, and its expected profits thus increase. Therefore, Proposition 1 predicts that news about increased drilling restrictions should have a negative effect on the stock prices of oil and gas firms with little existing capacity—those firms who would still need to invest to develop their current reserves—while firms with large developed reserves can even see their stock market valuations increase due to reduced competition from entrants in the product market.

While we will formally test these predictions in the second part of the paper, it is worth highlighting that they are highly consistent with recent discussions around the possible effects of expected *reductions* in constraints on the creation of future oil capacity by the incoming Trump administration (which would correspond to a lower $\bar{\tau}_0$). 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"* (Lee, 2024a). It also 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"* (Lee, 2024b). These articles crucially highlights how restrictions on new drilling can affect incumbents and new firms differentially in ways that are highly consistent with our theoretical framework.

1.3 Model with certain carbon taxes

The second source of transition risk we consider is the possible introduction of a carbon tax. To establish a benchmark, we first consider a tax that is implemented with certainty in the future, and study its effects on the energy sector. In particular, we assume that a tax τ_1 is implemented in period 1, so that fossil fuel producers now only earn $(1-\tau_1)P_1$ from selling an additional unit of energy in period 1. We derive the following result.

Proposition 2. *Increases in carbon taxes implemented with certainty in period 1 cause a reduction in the newly installed production capacity by fossil fuel entrants, as well as a reduction in the fossil fuel capacity carried into the future as inventory by incumbents. As a consequence, the incumbent increases its date-0 energy supply, which reduces the date-0 price of energy. Expected profits of both incumbents and entrants decline.*

This Proposition highlights that if fossil fuel firms expect the introduction of carbon taxes with certainty in the future, then they will have the incentive to increase current energy supply, as the carbon tax will reduce future profits. As period-0 supply increases, current energy prices decline. Our result is therefore a version of the "green paradox" that has been discussed in the literature, in which expectations about future climate policies can induce the fossil fuel sector to raise current production, and thus to increase present-day carbon emissions. In the next section, we show how this result crucially relies on the expectation that the carbon tax will be implemented with certainty. Introducing uncertainty can induce existing fossil fuel companies to modify their production and inventory decisions in interesting ways.

1.4 Model with uncertain carbon tax

We now introduce a carbon tax that is implemented only with some probability in the future. Specifically, 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, in which case a carbon tax τ_1 is introduced on fossil fuel firms' revenues. Demand for energy is the same across the two states, and thus the only difference between the states is the carbon tax. The Appendix provides more details about the updated problem of fossil fuel firms and the solution of this model. Throughout the paper, we make the following realistic assumption.

Assumption 2. *In period 1, the incumbent has a higher marginal cost of extracting its last unit of reserves than the entrant has.*

Since our model assumes that incumbents and entrants have the same convex marginal cost curve of extracting developed reserves, Assumption 2 corresponds to the entrant arriving in period 1 with fewer developed reserves than the incumbent, a condition that will hold if $\bar{f}_0$ is sufficiently large. Assumption 2 could also be microfounded from alternative realistic assumptions in a richer model. For example, some of the incumbents' capacity was installed at times in which oil prices were expected to be higher for longer, and therefore includes fields such as the Canadian tar sands with extraction technologies such that marginal oil extraction is only profitable at relatively higher prices (Heyes et al., 2018). New entrants, aware of the possibility of carbon taxes and the climate transition, tend to focus their investment in new capacity on fields with lower marginal cost of extraction, often focusing on shale gas extraction that is profitable at lower oil prices (Rystad Energy, 2024). An alternative setup that incorporates these forces would also yield a lower marginal cost of extraction for new entrants. There is substantial evidence that, indeed, newly added capacity focuses on cheaper-to-extract oil: for example, consider the following quotes: *"Oil majors are now hedging their bets by targeting new oilfields that can be profitable even at $30 per barrel oil, reflecting executives' belief that high prices are anything but guaranteed"* (Kimani, 2024), and *"Rystad Energy's annual cost of supply analysis has revealed that costs within the upstream sector have come down considerably in 2021, making new oil more competitive and significantly cheaper to produce. The average breakeven price for new oil projects has dropped to around $47 per barrel—down around 8% over the past year and 40% since 2014"* (Rystad Energy, 2021).

We now show that carbon taxes implemented in the future with uncertainty can have non-monotone effects on current energy prices, including a reversion of the "green paradox."

Proposition 3. *The effect on date-0 energy prices of expected increases in a future carbon taxes* τ_1 *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* $\frac{dP_0}{d\tau_1} < 0$ *["Green Paradox"].*
- *For high enough values of the expected tax rate, further increases in the expected 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. Consider first the case where the tax is sufficiently small that both incumbent and new entrant fully exhaust their capacity in period 1 in both the T and NT states. In that case, the optimal period-0 fossil fuel supply by the incumbent is:

$$f_0^I = \frac{\bar{f}_0}{2} + \frac{\kappa_1}{2}\Bigg[P_0 - p_T(1-\tau_1)P_{1,T} - (1-p_T)P_{1,NT}\Bigg], \tag{7}$$

while optimal capacity installation by the entrant is:

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\Bigg[p_T(1-\tau_1)P_{1,T} + (1-p_T)P_{1,NT}\Bigg]. \tag{8}$$

These optimality conditions highlight that the decisions of both incumbent and new entrant depend on the probability-weighted average of the (post-tax) prices in state T, $(1-\tau_1)P_{1,T}$, and in state NT, $P_{1,NT}$. As the carbon tax increases, profits in state T (and thus expected profits in period 1) fall for both producers. As a result, the entrant's incentive to invest in new capacity and the incumbent's incentive to carry inventory into period 1 are reduced, leading to lower supply in period 1, similar to the case with the certain tax discussed in the previous section. The incumbents' decision to carry less inventory into period 1 corresponds to a decision to extract more developed reserves in period 0, leading to a fall in period-0 equilibrium prices. As discussed above, this behavior—having higher extraction and higher emissions today in anticipation of possible higher taxes tomorrow—is sometimes referred to as the "green paradox."

Now, suppose that the expected state-T tax rate continues to increase. This makes it less and less profitable for the incumbent to extract its full reserves in state T, up to the point where it becomes economically preferable to leave some oil in the ground—sometimes called leaving the marginal oil "stranded"—as opposed to extracting it (one can think about the decision to leave oil stranded as similar to not exercising a real option to extract it). This will happen when the post-tax price $(1-\tau_1)P_{1,T}$ is lower than the marginal cost of extracting the final unit of reserves. Note that because of Assumption 2, it is the incumbent (whose marginal cost for its last unit is higher) that will first choose to leave some inventory stranded. We refer to the tax rate at which the incumbent's last unit of period-1 reserves is stranded in state T as τ_{strand}.

When the tax rate reaches τ_{strand}, the optimality condition for the new entrant stays the same (equation 8), but the incumbent's level of optimal *marginal* oil extraction in period 0—and thus the decision of optimal inventory to carry into period 1—becomes:

$$f_0^I = \frac{1-p_T}{2-p_T}\bar{f}_0 + \frac{\kappa_1}{2-p_T}\Bigg[P_0 - (1-p_T)P_{1,NT}\Bigg]. \tag{9}$$

A key insight is that the incumbent's intertemporal inventory decision no longer directly depends on the tax rate τ_1 once $\tau_1 > \tau_{strand}$: since some reserves are already stranded in state T, further increases in τ_1 have no direct effect on the incumbents' *marginal* decision of whether to extract reserves today or carry them as inventory to tomorrow, though higher taxes will continue to strand additional *inframarginal* units of oil, which reduces the incumbent's total profits.

Interestingly, tax increases beyond τ_{strand} continue to have *indirect* general-equilibrium effects on the incumbents' period-0 extraction decision. Specifically, since higher taxes continue to induce the new entrant to reduce investment (see equation 8), they raise the equilibrium price in the period-1 state where the tax is not imposed, the NT state. This, in turn, actually raises the expected value of a marginal period-1 unit of reserves for the incumbent: its value in state T continues to be zero—the unit is still stranded and will not be extracted—but it can now be sold at higher expected prices in the NT state. This provides incentives for the incumbent to *increase* the amount of reserves to carry into period 1.

The net effect of these forces is that for sufficiently high levels of the carbon tax—those levels where some of the incumbent inventory will already by stranded in the T state—the time-0 energy price can actually *increase* in response to further increases in the expected tax rate. As this discussion highlights, the *uncertainty* about the implementation of the tax, combined with the competitive interactions between entrants and incumbents and the incumbent's real option to leave some developed reserves stranded, plays a central role in determining this nonmonotonicity, which effectively reverses the "green paradox" effect at high levels of expected carbon taxes τ in state T.

Despite the nonmonotonic effects of taxes on period-0 energy prices, the model suggests that both incumbent and newly entering fossil fuel firms will see declining valuations as expected taxes in the T-state increase—after all, higher taxes will strand more and more of the incumbent's inventory in state T, which reduces its value even if it does not directly affect its marginal extraction decision—with smaller effects for firms with larger existing production capacities. We will find support for this prediction in the data.

Generalization. The previous result assumes that the tax is exactly zero in the NT state. But an analysis of the economic forces involved (and discussed intuitively above) suggests that a carbon tax equal to zero in the NT state is not necessary in order to obtain our result. It is sufficient that one of the future states of the world is expected to have a lower carbon tax than the other, as long as it is still be profitable for the incumbent to fully exhaust its production capacity in that lower-tax state (consistent with Assumption 1). We derive the following result.

Proposition 4. *Consider a carbon tax rate equal to τ_1 implemented in the NT state, and a tax rate equal to $\tau_1 + \Delta$, $\Delta > 0$, implemented in the T state. Suppose that τ_1 and Δ are such that the incumbent firm fully exhausts its production capacity in the NT state only, while the entrant firm has no stranded assets in either state. Then, we have the following result:*

- *Increases in the carbon tax spread between the two states cause an increase in the date-0 energy price, that is $\frac{dP_0}{d\Delta} > 0$.*

The intuition behind Proposition 3 also applies here: higher taxes in the T-state discourage investment in production capacity by the entrant. The incumbent already expects its marginal inventory to be stranded in the T state, therefore its inventory decisions at the margin only depend on energy prices in the NT state. As the energy price in the NT state increases due to lower supply by the entrant, the incumbent firm raises its fossil fuel inventory to be carried into the future. This lowers current fossil fuel supply, and increases the period-0 energy price.[5]

---

[5] The effect on the period-0 energy price of changes in the tax level τ_1 in both states is, in general, uncertain. On the one hand, energy price in the NT state is higher because of the lower supply from the entrant, which induces the incumbent to increase its inventory. On the other, the higher tax reduces profits in the NT state, and this force induces the incumbent to reduce its future inventory.

1.5 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 the economy's full energy demand.

To explore the effects of such a technological breakthrough, we introduce a renewable energy firm that must invest in capacity today to potentially supply energy in the future. With probability p_{BT} a breakthrough technology is developed in period 1, which allows renewable energy firms to serve all sectors of the economy, and thus to compete with fossil fuel firms everywhere. Conversely, with probability $1-p_{BT}$, no such breakthrough happens, and renewable firms can only serve a fraction q of future energy demand. This captures the fact that current renewable technologies cannot currently serve some sectors of the economy: 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 energy demand can only be met via fossil fuels (see Gowrisankaran et al., 2016). This scenario is called the Current Technology (CT) state. For simplicity, we consider the case where $q = 0$, meaning that in the absence of a technological breakthrough, renewable firms are unable to supply any energy.[6]

The key choice of this renewable firm is how much production capacity to install in period 0, which can then (potentially) 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 do 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 state, $P_{1,BT}$, which is the only market where it is able to sell. The firm's problem is therefore:

$$\max_{C \geq 0} \; -\frac{1}{2\delta}C^2 + p_{BT} C P_{1,BT}, \tag{10}$$

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

$$C = p_{BT} \delta P_{1,BT}. \tag{11}$$

We derive the following result:

Proposition 5. *Suppose that both fossil fuel firms fully exhaust their production capacity in both states in period 1. Then, increases in the probability of the Breakthrough Technology state cause a reduction in the date-0 energy price. That is,* $\frac{dP_0}{dp_{BT}} < 0$.
If the incumbent fossil fuel firm fully exhausts its production capacity in the Current Technology state only (and thus has some stranded assets in the Breakthrough Technology state), then the effect of increases in the probability of the Breakthrough Technology state on the date-0 energy price is in general ambiguous. However, we have $\frac{dP_0}{dp_{BT}} < 0$ *as* $p_{BT} \to 1$.

The Breakthrough Technology state features lower profits for fossil fuel firms because of the competition from the renewable sector. If the difference in energy prices across states is not very large—perhaps because of limited capacity investment by renewable firms—then it is optimal

---

[6] In the richer model presented in the next section, we allow renewable energy firms to also supply *some* of the energy demand even with current technologies, but few additional insights derive from this complication.

for the incumbent firm to fully exhaust its inventory in both states. In that case, inventory decisions are made by taking into account the weighted average prices of energy across both the BT and the CT states, similar to equation (7) in the case of carbon taxes. As p_{BT} increases, renewable firms invest more in production capacity, as they expect to be able to sell in the future with higher probability. The expected energy price in the BT state therefore falls, because of the higher supply of clean energy. The probability of that state also increases. As a consequence, the incumbent's expected value of carrying inventory into the future falls, and it is thus optimal for this firm to increase energy supply in period 0, pushing down period-0 energy prices.

If instead the price difference across the two states is very large, perhaps due to the low cost of installing renewable capacity at date 0, this result can be overturned. As p_{BT} increases, the renewable firm installs more and more capacity. Eventually, the resulting energy price in the BT state falls so much that it is no longer profitable for the fossil fuel incumbent to extract its full reserves: similar to the case where the carbon tax is very high, some of the incumbent's oil reserves will be stranded in the BT state. Just like in the case of a high carbon tax (equation 9), the incumbent's marginal inventory decisions will no longer take into account the BT price, but will instead be based on the price in the CT state—the only state the incumbent is expecting to sell its marginal unit of inventory—multiplied by the probability of that state: $(1 - p_{BT})P_{1,CT}$.

Since the entrant's capacity investments continue to decline as p_{BT} increases, expected prices in the CT state actually increase as p_{BT} increases. As a result, the effect of increases in p_{BT} on the expected period-1 value of a unit of oil reserves to the incumbent, $(1 - p_{BT})P_{1,CT}$, is ambiguous. The key difference with the carbon tax case is that in the breakthrough technology case, the increase in the price the incumbent can obtain the CT state (which increases in p_{BT}) is offset by a decreasing likelihood of the CT state (which is $1 - p_{BT}$). We prove that for high enough p_{BT} the probability of the CT state is sufficiently low that even if energy prices in that state are increasing in in p_{BT}, it is optimal for the incumbent to reduce its future inventory.

As before, increases in p_{BT} generally lead to declining valuations for energy firms, with larger declines for entrants than for incumbents with developed reserves. Valuations of renewable energy providers are increasing in p_{BT}. Our empirical analysis will find evidence consistent with these predictions.

1.6 General Insight: Uncertainty, Stranded Assets, and the Green Paradox

The literature studying climate transition risks has highlighted the possibility that, in response to anticipated future transition risk realizations, fossil fuel firms may end up *increasing* their current supply, thus lowering prices and increasing today's emissions (the "green paradox").

Our model shows that under certain conditions, this effect can actually be reversed: worsening expectations related to future transition risk realizations can actually induce fossil fuel firms to reduce current energy supply, thus causing an increase in energy prices. In order for this to happen, there needs to be some *uncertainty* related to the realization of climate transition risks. In particular, there should be some states of the world with transition risk realizations characterized by low profits for fossil fuel companies, in order to discourage investments in new production capacity, and some states where transition risks do not materialize and the remaining oil producers can benefit from high energy prices. In addition, some of the the low-profit states should leave assets stranded for some firms, giving a positive value to the real option of not fully extracting the oil.

1.7 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 the possible introduction of carbon taxes. We now argue that these two sources of transition risk are, in fact, 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 high carbon taxes. This is because carbon taxes are policy choices, and policy makers will be more willing to impose high carbon taxes to reduce greenhouse gas emissions in states of the world when reliable and affordable sources of clean energy are available.

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

$$W_{1,s} = \frac{e_{1,s}^{1-\gamma} - 1}{1-\gamma} - \frac{\lambda}{2} f_{1,s}^2. \tag{12}$$

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

$$\max_{\tau_{1,s} \in [0,1]} W_{1,s}. \tag{13}$$

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 assume that the planner announces the period-1 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 technological state of the world is resolved. We assume that the agents in the economy anticipate this time-consistency problem, and expect carbon taxes to be set optimally in each state. Optimal taxes are thus consistent with a subgame perfect equilibrium.

We derive the following result related to the optimal carbon tax policy.

Proposition 6. *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 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.

2 Full Model

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

2.1 Summary of Setup

The model setup is similar to the one described in the previous section. In particular, we denote with p_{BT} the probability that the Breakthrough Technology scenario occurs, which allows renewable energy producers to serve all sectors of the economy. Motivated by the previous section, we assume that the government may impose a tax on new fossil fuel drilling in period 0, $\bar{\tau}_0$, and a carbon tax in period 1, but only in case the BT scenario realizes: $\tau_{1,BT}$.

One difference with the simpler model presented before is that we allow the renewable energy sector to serve some (but not all) sectors of the economy even if the technological breakthrough does not occur ($1 > q > 0$). 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. Importantly, energy prices can be different across these two markets, and we will investigate how the various transition risks affect the gap in energy prices across them.

The decision problems of the various firms in the economy are analogous to those in the previous section. The main difference is that if the CT state realizes, then renewable firms are only 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

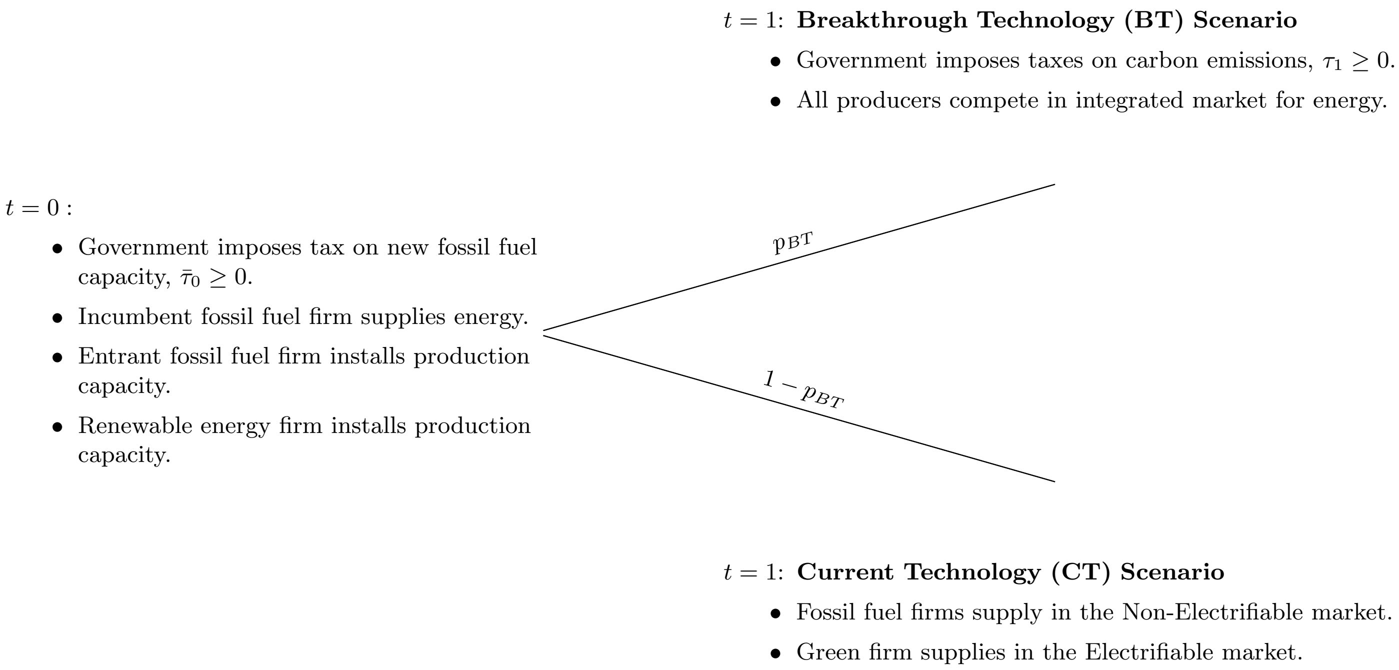
We formalize at the outset that the key results that we derived in Section 1 continue to hold. In particular, we have the following proposition.

Proposition 7. *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, $\bar{\tau}_0$, increases the price of energy in period 0.*
- *An increase in the probability of a technological breakthrough in renewable energy, p_{BT}, generally decreases the price of energy in period 0, although the response can be uncertain.*[7]
- *For low enough carbon taxes, $\tau_{1,BT}$, 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.*

---

[7] The same discussion as in Section 1.5 applies. We verify numerically using the full model that the date-0 energy price is generally decreasing in the transition probability for most parameter values.


$t = 1$: **Breakthrough Technology (BT) Scenario**

- Government imposes taxes on carbon emissions, $\tau_1 \geq 0$.
- All producers compete in integrated market for energy.

$t = 0$:

- Government imposes tax on new fossil fuel capacity, $\bar{\tau}_0 \geq 0$.
- Incumbent fossil fuel firm supplies energy.
- Entrant fossil fuel firm installs production capacity.
- Renewable energy firm installs production capacity.

$t = 1$: **Current Technology (CT) Scenario**

- Fossil fuel firms supply in the Non-Electrifiable market.
- Green firm supplies in the Electrifiable market.

Figure 2: Timeline of the model.

We now use the model to illustrate through numerical analyses 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. All the numerical examples are based on the following calibration: $\bar{f}_0^I = 1.7$, $\kappa_1 = 0.4$, $\kappa_2 = 0.15$, $\delta = 0.3$, $W = 3$, $q = 0.2$, $\tau_{1,BT} = \bar{\tau}_0 = 0$ (except for the case in which we study changes in the tax rates). We choose parameters such that the incumbent fossil fuel firm is not always unconstrained in all states, and has more production capacity than the entrant firm in period 1, consistent with Assumptions 1 and 2 above.

2.3 Analysis of Taxes on New Fossil Fuel Production Capacity

We first consider the effects of changes in the tax on new fossil fuel production capacity, $\bar{\tau}_0$. Figure 3 shows how energy prices and other equilibrium quantities vary with this policy instrument for a model calibration that fixes the probability of a technological breakthrough at $p_{BT} = 0.5$.

To organize the various results, we start by describing the time-0 decisions of the different energy firms that lead to their period-1 energy production capacities. Specifically, Panel D shows the time-1 production capacity of the different energy firms as a function of $\bar{\tau}_0$. As expected, an increase in the tax on new fossil fuel capacity development leads to a decline in the period-1 capacity developed by new entrants. This has a direct effect on energy prices in period 1, shown in Panel B: the reduction in capacity by new entrants raises prices in all period-1 markets where fossil fuel firms operate (the integrated market in the BT state and the NE market in the CT state). In turn, in response to higher prices in the BT scenario, renewable firms increase their period-1 capacity (Panel D), leading to a declining price in the CT-E market where they would be only energy supplier (with fossil fuel firms serving the higher-priced CT-NE market).

Panel B highlights that transition risks can have rich implications on energy prices in different states of the world. Importantly, at higher levels of taxes, the price differences across the electrifiable and non-electrifiable markets in the CT state increase. This divergence may have

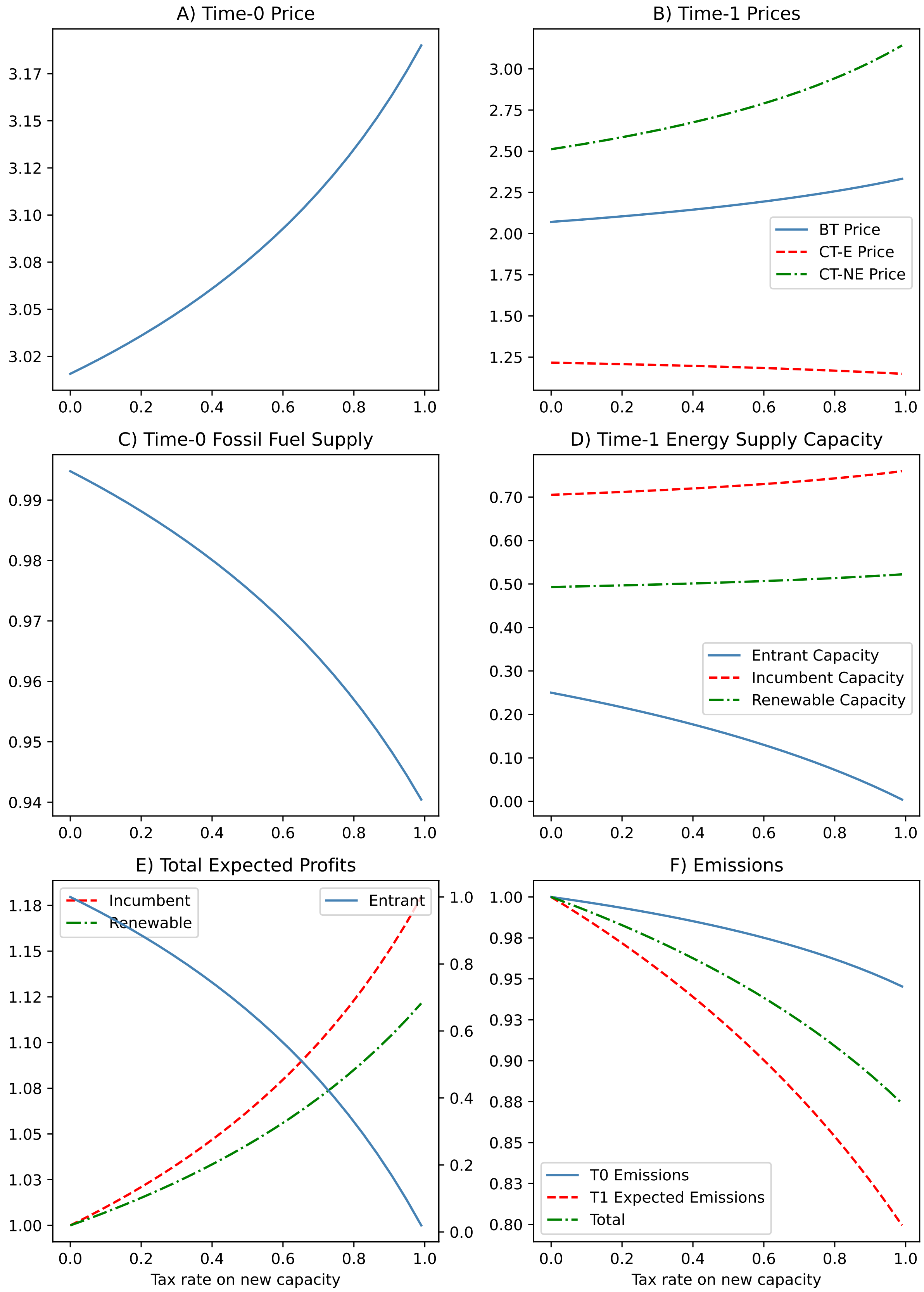


Figure 3: **Equilibrium effects of changes in the tax rate on new production capacity.** Note that profits for each producer are normalized by their profits for $\bar{\tau}_0 = 0$, and emissions are normalized for each period and total by the corresponding value for $\bar{\tau}_0 = 0$. Profits for the entrant fossil fuel firm in Panel E are shown on the right axis. BT scenario probability is fixed at $p_{BT} = 0.5$.

important implications for the composition of economic activity in the absence of a technological breakthrough, as different firms and sectors may and up facing different costs depending on the ability to electrify (and thus their access cheap renewable energy). It also may lead to volatility of energy costs over time, as energy consumers need to shift from renewables to fossil fuels when renewable sources are unavailable (due to intermittency of the renewables production).

Incumbents also adjust their time-0 decision when taxes on the development of new oil capacity increase. As described in Section 1.2, higher expected prices in the BT state and the CT-NE market lead incumbents to increase their time-1 inventory (Panel D). They do so by supplying less energy today (Panel C). The time-0 energy price therefore increases (Panel A).

Finally, Panel E shows expected profits for the different energy firms. Increased drilling restrictions benefit incumbents as well as renewable energy firms, both of which now face less competition. Valuations of new entrants (shown on the right axis in Panel E) decline as their investment activities get taxed at higher rates. Panel F shows that restrictions on drilling activities are successful at reducing emissions at both time 0 and at time 1.

2.4 Analysis of Changes in the Probability of a Technological Breakthrough

We next study the effects of changes in the probability of a technological breakthrough that allows the renewable sector to supply energy to the entire economy, represented by the parameter p_{BT}. We assume throughout this simulation that carbon taxes ($\tau_{1,BT}$) and production capacity taxes ($\bar{\tau}_0$) are zero. Figure 4 shows how equilibrium outcomes change as p_{BT} increases.

As the probability of the Breakthrough Technology scenario increases, the renewable firm increases its installed capacity (Panel D). This results from the fact that the renewable firm views it as more likely that it will be able to supply energy to the entire economy in period 1, and hence wants to increase its capacity to capture this additional demand.

In contrast, both fossil fuel firms anticipate that, as p_{BT} increases, they will face increased competition from the renewable sector, and will face that competition with higher probability. The new entrant reduces its investment, while the incumbent reduces its time-1 inventory (Panel D), choosing instead to increase its time-0 extraction (Panel C). As a result, time-0 prices fall (Panel A), and time-0 emissions rise (Panel F), consistent with predictions from the "green paradox" literature.[8] On the flip side, expected time-1 emissions and overall expected emissions across the two periods decline. However, since 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—the aggregate effects on the climate are uncertain.

The firms' production and investment responses to increases in p_{BT} have the following effects on period-1 equilibrium prices, shown in Panel B. First, the increasing supply of green energy pushes the period-1 price down in both markets where renewable energy firms are active, the BT market as well as the CT-E market. Second, the lower installed capacity from fossil fuel entrants and the reduced period-1 inventory of the incumbent increase period-1 prices in the CT-NE market. The different dynamics of energy prices between the electrifiable and non-electrifiable markets arise due to the fact that, if the technological breakthrough does not occur, renewable firms will be unable to supply energy to the non-electrifiable sectors of the economy, and the supply from the fossil fuel sector is also lower.

---

[8] As section 1.5 reports, it is possible that, for some range of p_{BT}, the time-0 price of energy is actually increasing in p_{BT}, for a mechanism similar to that discussed in the case of carbon taxes: the lower supply from the new entrant may induce incumbents to supply less, not more, at time 0.

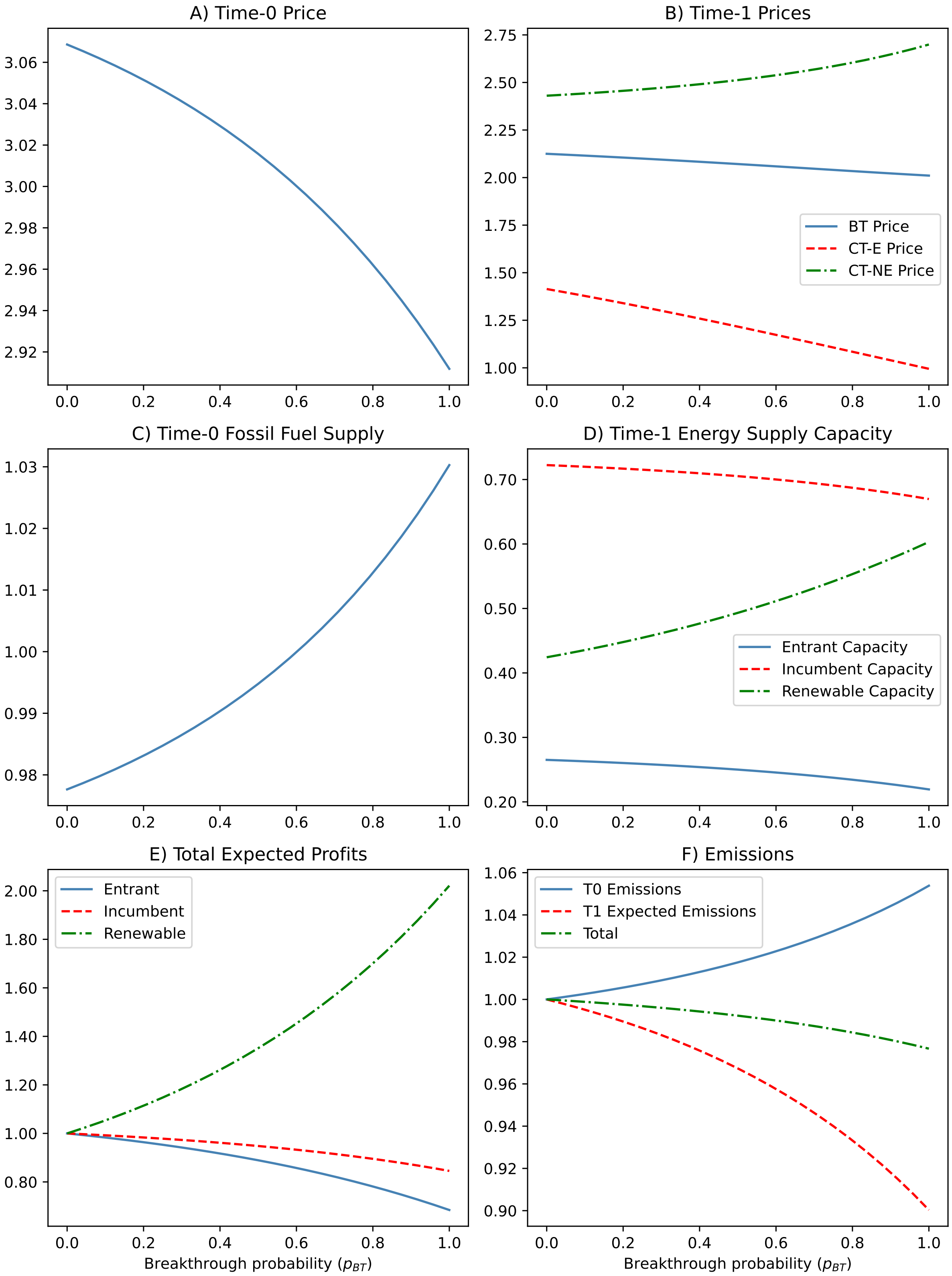


Figure 4: **Equilibrium effects of changes in the probability of a technological breakthrough, p_{BT}.** Note that profits for each producer are normalized by their profits for $p_{BT} = 0$, and emissions are normalized for each period and total by the corresponding value for $p_{BT} = 0$.

Expected profits (and hence valuations) of both types of fossil fuel firms decline as p_{BT} increases, with larger negative effects on the valuations of new entrants (Panel F). 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 an analysis of the effects of the introduction of a tax on carbon emissions in the BT state (taxes are always zero in the CT state).[9] Figure 5 shows how the equilibrium outcomes in the model change as the tax rate $\tau_{1,BT}$ on carbon emissions in the BT scenario increases for a fixed value of the breakthrough probability ($p_{BT} = 0.5$).

We can immediately note the non-monotonicity of the time-0 energy price as a function of the carbon tax (Panel A), consistent with Proposition 3: for low levels of the tax, tax increases reduce the current energy price; if the tax rate is high enough, then further increases will increase the current energy price. As explained in Section 1.4, this non-monotonicity is due to the uncertainty in the level of the tax, and a calculation by incumbents that it may be worth increasing time-1 inventory to profit in states of the world where the carbon tax is not enacted and oil is scarce and valuable, even at the cost of having stranded oil if the tax is enacted.

To dig deeper into this mechanism, Figure 6 plots the fraction of incumbents' oil that is stranded in the BT state. For low values of the carbon tax, the incumbent is fully exhausting its production capacity in the BT state, so no oil is stranded. This corresponds to the range (in this calibration) of a carbon tax between 0 and 0.2. As shown in Panels A, C, and F of Figure 5, in this range we see that the carbon tax induces higher time-0 energy supply and lower time-0 energy prices, leading to an increase in emissions (the "green paradox").

Once the tax rate rises above 0.2 (τ_{strand}), it becomes unprofitable for the incumbent to extract all its inventory in the BT state, leaving the incumbent with some stranded oil inventory in that state (Figure 6). As discussed in Section 1.4, at that point, further increases in the tax have no further direct effects on the incumbent's marginal inventory decision, since it will not in any case extract its marginal inventory in the BT state (when the tax is enacted). But the increase in the carbon tax still discourages the entrant from installing new capacity (Panel D, Figure 5). In turn, this makes oil scarcer in the CT-NE market, raising the price in that market (Panel B) and incentivizing the incumbent to actually increase its period-1 inventory (Panel D). This leads to lower time-0 extraction and a higher time-0 price (Panels A and C).

To these mechanics, present already in the simple model presented in Section 1.4, the full model adds the behavior of renewable energy firms. The increase in carbon taxes induces renewable firms to increase their time-0 investment, driven by their higher expected profits if the BT state materializes. In turn, this leads to a decrease in energy price in the CT-E market. Therefore, expectations about carbon taxes also increase the gap between energy prices in the two markets in the Current Technology scenario (visible in Panel B), with the possible across-industry reallocation effects discussed above.

Note that, eventually, the tax rate in the BT scenario becomes so high that even entrants find it optimal to leave some 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

---

[9] 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.

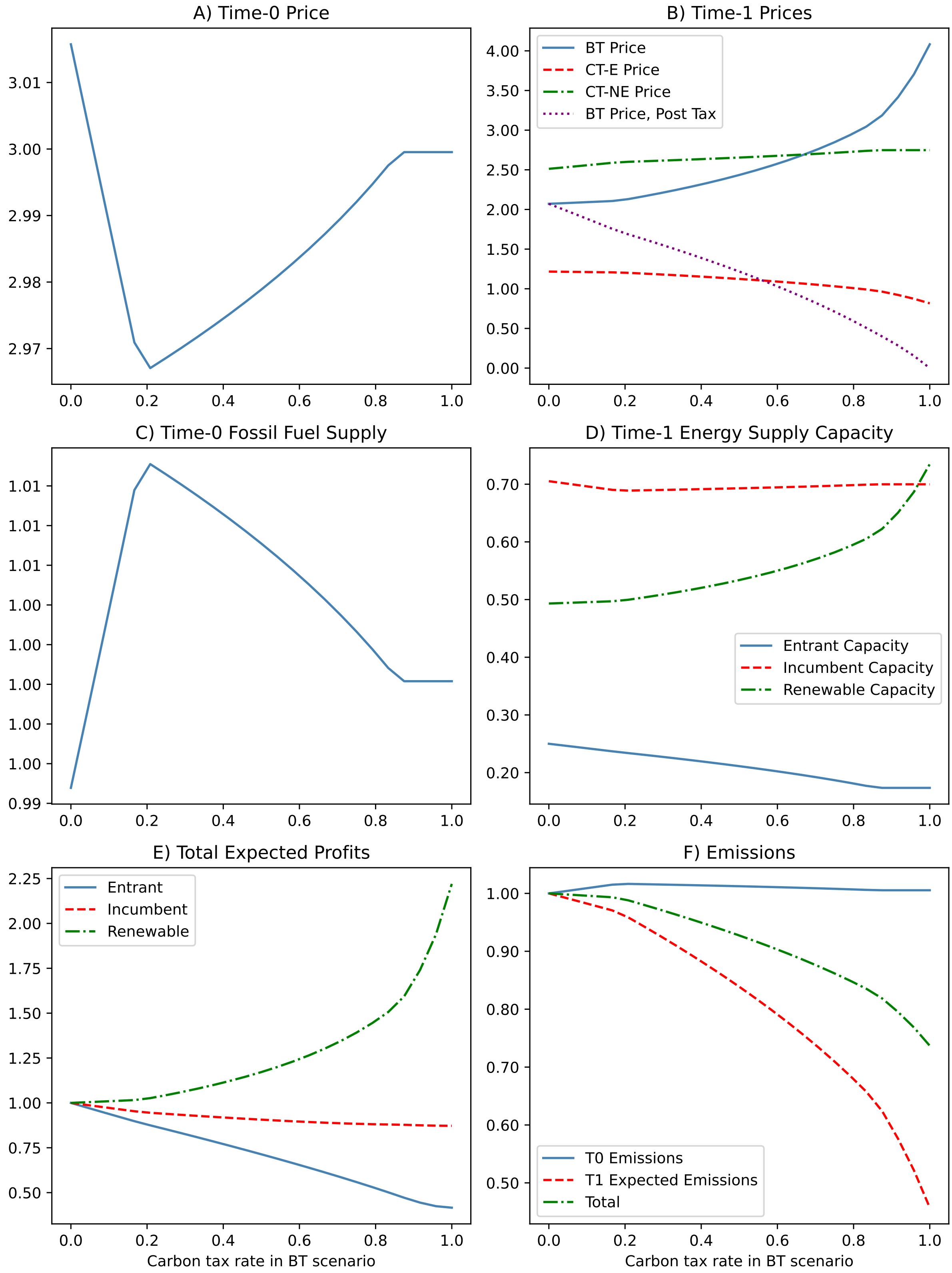


Figure 5: **Equilibrium effects of changes in BT carbon tax rate.** Note that profits for each producer are normalized by their profits for $\tau_{1,BT} = 0$, and emissions are normalized for each period and total by the corresponding value for $\tau_{1,BT} = 0$. BT scenario probability is fixed at $p_{BT}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

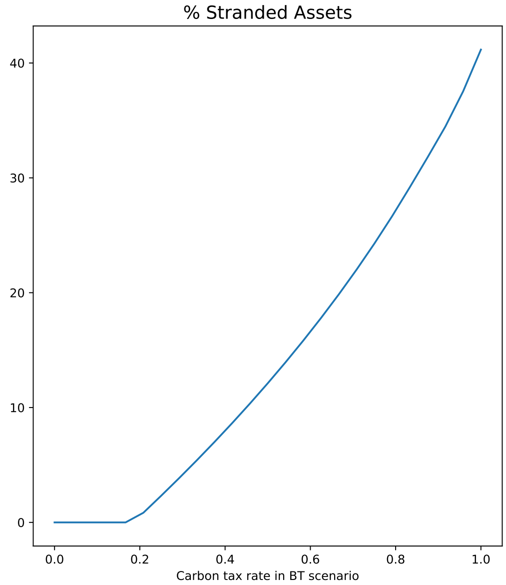


Figure 6: Fossil fuel stranded assets in the BT scenario as a function of the tax rate in the BT scenario. BT scenario probability is fixed at $p_{BT} = 0.5$.

affect the price in the CT scenario and the incumbent's incentive to increase its inventory. This corresponds to the rightmost region of Figure 5, where the response of period-0 price and fossil fuel supply to the carbon tax becomes flat.

Panel E of Figure 5 also shows that news about future carbon taxes have a negative effect on the 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.

3 Empirical Analysis

We now test the main empirical implications of the model. We first study how expectations about climate transition risk realizations affect the valuations of the different types of energy firms, before analyzing how transition risks affect oil prices. We explore differential effects on the valuations of renewable energy firms and on fossil fuel firms positioned on a continuum from entrants to incumbents according to their fraction of developed reserves.

Specifically, we study how these asset prices respond to *news* about each of the three transition risks studied above, which we measure using high-frequency climate transition risk news indices that we construct using data from the *New York Times* (NYT).

3.1 Climate Transition News Indices

We build our climate transition news indices by analyzing news coverage in the NYT using GPT-4o Mini, a state-of-the-art language model created by OpenAI. We begin by summarizing how we construct these climate news indices, and provide additional details in Appendix D.

We start by obtaining all NYT articles covering a 12-year period between 2012 and 2023 via LexisNexis. We narrow our focus to the following sections in the NYT: "Business Financial", "National", "Foreign", "Metropolitan", "Science", "Climate", "U.S.", "Editorial", and

"Business". This excludes sections such as "Travel" as well as the "Opinion" section to better capture direct news such as new policy announcements. From these articles, we select those containing at least one of the following keywords related to the three types of transition risks we are interested in studying: "carbon," "renewable," "drilling," "fossil," "oil and gas," "emissions," "solar," or "pipeline". This approach extracts a broad set of 33,960 articles, including many that are unrelated to climate transition risks.

To construct our transition risk measures, we upload each article to the GPT-4o Mini model, along with a prompt to identify whether the article contains news about a climate transition risk, to determine the type of transition risk, and to quantify the importance of the content. The prompts are provided in Appendix D. We explore three types of transition risks: (1) 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 outcome of the GPT processing step yields, for each article, a score for each transition risk type, with positive scores indicating an increasing transition risk and negative scores a decreasing risk; irrelevant articles get a score of 0. Larger absolute scores are assigned to risks that GPT determines to be more likely or more important based on the content of the articles (see Appendix D). Within each of the three transition risk categories, we aggregate the scores by taking the sum across all articles in a week,[10] creating the *NYT-Emission Cost News Index*, the *NYT-Renewable Breakthrough News Index*, and the *NYT-Oil Capacity News Index*.

Figure 1 plots the time series of the three news indexes, with labels indicating important events. The *NYT-Emission Cost News Index* and the *NYT-Oil Capacity News Index* were, on average, more positive during the Obama and Biden periods, and more negative during 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 (in both directions) around regulations which influence fossil fuel production, like the the Trump administration's approval of offshore oil drilling in 2017, the review of the Keystone XL oil pipeline in 2017, and its permit revocation in 2021 by the Biden administration. The intensity of the *NYT-Renewable Breakthrough News Index* is generally positive and has increased in recent years, with spikes around events favoring renewable energy or announcing technological breakthroughs (e.g., the unveiling of zinc air batteries making energy storage more affordable in 2018, and China scaling up production of sodium batteries in 2023).

The weekly correlations between the three climate transition news indices are positive but moderate in size, as reported in Table 2. This suggests that despite some common events affecting all three types of transition risks, they each capture distinct concepts. The correlations between our news indices and existing measures of climate transition risk introduced by Ardia et al. (2023), Faccini et al. (2023) and Bua et al. (2024) are all relatively small, and mostly positive as reported in Table 2.[11] Armed with these high-frequency indices of transition risk, we now move to the empirical tests of the implications of our model.

---

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

[11] While a variety of transition risk measures exist in the literature, we choose to build our own measures to separately identify the different types of transition risk that are analyzed in our theoretical model.

Table 2: Index Correlations

	(1)	(2)	(3)	(4)	(5)	(6)
(1) NYT-EmissionCostNews	1.00					
(2) NYT-RenewableBTNews	0.22	1.00				
(3) NYT-OilCapacityNews	0.49	0.23	1.00			
(4) Bua-TransitionRisk	0.11	0.06	0.12	1.00		
(5) Faccini-ClimatePolicy	0.37	0.19	0.35	0.13	1.00	
(6) Ardia-MediaClimateChangeConcern	-0.02	0.21	0.16	-0.08	0.46	1.00

3.2 Stock Price Reactions of Energy Firms

We start our analysis by studying the model's predictions for energy firms' stock price response to transition risk news. We obtain prices of stocks listed on the NYSE, AMEX and NASDAQ with data available on CRSP and industry classification (GICS codes) from Compustat.

We use the GICS codes to identify fossil fuel firms, focusing on companies engaged in the exploration and production of oil and gas (see more details in Appendix D). This helps us identify 160 fossil fuel firms. Instead of having distinct categories for entrants and incumbents, we place these fossil fuel firms on a continuum according to the characteristics of their reserves. Specifically, for each fossil fuel firm and year, we compute their "developed ratio," which we define as the ratio between the amount of proved *developed* reserves for oil, natural gas, and natural gas liquids in barrel of oil equivalents (BOE) and the amount of *total* proved reserves for these resources in BOE, obtained from Compustat and the SEC's EDGAR database. Recall that from the model, the key difference between incumbents and entrants was the extent of capital expenditure required to extract oil. The distinction between developed and undeveloped reserves captures this difference 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 expected to be recovered from new wells on undrilled proved acreage, or from existing wells where a relatively major expenditure is required for recompletion."*

Firms with a higher "developed ratio" have already developed more of their reserves, suggesting they can extract this capacity without substantial new investments, similar to the incumbents in the model. Conversely, firms with a lower "developed ratio" have not yet built the infrastructure to develop most of their reserves, similar to new entrants in the model. The median developed ratio in our sample is 0.65, with a 10–90 percentile range of 0.27 to 1.

To identify renewable energy firms, we use the holdings of the Invesco Solar ETF and the First Trust Global Wind Energy ETF, which include 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.[12]

Specification. We base our empirical analysis of stock prices on the following regression:

$$R_{i,t} = \alpha_k + \gamma_i + \beta_{1,k}\nu_{k,t}\text{Fos}_i + \beta_{2,k}\nu_{k,t}\text{Fos}_i\text{DevRat}_{i,t} + \beta_{3,k}\nu_{k,t}\text{Ren}_i + \epsilon_{k,i,t}, \tag{14}$$

---

[12] U.S.-listed oil and gas companies do not generally have substantial investments in renewable energy sources, in contrast to some of their European competitors (van Benthem et al., 2022).

where $R_{i,t}$ is the market-hedged return of stock i at week t,[13] and γ_i represents firm fixed effects. To estimate the stock-price response to news about transition risks, we first estimate an AR(1) model for each news index k using weekly data; we refer to the AR(1) innovations from this time-series model as $\nu_{k,t}$. We focus on AR(1) innovations because returns should reflect the unexpected component of the news, though the low persistence of the news series means that results are similar if we include the index directly instead of the innovations. We scale the residuals by their sample standard deviation to make magnitudes comparable across transition news indices. In regression 14, we interact these news index residuals $\nu_{k,t}$ with dummies for fossil fuel companies (Fos_i) and renewable companies (Ren_i). Finally, we include in the regression the interaction of the next index innovations with the fossil fuel dummy and the developed ratio of firm i at time t, $\text{DevRat}_{i,t}$.

Results. Table 3 reports the results of regression 14. For readability, the table reports only the coefficients that involve the transition news term $\nu_{k,t}$. The findings are highly consistent with our theoretical predictions.

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 of emissions, or a higher probability of a renewable breakthrough. Quantitatively, a one-standard-deviation higher innovation in the *NYT-Emission Cost News Index* is associated with a 2.6 ppt higher return for renewable companies in that week. Renewable energy firms also outperform upon news about restrictions of new oil capacity, though these estimates are not statistically significant.

Table 3: Stock Returns and NYT Index

	Emission Cost (1)	Renewable Breakthrough (2)	Oil Capacity (3)
Fossil Fuel Company × Index AR(1) Innovation	-0.0054**	-0.0079***	-0.0044**
	(0.0026)	(0.0021)	(0.0022)
Fossil Fuel Company × Index AR(1) Innovation × Developed Ratio	0.0094**	0.0118***	0.0073**
	(0.0037)	(0.0032)	(0.0034)
Renewable × Index AR(1) Innovation	0.0026**	0.0027***	0.0012
	(0.0011)	(0.0007)	(0.0009)
Company FE	Yes	Yes	Yes
Remove Market from Stock Returns	Yes	Yes	Yes
R^2	0.607	0.626	0.584
Observations	50851	50851	50851

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 also dropped observations with stock price < \$1 if it was preceded by a month of stock prices < \$1. Standard errors are in parentheses and are clustered at the company level. Significance levels: * (p<0.10), ** (p<0.05), *** (p<0.01).

The price responses of fossil fuel stocks correspond closely to our theoretical predictions. Upon the arrival of news about each of the transition risks, we find that companies with a low developed ratio face a significant drop in stock prices, while the stock prices of companies with

---

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

a higher developed ratio drop by less, and might even increase. This finding is exactly in line with the predictions of the model: entrants are hurt more by transition risks than incumbents.

Appendix D.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: remove section filtering in the construction of the news indices; change the window used to estimate the market beta; and when we use the oil developed reserves ratio rather than the total developed reserves ratio.

3.3 Oil Futures Price Response to Transition News

We next study the effects of transition risk realizations on energy prices, with a focus on the effect on oil futures. Contrary to the previous analysis, which exploits the power of the cross-section of different types of energy firms, this is essentially a time-series macroeconomic analysis, where isolating the effects of transition risk from other confounding events (e.g., geopolitical events) is significantly harder. Because of this, and because some of the model's predictions with respect to oil prices are ambiguous, we expect the results in this section to be somewhat weaker than those in the previous section. We employ 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 full-sample standard deviation to make magnitudes comparable across the three indices. The regression also includes controls for other key 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 in the literature, 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.[14]

We obtain daily settlement prices for WTI crude oil futures with various maturities from Bloomberg, and compute the percentage changes for the closing prices at the end of each month. To reduce micro-structure noise associated with futures of specific maturities, we compute three equal-weighted average returns of futures of different maturities as the key dependent variables for our studies: 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 along with the 60-month future; we also construct a measure that equal-weights returns averaging all 1-month to 24-month futures as well as the 60-month future.

We include 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).[15] We also control for the stock market

---

[14] We also run the same regression at the weekly frequency (holding key control variables constant throughout the month). The results are directionally similar to the monthly regression, but usually not statistically significant.

[15] The U.S. inflation rate is computed as the percentage change in the U.S. consumer price index (CPI). Both

excess returns and an additional demand factor OECD liquid fuel consumption change from EIA. The data spans a 12-year period between 2012 and 2023. See Appendix Table 10 for a detailed overview of the data and its sources. Table 4 shows the results of the regression, with each column corresponding to a different dependent variable.

Table 4: 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	0.0120**	0.0078*	0.0111**
	(0.0059)	(0.0041)	(0.0048)
Index AR(1) Innovation - Renewable Breakthrough	-0.0139**	-0.0094**	-0.0122**
	(0.0056)	(0.0042)	(0.0047)
Index AR(1) Innovation - Oil Capacity	-0.0115*	-0.0058	-0.0071
	(0.0061)	(0.0041)	(0.0049)
Controls	Yes	Yes	Yes
p-value Emission Cost = Renewable Breakthrough	0.0044	0.0062	0.0013
p-value Emission Cost = Oil Capacity	0.017	0.041	0.028
p-value Renewable Breakthrough = Oil Capacity	0.79	0.56	0.47
R^2	0.486	0.450	0.517
Observations	143	143	143

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: * ($p<0.10$), ** ($p<0.05$), *** ($p<0.01$).

The results we obtain for the *NYT-Renewable Breakthrough News Index* align with the prediction of the model: oil futures price generally decrease in response to news about a possible renewable energy technology breakthrough, consistent with oil companies deciding to shift production forward in anticipation of higher future competition from the renewable sector.

Oil futures prices across all maturities increase on news of higher future emission costs; as discussed before, this is consistent with the model in the scenario where some incumbents' assets will be stranded in the carbon tax scenario. Our model also predicts that oil futures prices should rise upon news about restrictions in building new capacity. The observed relationship between oil future prices and innovations in the *NYT-Oil Capacity News Index* instead is negative though usually not statistically significantly so.

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

---

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.

4 Conclusions

We explore how different climate transition risks can affect the price of energy and the valuation of energy firms. Our analysis delivers two general 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 firms 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 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 U.S., 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.

References

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous, "The Environment and Directed Technical Change," *American Economic Review*, 2012, *102* (1), 131–166.

Acemoglu, Daron, Ufuk Akcigit, Douglas Hanley, and William Kerr, "Transition to Clean Technology," *Journal of Political Economy*, 2016, *124* (1), 52–104.

Acharya, Viral V., Robert F. Engle, and Olivier Wang, "Strategic Commitments to Decarbonize: The Role of Large Firms, Common Ownership, and Governments," 2023. Working Paper.

Adolfsen, Jakob Feveile, Malte Heissel, Ana-Simona Manu, and Francesca Vinci, "Burn Now or Never? Climate Change Exposure and Investment of Fossil Fuel Firms," ECB Working Paper Series 2945, European Central Bank 2024.

Aghion, Philippe, Antoine Dechezleprêtre, David Hemous, Ralf Martin, and John Van Reenen, "Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry," *Journal of Political Economy*, 2016, *124* (1), 1–51.

Alekseev, Georgij, Stefano Giglio, Quinn Maingi, Julia Selgrad, and Johannes Stroebel, "A Quantity-Based Approach to Constructing Climate Risk Hedge Portfolios," 2022. Working Paper.

Alquist, Ron, Lutz Kilian, and Robert J. Vigfusson, "Forecasting the Price of Oil," in "Handbook of Economic Forecasting," Vol. 2, Elsevier, 2013, pp. 427–507.

Ardia, David, Keven Bluteau, Kris Boudt, and Koen Inghelbrecht, "Climate change concerns and the performance of green vs. brown stocks," *Management Science*, 2023, *69* (12), 7607–7632.

Barnett, Michael, "A Run on Fossil Fuel? Climate Change and Transition Risk," 2023. Working Paper.

Bolton, Patrick and Marcin Kacperczyk, "Do Investors Care About Carbon Risk?," *Journal of Financial Economics*, 2021, *142* (2), 517–549.

Bua, Giovanna, Daniel Kapp, Federico Ramella, and Lavinia Rognone, "Transition versus physical climate risk pricing in European financial markets: A text-based approach," *The European Journal of Finance*, 2024, pp. 1–35.

Del Negro, Marco, Julian di Giovanni, and Keshav Dogra, "Is the Green Transition Inflationary?," Staff Reports 1053, Federal Reserve Bank of New York 2023.

Engle, Robert F., "Termination Risk and Sustainability," 2023. Working Paper.

Engle, Robert F., Stefano Giglio, Bryan Kelly, Heebum Lee, and Johannes Stroebel, "Hedging Climate Change News," *Review of Financial Studies*, 2020, *33* (3), 1184–1216.

Faccini, Renato, Rastin Matin, and George Skiadopoulos, "Dissecting climate risks: Are they reflected in stock prices?," *Journal of Banking & Finance*, 2023, *155*, 106948.

Ferrari, Alessandro and Valerio Nispi Landi, "Will the Green Transition be Inflationary? Expectations Matter," *IMF Economic Review*, August 2024.

Giglio, Stefano, Bryan Kelly, and Johannes Stroebel, "Climate Finance," *Annual Review of Financial Economics*, 2021, *13*, 15–36.

Golosov, Mikhail, John Hassler, Per Krusell, and Aleh Tsyvinski, "Optimal Taxes on Fossil Fuel in General Equilibrium," *Econometrica*, 2014, *82* (1), 41–88.

Gowrisankaran, Gautam, Stanley S Reynolds, and Mario Samano, "Intermittency and the value of renewable energy," *Journal of Political Economy*, 2016, *124* (4), 1187–1234.

Heyes, Anthony, Andrew Leach, and Charles F Mason, "The economics of Canadian oil sands," *Review of Environmental Economics and Policy*, 2018.

Hong, Harrison, Frank Weikai Li, and Jiangmin Xu, "Climate Risks and Market Efficiency," *Journal of Econometrics*, 2019, *208* (1), 265–281.

Känzig, Diego R., "The Unequal Economic Consequences of Carbon Pricing," 2023. Working Paper.

Kellogg, Ryan, "The End of Oil," Working Paper 33207, National Bureau of Economic Research November 2024.

Kilian, Lutz, "Not All Oil Price Shocks Are Alike: Disentangling Demand and Supply Shocks in the Crude Oil Market," *American Economic Review*, 2009, *99* (3), 1053–1069.

Kimani, Alex, "Oil Majors Pursue Projects with $30 per Barrel Breakeven," *OilPrice.com*, 2024.

Konradt, Maximilian and Beatrice Weder di Mauro, "Carbon Taxation and Greenflation: Evidence from Europe and Canada," 2022. Working Paper.

Lee, Jinjoo, "Is Trump Really Better Than Harris for Oil and Gas Investors," *The Wall Street Journal*, 2024.

Lee, Jinjoo, "Why Big Oil Doesn't Mind Big Regulation," *The Wall Street Journal*, 2024.

Lemoine, Derek and Christian Traeger, "Watch Your Step: Optimal Policy in a Tipping Climate," *American Economic Journal: Economic Policy*, 2014, *6* (1), 137–166.

Liu, Yan and Jing Cynthia Wu, "Reconstructing the Yield Curve," *Journal of Financial Economics*, 2021, *142* (3), 1395–1425.

Morenne, Benoît and Collin Eaton, "Trump's Oil and Gas Donors Don't Really Want to 'Drill, Baby, Drill'," *The Wall Street Journal*, 2024.

Pisani-Ferry, Jean, "Climate Policy is Macroeconomic Policy, and the Implications Will Be Significant," Policy Brief 21-20, Peterson Institute for International Economics 2021.

Ritchie, Hannah and Max Roser, "Energy Mix," `https://ourworldindata.org/energy-mix` 2020.

Rystad Energy, "Rystad Energy: As falling Costs Make New Oil Cheaper to Produce, Climate Policies May Fail Unless they Target Demand," *Rogtec Magazine*, 2021.

Rystad Energy, "Shale project economics still reign supreme as cost of new oil production rises further," 2024. Accessed: 2025-01-15.

Schnabel, Isabel, "A New Age of Energy Inflation: Climateflation, Fossilflation and Greenflation," Speech at a panel on "Monetary Policy and Climate Change" at The ECB and its Watchers XXII Conference 2022.

Sinn, Hans-Werner, "Public Policies Against Global Warming: A Supply Side Approach," *International Tax and Public Finance*, 2008, *15*, 360–394.

van Benthem, Arthur A., Edmund Crooks, Stefano Giglio, Eugenie Schwob, and Johannes Stroebel, "The Effect of Climate Risks on the Interactions Between Financial Markets and Energy Companies," *Nature Energy*, 2022, *7*, 820–828.

Williams, James H, Ryan A Jones, Ben Haley, Gabe Kwok, Jeremy Hargreaves, Jamil Farbes, and Margaret S Torn, "Carbon-neutral pathways for the United States," *AGU advances*, 2021, *2* (1), e2020AV000284.

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:

$$\max_{C\geq 0} \; -\frac{1}{2\delta}C^2 + C\Big[p_{BT}P_{1,BT} + (1-p_{BT})P_{1,E}\Big] \tag{15}$$

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

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

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 1.7, 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:

$$\max_{f_0^I} \; f_0^I P_0 - \frac{1}{2\kappa_1}(f_0^I)^2 + E[V_f^I] \tag{16}$$

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_{BT}, and $V_f^{I,CT}$ with probability $(1-p_{BT})$. These continuation values are given by

$$V_f^{I,BT} = \max_{f_{1,BT}^I} \; (1-\tau_{1,BT})P_{1,BT}f_{1,BT}^I - \frac{1}{2\kappa_1}(f_{1,BT}^I)^2, \tag{17}$$

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

$$V_f^{I,CT} = \max_{f_{1,E}^I, f_{1,NE}^I} \; P_{1,E}f_{1,E}^I + P_{1,NE}f_{1,NE}^I - \frac{1}{2\kappa_1}(f_{1,E}^I + f_{1,NE}^I)^2, \tag{18}$$

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:

$$\max_{\bar{f}_1^E} \; -\frac{1}{2(1-\bar{\tau}_0)\kappa_2}(\bar{f}_1^E)^2 + E[V_f^E] \tag{19}$$

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_{BT}, given by

$$V_f^{E,BT} = \max_{f_{1,BT}^E} \; (1-\tau_{1,BT})P_{1,BT} f_{1,BT}^E - \frac{1}{2\kappa_1}(f_{1,BT}^E)^2, \tag{20}$$

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

$$V_f^{E,CT} = \max_{f_{1,E}^E, f_{1,NE}^E} \; P_{1,E} f_{1,E}^E + P_{1,NE} f_{1,NE}^E - \frac{1}{2\kappa_1}(f_{1,E}^E + f_{1,NE}^E)^2, \tag{21}$$

subject to $0 \leq f_{1,E}^E + f_{1,NE}^E \leq \bar{f}_1^E$.

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

$$\frac{W}{P_0} = f_0^I, \tag{22}$$

$$\frac{W}{P_{1,BT}} = C + f_{1,BT}^I + f_{1,BT}^E, \tag{23}$$

$$q\frac{W}{P_{1,E}} = C + f_{1,E}^I + f_{1,E}^E, \text{ and} \tag{24}$$

$$(1-q)\frac{W}{P_{1,NE}} = f_{1,NE}^I + f_{1,NE}^E. \tag{25}$$

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.*
- *Quantities and prices satisfy the market clearing conditions.*

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 both fossil fuel firms 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

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

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

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

   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

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

   which gives the following interior solution

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

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

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

   which gives the following interior solution

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

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

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

   which gives the following interior solution

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

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

$$\begin{aligned}\max_{\bar{f}_1^E \geq 0} \; & -\frac{1}{2(1-\bar{\tau}_0)\kappa_2}(\bar{f}_1^E)^2 \\ & + p_{BT}\left[(1-\tau_{1,BT})P_{1,BT}\bar{f}_1^E - \frac{1}{2\kappa_1}\bar{f}_1^E\right] \\ & + (1-p_{BT})\frac{\kappa_1}{2}(1-\tau_{1,CT})^2(P_{1,,*})^2\end{aligned}$$

which gives the following interior solution

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

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

$$\begin{aligned}\max_{\bar{f}_1^E \geq 0} \; & -\frac{1}{2(1-\bar{\tau}_0)\kappa_2}(\bar{f}_1^E)^2 \\ & + p_{BT}\frac{\kappa_1}{2}(1-\tau_{1,BT})^2(P_{1,BT})^2 \\ & + (1-p_{BT})\left[(1-\tau_{1,CT})P_{1,*}\bar{f}_1^E - \frac{1}{2\kappa_1}(\bar{f}_1^E)^2\right]\end{aligned}$$

which gives the following interior solution

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

3. Production constraint always binding: this gives

$$\begin{aligned}\max_{\bar{f}_1^E \geq 0} \; & -\frac{1}{2(1-\bar{\tau}_0)\kappa_2}(\bar{f}_1^E)^2 \\ & + p_{BT}\left[(1-\tau_{1,BT})P_{1,BT}\bar{f}_1^E - \frac{1}{2\kappa_1}(\bar{f}_1^E)^2\right] \\ & + (1-p_{BT})\left[(1-\tau_{1,CT})P_{1,*}\bar{f}_1^E - \frac{1}{2\kappa_1}(\bar{f}_1^E)^2\right]\end{aligned}$$

which gives the following interior solution

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

Note that since in equilibrium fossil fuel firms will only supply in the CT market with the highest price, it has to be that $P_{1,NE} \geq P_{1,E}$. Indeed, if this was not the case, then fossil fuel supply in the NE market would be zero. But then, according to the market clearing condition (25), the price in the NE market would go to infinity, which is a contradiction. Excluding the knife-edge case where energy prices are equal in the two markets, it then follows that fossil fuel firms will only supply in the Non-Electrifiable market.

Appendix B Proofs

Proof of Proposition 1 and 2

We take into account also the carbon tax implemented in period 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

$$f_0^I = \frac{\kappa_1}{2}\Big[P_0 - (1-\tau_1)P_1\Big] + \frac{\bar{f}_0^I}{2} \tag{26}$$

$$f_1^I = \frac{\bar{f}_0^I}{2} - \frac{\kappa_1}{2}\Big[P_0 - (1-\tau_1)P_1\Big] \tag{27}$$

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

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}(1-\tau_1)P_1 \tag{28}$$

Substituting optimal quantities into market clearing conditions, we have

$$\frac{W}{P_0} = \frac{\kappa_1}{2}\Big[P_0 - (1-\tau_1)P_1\Big] + \frac{\bar{f}_0^I}{2} \tag{29}$$

$$\frac{W}{P_1} = \frac{\bar{f}_0^I}{2} - \frac{\kappa_1}{2}\Big[P_0 - (1-\tau_1)P_1\Big] + \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}(1-\tau_1)P_1 \tag{30}$$

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

$$\frac{df_0^I}{d\bar{\tau}_0} = \frac{\kappa_1}{2}\left[\frac{dP_0}{d\bar{\tau}_0} - (1-\tau_1)\frac{dP_1}{d\bar{\tau}_0}\right] \tag{31}$$

$$\frac{df_1^I}{d\bar{\tau}_0} = -\frac{df_0^I}{d\bar{\tau}_0} \tag{32}$$

$$\frac{d\bar{f}_1^E}{d\bar{\tau}_0} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}(1-\tau_1)\frac{dP_1}{d\bar{\tau}_0} - \frac{\kappa_1^2\kappa_2}{[\kappa_1 + (1-\bar{\tau}_0)\kappa_2]^2}(1-\tau_1)P_1 \tag{33}$$

and from market clearing conditions we have that

$$-\frac{W}{P_0^2}\frac{dP_0}{d\bar{\tau}_0} = \frac{df_0^I}{d\bar{\tau}_0} \tag{34}$$

$$-\frac{W}{P_1^2}\frac{dP_1}{d\bar{\tau}_0} = -\frac{df_0^I}{d\bar{\tau}_0} + \frac{d\bar{f}_1^E}{d\bar{\tau}_0} \tag{35}$$

We proceed by contradiction. Suppose that $\frac{dP_0}{d\bar{\tau}_0} < 0$. Then (34) implies that $\frac{df_0^I}{d\bar{\tau}_0} > 0$. From (31) we then get $\frac{dP_1}{d\bar{\tau}_0} < 0$ which implies, using (33), that $\frac{d\bar{f}_1^E}{d\bar{\tau}_0} < 0$, and using (35) 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, after substituting optimal quantities into the expressions for the profits, we find

$$\frac{d\Pi^E}{d\bar{\tau}_0} = \frac{1-\tau_1}{2}\left[\frac{d\bar{f}_1^E}{d\bar{\tau}_0}P_1 + \bar{f}_1^E\frac{dP_1}{d\bar{\tau}_0}\right] \tag{36}$$

Using (35), we have

$$\frac{W}{P_1^2}\frac{dP_1}{d\bar{\tau}_0} + \frac{d\bar{f}_1^E}{d\bar{\tau}_0} < 0 \tag{37}$$

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

$$\frac{d\Pi^I}{d\bar{\tau}_0} = \frac{dP_0}{d\bar{\tau}_0}\left[\frac{\kappa_1}{2}(P_0 - (1-\tau_1)P_1) + \frac{1}{2}\bar{f}_0^I\right] + \frac{1-\tau_1}{2}\frac{dP_1}{d\bar{\tau}_0}\left[\bar{f}_0^I - \kappa_1(P_0 - (1-\tau_1)P_1)\right] \tag{38}$$

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.

Turning now to the proof of Proposition 2, the derivatives of the optimal quantities with respect to the carbon tax are given by

$$\frac{df_0^I}{d\tau_1} = \frac{\kappa_1}{2}\left[\frac{dP_0}{d\tau_1} - (1-\tau_1)\frac{dP_1}{d\tau_1} + P_1\right] \tag{39}$$

$$\frac{d\bar{f}_1^E}{d\tau_1} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[(1-\tau_1)\frac{dP_1}{d\tau_1} - P_1\right] \tag{40}$$

while market clearing conditions give

$$-\frac{W}{P_0^2}\frac{dP_0}{d\tau_1} = \frac{df_0^I}{d\tau_1} \tag{41}$$

$$-\frac{W}{P_1^2}\frac{dP_1}{d\tau_1} = -\frac{df_0^I}{d\tau_1} + \frac{d\bar{f}_1^E}{d\tau_1} \tag{42}$$

Suppose again by contradiction that $\frac{dP_0}{d\tau_1} > 0$, which immediately implies using (41) that $\frac{df_0^I}{d\tau_1} < 0$. Then, (39) gives $P_1 - (1-\tau_1)\frac{dP_1}{d\tau_1} < 0$, which immediately implies $\frac{dP_1}{d\tau_1} > 0$ and, using (40), $\frac{d\bar{f}_1^E}{d\tau_1} > 0$. But then, (42) gives $\frac{dP_1}{d\tau_1} < 0$, which is a contradiction. Therefore, it must be $\frac{dP_0}{d\tau_1} \leq 0$. Finally, assuming $\frac{dP_0}{d\tau_1} = 0$ and following the previous steps gives $\frac{dP_1}{d\tau_1} > 0$ and $\frac{dP_1}{d\tau_1} = 0$. Therefore, it must be $\frac{dP_0}{d\tau_1} < 0$. It immediately follows that both supply from the incumbent in period 1 and investment in new capacity by the entrant are decreasing in τ_1.

Entrant's profits now change according to

$$\frac{d\Pi_1^E}{d\tau_1} = \frac{1}{2}\left[\frac{d\bar{f}_1^E}{d\tau_1}(1-\tau_1)P_1 + \bar{f}_1^E\left((1-\tau_1)\frac{dP_1}{d\tau_1} - P_1\right)\right] \tag{43}$$

Which is negative, given $\frac{d\bar{f}_1^E}{d\tau_1} < 0$ and (40). Finally, profits for the incumbent change according to

$$\frac{d\Pi_1^I}{d\tau_1} = -\frac{1}{2}f_0^I\frac{df_0^I}{d\tau_1} + (\bar{f}_0 - f_0^I)\left((1-\tau_1)\frac{dP_1}{d\tau_1} - P_1\right) + 2\frac{df_0^I}{d\tau_1}\left[\frac{1}{\kappa_1}(\bar{f}_0^I - f_0^I) - (1-\tau_1)P_1\right] \tag{44}$$

The first term on the RHS of the previous expression is negative, since $\frac{df_0^I}{d\tau_1} > 0$. The second and third term are also negative, using (40) and $f_0^I < \bar{f}_0^I$), and using the optimality condition for f_0^I. It then follows that $\frac{d\Pi_1^I}{d\tau_1} < 0$. □

Proof of Proposition 3

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

$$\max_{0 \leq f_0^I \leq \bar{f}_0^I} \; f_0^I P_0 - \frac{1}{2\kappa_1}(f_0^I)^2 + E[V_1^I] \tag{45}$$

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

$$V_{1,T}^I = \max_{0 \leq f_{1,T}^I \leq \bar{f}_0^I - f_0^I} (1 - \tau_1) P_{1,T} f_{1,T}^I - \frac{1}{2\kappa_1}(f_{1,T}^I)^2, \tag{46}$$

and

$$V_{1,NT}^I = \max_{0 \leq f_{1,NT}^I \leq \bar{f}_0^I - f_0^I} P_{1,NT} f_{1,NT}^I - \frac{1}{2\kappa_1}(f_{1,NT}^I)^2, \tag{47}$$

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

$$f_0^I = \frac{\bar{f}_0^I}{2} + \frac{\kappa_1}{2}\Big[P_0 - p_T(1-\tau_1)P_{1,T} - (1-p_T)P_{1,NT}\Big] \tag{48}$$

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

$$f_0^I = \frac{1-p_T}{2-p_T}\bar{f}_0^I + \frac{\kappa_1}{2-p_T}\Big[P_0 - (1-p_T)P_{1,NT}\Big] \tag{49}$$

Note that since demand for energy is the same in both states, in equilibrium we always have $(1-\tau_1)P_{1,T} \leq P_{1,NT}$, 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

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\Big[p_T(1-\tau_1)P_{1,T} + (1-p_T)P_{1,NT}\Big] \tag{50}$$

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

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-p_T)(1-\bar{\tau}_0)\kappa_2}(1-p_T)P_{1,NT} \tag{51}$$

Finally, market clearing conditions are now given by

$$\frac{W}{P_0} = f_0^I \tag{52}$$

$$\frac{W}{P_{1,T}} = f_{1,T}^I + f_{1,T}^E \tag{53}$$

$$\frac{W}{P_{1,NT}} = f_{1,NT}^I + f_{1,NT}^E \tag{54}$$

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

$$\frac{df_0^I}{d\tau_1} = \frac{\kappa_1}{2}\left[\frac{dP_0}{d\tau_1} - p_T(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} + p_T P_{1,T} - (1-p_T)\frac{dP_{1,NT}}{d\tau_1}\right] \tag{55}$$

$$\frac{d\bar{f}_1^E}{d\tau_1} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[p_T(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} - p_T P_{1,T} + (1-p_T)\frac{dP_{1,NT}}{d\tau_1}\right] \tag{56}$$

and

$$-\frac{W}{P_0^2}\frac{dP_0}{d\tau_1} = \frac{df_0^I}{d\tau_1} \tag{57}$$

$$-\frac{W}{P_{1,T}^2}\frac{dP_{1,T}}{d\tau_1} = -\frac{df_0^I}{d\tau_1} + \frac{d\bar{f}_1^E}{d\tau_1} \tag{58}$$

$$-\frac{W}{P_{1,NT}^2}\frac{dP_{1,NT}}{d\tau_1} = -\frac{df_0^I}{d\tau_1} + \frac{d\bar{f}_1^E}{d\tau_1} \tag{59}$$

Suppose by contradiction that $\frac{dP_0}{d\tau_1} > 0$. Then, using (57), we have $\frac{df_0^I}{d\tau_1} < 0$. It follows from (55) that

$$-p_T(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} + p_T P_{1,T} - (1-p_T)\frac{dP_{1,NT}}{d\tau_1} < 0 \tag{60}$$

which in turn implies, using (56), that $\frac{d\bar{f}_1^E}{d\tau_1} > 0$. But then it follows from (58) and (59) that $\frac{dP_{1,T}}{d\tau_1} < 0$ and $\frac{dP_{1,NT}}{d\tau_1} < 0$, which contradicts (60). 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

$$\frac{df_0^I}{d\tau_1} = \frac{\kappa_1}{2-p_T}\left[\frac{dP_0}{d\tau_1} - (1-p_T)\frac{dP_{1,NT}}{d\tau_1}\right] \tag{61}$$

$$\frac{df_{1,T}^I}{d\tau_1} = \kappa_1\left[(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} - P_{1,T}\right] \tag{62}$$

and using market clearing in the T state

$$-\frac{W}{P_{1,T}^2}\frac{dP_{1,T}}{d\tau_1} = \frac{df_{1,T}^I}{d\tau_1} + \frac{d\bar{f}_1^E}{d\tau_1} \tag{63}$$

Suppose now that $\frac{dP_0}{d\tau_1} < 0$. Using (57), we have $\frac{df_0^I}{d\tau_1} > 0$ which implies, using (61), that $\frac{dP_{1,NT}}{d\tau_1} < 0$. But then, using (59), we have that $\frac{d\bar{f}_1^E}{d\tau_1} > 0$ which implies, using (56), that $\frac{dP_{1,T}}{d\tau_1} > 0$. From (63) we then get $\frac{df_{1,T}^I}{d\tau_1} < 0$ which implies, using (62), that

$$(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} - P_{1,T} < 0 \tag{64}$$

But this, using (56), 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 (63) and $\frac{df_{1,T}^I}{d\tau_1} = 0$ from (62), 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 4

Optimal quantities are given by

$$f_0^I = \frac{1-p_T}{2-p_T}\bar{f}_0^I + \frac{\kappa_1}{2-p_T}\left[P_0 - (1-p_T)(1-\tau_1)P_{1,NT}\right] \tag{65}$$

$$f^I_{1,T} = (1-\tau_1-\Delta)\kappa_1 P_{1,T} \tag{66}$$

$$\bar{f}^E_1 = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1+(1-\bar{\tau}_0)\kappa_2}\Big[p_T(1-\tau_1-\Delta)P_{1,T}+(1-p_T)(1-\tau_1)P_{1,NT}\Big] \tag{67}$$

Taking the derivatives with respect to Δ, we get

$$\frac{df^I_0}{d\Delta} = \frac{\kappa_1}{2-p_T}\left[\frac{dP_0}{d\Delta}-(1-p_T)(1-\tau_1)\frac{dP_{1,NT}}{d\Delta}\right] \tag{68}$$

$$\frac{df^I_{1,T}}{d\Delta} = \kappa_1\left[(1-\tau_1-\Delta)\frac{dP_{1,T}}{d\Delta}-P_{1,T}\right] \tag{69}$$

$$\frac{d\bar{f}^E_1}{d\tau_1} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1+(1-\bar{\tau}_0)\kappa_2}\left[p_T(1-\tau_1-\Delta)\frac{dP_{1,T}}{d\Delta}-p_T P_{1,T}+(1-p_T)(1-\tau_1)\frac{dP_{1,NT}}{d\Delta}\right] \tag{70}$$

Note that these expressions are analogous to those in the second half of the proof of Proposition B, with the tax rate in the BT state being now $\tau_1+\Delta$, and multiplying the derivative of the NT price by $(1-\tau_1)$. Therefore, we can follow the same steps to show that $\frac{dP_0}{d\Delta} > 0$.

Proof of Proposition 5

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

$$\frac{W}{P_0} = f^I_0 \tag{71}$$

$$\frac{W}{P_{1,BT}} = C + f^I_{1,BT} + f^E_{1,BT} \tag{72}$$

$$\frac{W}{P_{1,CT}} = f^I_{1,CT} + f^E_{1,CT} \tag{73}$$

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

$$\frac{df^I_0}{dp_{BT}} = \frac{\kappa_1}{2}\left[\frac{dP_0}{dp_{BT}}-(1-\tau_{1,BT})\left(P_{1,BT}+p_{BT}\frac{dP_{1,BT}}{dp_{BT}}\right)-(1-p_{BT})\frac{dP_{1,CT}}{dp_{BT}}+P_{1,CT}\right] \tag{74}$$

$$\frac{d\bar{f}^E_1}{dp_{BT}} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1+(1-\bar{\tau}_0)\kappa_2}\left[(1-\tau_{1,BT})\left(P_{1,BT}+p_{BT}\frac{dP_{1,BT}}{dp_{BT}}\right)+(1-p_{BT})\frac{dP_{1,CT}}{dp_{BT}}-P_{1,CT}\right] \tag{75}$$

$$\frac{dC}{dp_{BT}} = \delta\left(P_{1,BT}+p_{BT}\frac{dP_{1,BT}}{dp_{BT}}\right) \tag{76}$$

and

$$-\frac{W}{P_0^2}\frac{dP_0}{dp_{BT}} = \frac{df^I_0}{dp_{BT}} \tag{77}$$

$$-\frac{W}{P_{1,BT}^2}\frac{dP_{1,BT}}{dp_{BT}} = \frac{dC}{dp_{BT}}-\frac{df^I_0}{dp_{BT}}+\frac{d\bar{f}^E_1}{dp_{BT}} \tag{78}$$

$$-\frac{W}{P_{1,CT}^2}\frac{dP_{1,CT}}{dp_{BT}} = -\frac{df^I_0}{dp_{BT}}+\frac{d\bar{f}^E_1}{dp_{BT}} \tag{79}$$

As usual, we prove the proposition by contradiction. Suppose that $\frac{dP_0}{dp_{BT}} > 0$. Using (77), this implies that $\frac{df_0^I}{dp_{BT}} < 0$. It then follows from (74) that

$$-(1-\tau_{1,BT})\Big(P_{1,BT}+p_{BT}\frac{dP_{1,BT}}{dp_{BT}}\Big)-(1-p_{BT})\frac{dP_{1,CT}}{dp_{BT}}+P_{1,CT}<0 \tag{80}$$

which immediately implies, using (75), that $\frac{d\bar{f}_1^E}{dp_{BT}} > 0$. Using (79), we then have $\frac{dP_{1,CT}}{dp_{BT}} < 0$, which implies, using (80), that

$$P_{1,BT}+p_{BT}\frac{dP_{1,BT}}{dp_{BT}}>0 \tag{81}$$

which immediately implies, using (76) and (78), that $\frac{dC}{dp_{BT}} > 0$ and $\frac{dP_{1,BT}}{dp_{BT}} < 0$. 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 (74), that $\frac{df_0^I}{dp_{BT}} > 0$, which is a contradiction. Therefore, it must be $\frac{dP_0}{dp_{BT}} \leq 0$. Following the same steps, we get the same contradiction if $\frac{dP_0}{dp_{BT}} = 0$, so that it must be $\frac{dP_0}{dp_{BT}} < 0$.

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

$$\frac{df_0}{dp_{BT}}=\frac{1}{(2-p_{BT})^2}\left[\kappa_1\Big(P_0-(1-p_{BT})P_{1,CT}\Big)-\bar{f}_0\right]+\frac{\kappa_1}{2-p_{BT}}\left[\frac{dP_0}{dp_{BT}}-(1-p_{BT})\frac{dP_{1,CT}}{dp_{BT}}+P_{1,CT}\right] \tag{82}$$

$$\frac{df_{1,BT}^I}{dp_{BT}}=(1-\tau_{1,BT})\kappa_1\frac{dP_{1,BT}}{dp_{BT}} \tag{83}$$

and

$$-\frac{W}{P_{1,BT}^2}\frac{dP_{1,BT}}{dp_{BT}}=\frac{dC}{dp_{BT}}+\frac{df_{1,BT}^I}{dp_{BT}}+\frac{d\hat{f}_1}{dp_{BT}} \tag{84}$$

Note that the first term in bracket on the right hand side of equation (82) is negative, using the expression for the optimal f_0 and the fact that $f_0 < \bar{f}_0$. We first show that $\frac{dC}{dp_{BT}} \geq 0$. Suppose that the opposite holds, which immediately implies from (76) that

$$P_{1,BT}+p_{BT}\frac{dP_{1,BT}}{dp_{BT}}<0 \tag{85}$$

and consequently $\frac{dP_{1,BT}}{dp_{BT}} < 0$. It then follows from (83) that $\frac{df_{1,BT}^I}{dp_{BT}} < 0$, and using (84) it follows that $\frac{d\hat{f}_1}{dp_{BT}} > 0$. Then, from (85) and (75) we get

$$(1-p_{BT})\frac{dP_{1,CT}}{dp_{BT}}-P_{1,CT}>0 \tag{86}$$

and consequently $\frac{dP_{1,CT}}{dp_{BT}} > 0$. It then follows from (79) that $\frac{df_0}{dp_{BT}} > 0$ and from (77) that $\frac{dP_0}{dp_{BT}} < 0$. But then, (82) implies that $-(1-p_{BT})\frac{dP_{1,CT}}{dp_{BT}} + P_{1,CT} > 0$, which contradicts (86). Therefore, it must be $\frac{dC}{dp_{BT}} \geq 0$, which immediately implies that

$$P_{1,BT}+p_{BT}\frac{dP_{1,BT}}{dp_{BT}}\geq 0 \tag{87}$$

We now show that it must be $\frac{d\hat{f}_1}{dp_{BT}} \leq 0$. Suppose that the opposite holds. Then, from (83) and (84), it must be that $\frac{dP_{1,BT}}{dp_{BT}} < 0$. It then follows, from (75) and (87), and noting that $(1-\tau_1)P_{1,BT} < P_{1,CT}$, that (86) holds, and consequently $\frac{dP_{1,CT}}{dp_{BT}} > 0$. But from (79), it must be $\frac{df_0}{dp_{BT}} > 0$, which immediately implies, using (77), that $\frac{dP_0}{dp_{BT}} < 0$. But then (82) implies that $-(1-p_{BT})\frac{dP_{1,CT}}{dp_{BT}} + P_{1,CT} > 0$, which contradicts (86). Therefore, it must be $\frac{d\hat{f}_1}{dp_{BT}} \leq 0$, which immediately implies, using (75) and (87), that

$$(1 - p_{BT}) \frac{dP_{1,CT}}{dp_{BT}} - P_{1,CT} \leq 0 \tag{88}$$

Suppose now that $\frac{dP_{1,CT}}{dp_{BT}} < 0$. Then it follows immediately from $\frac{d\hat{f}_1}{dp_{BT}} \leq 0$, (79) and (77) that $\frac{df_0}{dp_{BT}} < 0$ and $\frac{dP_0}{dp_{BT}} > 0$. But note that, using (82) and the expression for the optimal f_0^I, we have

$$\frac{df_0}{dp_{BT}} - \frac{\kappa_1}{2 - p_{BT}} \frac{dP_0}{dp_{BT}} = \frac{1}{2 - p_{BT}} \left[\kappa_1 P_{1,CT} - (\bar{f}_0 - f_0) \right] - \kappa_1 \frac{(1 - p_{BT})}{2 - p_{BT}} \frac{dP_{1,CT}}{dp_{BT}} \tag{89}$$

The left-hand side of (89) is negative. But $\kappa_1 P_{1,CT} > \bar{f}_0 - f_0$, since the production constraint in the CT state is binding. Therefore, the right-hand side of (89) is positive, which is a contradiction. It follows that it must be $\frac{dP_{1,CT}}{dp_{BT}} \geq 0$.

These conditions do not allow to pin down with certainty the sign of $\frac{dP_0}{dp_{BT}}$. In particular, we can see from (89) that the first term is positive, while the second is negative. However, as $p_{BT} \to 1$, the second term goes to zero and only the positive term remains, which gives $\frac{df_0}{dp_{BT}} > 0$ and $\frac{dP_0}{dp_{BT}} < 0$.

We show how the various firm's profits move with p_{BT} in the proof of Proposition 7 using the more general model.

□

Proof of Proposition 6

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

$$f_{1,CT}^I = f_{1,CT}^E = (1 - \tau_{1,CT}) \kappa_1 P_{1,CT} \tag{90}$$

Plugging these quantities into the market clearing condition (73) we obtain the following expression for the equilibrium price

$$P_{1,CT} = \sqrt{\frac{W}{2\kappa_1 (1 - \tau_{1,CT})}} \tag{91}$$

The first order condition for the planner's problem is

$$\left[2\kappa_1 (1 - \tau_{1,CT}) P_{1,CT} \right]^{-\gamma} = \lambda 2\kappa_1 (1 - \tau_{1,CT}) P_{1,CT} \tag{92}$$

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

$$\tau_{1,CT}^* = 1 - \frac{1}{\lambda^{\frac{2}{1+\gamma}} 2W\kappa_1} \tag{93}$$

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

$$f_{1,BT}^I = f_{1,BT}^E = (1 - \tau_{1,BT}) \kappa_1 P_{1,BT} \tag{94}$$

Using market clearing condition (72), the equilibrium price is now given by

$$P_{1,BT} = \frac{\sqrt{C^2 + 8\kappa_1 (1 - \tau_{1,BT}) W} - C}{4\kappa_1 (1 - \tau_{1,BT})} \tag{95}$$

The optimality condition for the planner is now

$$\left[C + 2\kappa_1(1-\tau_{1,BT})P_{1,BT}\right]^{-\gamma} = \lambda 2\kappa_1(1-\tau_{1,BT})P_{1,BT} \tag{96}$$

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

$$\left[2\lambda\kappa_1(1-\tau_{1,BT})W\right]^{\frac{1}{1-\gamma}} - \left[\frac{1}{\lambda(2\kappa_1 W)^{\gamma}(1-\tau_{1,BT})^{\gamma}}\right]^{\frac{1}{1-\gamma}} = C > 0 \tag{97}$$

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

$$\tau^*_{1,BT} > 1 - \frac{1}{\lambda^{\frac{2}{1+\gamma}} 2W\kappa_1} = \tau^*_{1,CT} \tag{98}$$

Finally, note that the left-hand side of (97) is decreasing in λ and increasing in $\tau_{1,BT}$. Therefore, as λ increases, the optimal tax rate that satisfies (97) also has to increase. □

B.1 Proof of Proposition 7: 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

$$-\frac{W}{(P_0)^2}\frac{dP_0}{\bar{\tau}_0} = \frac{df_0^I}{d\bar{\tau}_0} \tag{99}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\bar{\tau}_0} = \frac{dC}{d\bar{\tau}_0} - \frac{df_0^I}{d\bar{\tau}_0} + \frac{d\bar{f}_1^E}{d\bar{\tau}_0} \tag{100}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\bar{\tau}_0} = \frac{dC}{d\bar{\tau}_0} \tag{101}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\bar{\tau}_0} = -\frac{df_0^I}{d\bar{\tau}_0} + \frac{d\bar{f}_1^E}{d\bar{\tau}_0} \tag{102}$$

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

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[p_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-p_{BT})P_{1,NE}\right] \tag{103}$$

$$f_0^I = \frac{1}{2}\bar{f}_0^I + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\left[p_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-p_{BT})P_{1,NE}\right] \tag{104}$$

$$C = \delta\left[p_{BT}P_{1,BT} + (1-p_{BT})P_{1,E}\right] \tag{105}$$

which implies

$$\begin{aligned}\frac{d\bar{f}_1^E}{d\bar{\tau}_0} &= -\frac{\kappa_1^2\kappa_2}{[\kappa_1 + (1-\bar{\tau}_0)\kappa_2]^2}\left[p_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-p_{BT})P_{1,NE}\right] \\ &+ \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[p_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\bar{\tau}_0} + (1-p_{BT})\frac{dP_{1,NE}}{d\bar{\tau}_0}\right]\end{aligned} \tag{106}$$

$$\frac{df_0^I}{d\bar{\tau}_0} = \frac{\kappa_1}{2}\frac{dP_0}{d\bar{\tau}_0} - \frac{\kappa_1}{2}\left[p_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\bar{\tau}_0} + (1-p_{BT})\frac{dP_{1,NE}}{d\bar{\tau}_0}\right] \tag{107}$$

$$\frac{dC}{d\bar{\tau}_0} = \delta\left[p_{BT}\frac{dP_{1,BT}}{d\bar{\tau}_0} + (1-p_{BT})\frac{dP_{1,E}}{d\bar{\tau}_0}\right] \tag{108}$$

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 (99), this implies $\frac{df_0^I}{d\bar{\tau}_0} > 0$. It follows from (107) that

$$p_{BT}\frac{dP_{1,BT}}{d\bar{\tau}_0} + (1 - p_{BT})\frac{dP_{1,NE}}{d\bar{\tau}_0} < 0 \tag{109}$$

which implies, using (106) that $\frac{d\bar{f}_1^E}{d\bar{\tau}_0} < 0$. From (102), it then follows that $\frac{dP_{1,NE}}{d\bar{\tau}_0} > 0$, which implies, using (109), that $\frac{dP_{1,BT}}{d\bar{\tau}_0} < 0$. From (100), we then have $\frac{dC}{d\bar{\tau}_0} > 0$, which implies, from (101), that $\frac{dP_{1,E}}{d\bar{\tau}_0} < 0$. But then, (108) implies $\frac{dC}{d\bar{\tau}_0} < 0$, which is a contradiction. Therefore, we must have $\frac{dP_0}{d\bar{\tau}_0} \geq 0$. Assuming $\frac{dP_0}{d\bar{\tau}_0} = 0$ and following the same steps, we find immediately that it must be $\frac{dP_0}{d\bar{\tau}_0} > 0$. The proof for the case where the production constraint of the incumbent is binding in the CT state only is analogous.

□

B.2 Proof of Proposition 7: Effects of Changes in the Transition Probability

First, note that from the market clearing conditions 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

$$\frac{W}{P_0} = f_0^I \tag{110}$$

$$\frac{W}{P_{1,BT}} = C + \bar{f}_0^I - f_0^I + \bar{f}_1^E \tag{111}$$

$$q\frac{W}{P_{1,E}} = C \tag{112}$$

$$(1-q)\frac{W}{P_{1,NE}} = \bar{f}_0^I - f_0^I + \bar{f}_1^E \tag{113}$$

Differentiating both sides of the previous equations with respect to p_{BT}, we obtain

$$-\frac{W}{(P_0)^2}\frac{dP_0}{dp} = \frac{df_0^I}{dp} \tag{114}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{dp} = \frac{dC}{dp} - \frac{df_0^I}{dp} + \frac{d\bar{f}_1^E}{dp} \tag{115}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{dp} = \frac{dC}{dp} \tag{116}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{dp} = -\frac{df_0^I}{dp} + \frac{d\bar{f}_1^E}{dp} \tag{117}$$

Moreover, optimal quantities are given by

$$\bar{f}_1^E = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[p_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-p_{BT})P_{1,NE}\Big] \tag{118}$$

$$f_0^I = \frac{1}{2}\bar{f}_0^I + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\Big[p_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-p_{BT})P_{1,NE}\Big] \tag{119}$$

$$C = \delta \Big[p_{BT} P_{1,BT} + (1 - p_{BT}) P_{1,E} \Big] \tag{120}$$

which implies

$$\frac{d\bar{f}_1^E}{dp} = \frac{\kappa_1 \kappa_2}{\kappa_1 + \kappa_2} \left[(1 - \tau_{1,BT}) P_{1,BT} - P_{1,NE} + p_{BT} (1 - \tau_{1,BT}) \frac{dP_{1,BT}}{dp} + (1 - p_{BT}) \frac{dP_{1,NE}}{dp} \right] \tag{121}$$

$$\frac{df_0^I}{dp} = \frac{\kappa_1}{2} \frac{dP_0}{dp} - \frac{\kappa_1}{2} \left[(1 - \tau_{1,BT}) P_{1,BT} - P_{1,NE} + p_{BT} (1 - \tau_{1,BT}) \frac{dP_{1,BT}}{dp} + (1 - p_{BT}) \frac{dP_{1,NE}}{dp} \right] \tag{122}$$

$$\frac{dC}{dp} = \delta \left[P_{1,BT} - P_{1,E} + p_{BT} \frac{dP_{1,BT}}{dp} + (1 - p_{BT}) \frac{dP_{1,E}}{dp} \right] \tag{123}$$

Let us show that we have $\frac{dP_0}{dp} \leq 0$. By contradiction, suppose $\frac{dP_0}{dp} > 0$. Then, (114) implies $\frac{df_0^I}{dp} < 0$. But then, using (122), we have

$$(1 - \tau_{1,BT}) P_{1,BT} - P_{1,NE} + p_{BT} (1 - \tau_{1,BT}) \frac{dP_{1,BT}}{dp} + (1 - p_{BT}) \frac{dP_{1,NE}}{dp} > 0 \tag{124}$$

It then follows from (121) that $\frac{d\bar{f}_1^E}{dp} > 0$, which implies, using (117), that $\frac{dP_{1,NE}}{dp} < 0$. Now, note that market clearing conditions and $P_{1,E} \leq P_{1,NE}$ imply that $P_{1,BT} < P_{1,NE}$. Using (124), it then follows that $\frac{dP_{1,BT}}{dp} > 0$, which in turn implies, using (115), that $\frac{dC}{dp} < 0$. But then, (116) implies that $\frac{dP_{1,E}}{dp} > 0$, which in turn implies, using (123), that $\frac{dC}{dp} > 0$. This is a contradiction, so we must have $\frac{dP_0}{dp} \leq 0$. Assuming then $\frac{dP_0}{dp} = 0$ and following the previous steps yields immediately a contradiction, hence it must be $\frac{dP_0}{dp} > 0$.

Finally, following the same steps as in the proof of Proposition 5, we can immediately see that if the incumbent fully exhausts its production capacity in the CT state only, then the effect of changes in the breakthrough probability on the date-0 energy price is in general ambiguous.

We now show how profits of the various firms change with changes in the probability of the technological breakthrough. To ease notation, suppose that the taxes on carbon emissions and new production capacity are set to zero, as this has no consequences for the proof. Let us start from the entrant fossil fuel firm. Assuming that the production constraint is always binding, we have

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

which implies that total expected profits in period 0 are

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

It follows that

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

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

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

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

We showed before 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 the incumbent's optimality condition 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

$$\Pi_0^R = C\left[p_{BT}P_{1,BT} + (1-p_{BT})P_{1,E}\right] - \frac{1}{2\delta}C^2$$

using

$$C = \delta\left[p_{BT}P_{1,BT} + (1-p_{BT})P_{1,E}\right]$$

we have

$$\Pi_0^R = \frac{\delta}{2}\left[p_{BT}P_{1,BT} + (1-p_{BT})P_{1,E}\right]^2$$

Therefore, this implies

$$\frac{d\Pi_0^R}{dp} = \delta\left[p_{BT}P_{1,BT} + (1-p_{BT})P_{1,E}\right]\left[P_{1,BT} - P_{1,E} + p_{BT}\frac{dP_{1,BT}}{dp_{BT}} + (1-p_{BT})\frac{dP_{1,E}}{dp_{BT}}\right] \geq 0$$

where the results follows from $\frac{dC}{dp} \geq 0$ and (123).

☐

B.3 Proof of Proposition 7: Effects of Carbon Tax

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

$$-\frac{W}{(P_0)^2}\frac{dP_0}{\tau_{1,BT}} = \frac{df_0^I}{d\tau_{1,BT}} \tag{125}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} - \frac{df_0^I}{d\tau_{1,BT}} + \frac{d\bar{f}_1^E}{d\tau_{1,BT}} \tag{126}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} \tag{127}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\tau_{1,BT}} = -\frac{df_0^I}{d\tau_{1,BT}} + \frac{d\bar{f}_1^E}{d\tau_{1,BT}} \tag{128}$$

Optimal quantities are now given by

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[p_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-p_{BT})P_{1,NE}\right] \tag{129}$$

$$f_0^I = \frac{1}{2}\bar{f}_0^I + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\left[p_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-p_{BT})P_{1,NE}\right] \tag{130}$$

$$C = \delta\Big[p_{BT}P_{1,BT} + (1-p_{BT})P_{1,E}\Big] \tag{131}$$

which implies that we have

$$\frac{d\bar{f}_1^E}{d\tau_{1,BT}} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\Big[-p_{BT}P_{1,BT} + p_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p_{BT})\frac{dP_{1,NE}}{d\tau_{1,BT}}\Big] \tag{132}$$

$$\frac{df_0^I}{d\tau_{1,BT}} = \frac{\kappa_1}{2}\frac{dP_0}{d\tau_{1,BT}} - \frac{\kappa_1}{2}\Big[-p_{BT}P_{1,BT} + p_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p_{BT})\frac{dP_{1,NE}}{d\tau_{1,BT}}\Big] \tag{133}$$

$$\frac{dC}{d\tau_{1,BT}} = \delta\Big[p_{BT}\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p_{BT})\frac{dP_{1,E}}{d\tau_{1,BT}}\Big] \tag{134}$$

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 (125), $\frac{df_0^I}{d\tau_{1,BT}} < 0$. It follows from (133) that

$$-p_{BT}P_{1,BT} + p_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p_{BT})\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0 \tag{135}$$

which in turn implies, using (132), that $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} > 0$. Using (128), it follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$, which implies, using (135), that $\frac{dP_{1,BT}}{d\tau_{1,BT}} > 0$. It then follows from (126) 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, (134) 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

$$\frac{W}{P_0} = f_0^I \tag{136}$$

$$\frac{W}{P_{1,BT}} = C + f_{1,BT}^I + \bar{f}_1^E \tag{137}$$

$$q\frac{W}{P_{1,E}} = C \tag{138}$$

$$(1-q)\frac{W}{P_{1,NE}} = \bar{f}_0^I - f_0^I + \bar{f}_1^E \tag{139}$$

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

$$-\frac{W}{(P_0)^2}\frac{dP_0}{d\tau_{1,BT}} = \frac{df_0^I}{d\tau_{1,BT}} \tag{140}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} + \frac{df_{1,BT}^I}{d\tau_{1,BT}} + \frac{d\bar{f}_1^E}{d\tau_{1,BT}} \tag{141}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} \tag{142}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\tau_{1,BT}} = -\frac{df_0^I}{d\tau_{1,BT}} + \frac{d\bar{f}_1^E}{d\tau_{1,BT}} \tag{143}$$

Optimal quantities are given by

$$f_0^I = \frac{\kappa_1}{2-p_{BT}}P_0 - \frac{(1-p_{BT})\kappa_1}{2-p_{BT}}P_{1,NE} + \frac{1-p_{BT}}{2-p_{BT}}\bar{f}_0^I \tag{144}$$

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1+(1-\bar{\tau}_0)\kappa_2}\Big[p_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-p_{BT})P_{1,NE}\Big] \tag{145}$$

$$f_{1,BT}^I = \kappa_1(1-\tau_{1,BT})P_{1,BT} \tag{146}$$

$$C = \delta\Big[p_{BT}P_{1,BT} + (1-p_{BT})P_{1,E}\Big] \tag{147}$$

which implies

$$\frac{df_0^I}{d\tau_{1,BT}} = \frac{\kappa_1}{2-p_{BT}}\frac{dP_0}{d\tau_{1,BT}} - \frac{(1-p_{BT})\kappa_1}{2-p_{BT}}\frac{dP_{1,NE}}{d\tau_{1,BT}} \tag{148}$$

$$\frac{d\bar{f}_1^E}{d\tau_{1,BT}} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1+(1-\bar{\tau}_0)\kappa_2}\Big[-p_{BT}P_{1,BT} + p_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p_{BT})\frac{dP_{1,NE}}{d\tau_{1,BT}}\Big] \tag{149}$$

$$\frac{df_{1,BT}^I}{d\tau_{1,BT}} = \kappa_1\Big[-P_{1,BT} + (1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}}\Big] \tag{150}$$

$$\frac{dC}{d\tau_{1,BT}} = \delta\Big[p_{BT}\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p_{BT})\frac{dP_{1,E}}{d\tau_{1,BT}}\Big] \tag{151}$$

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 (142) we have $\frac{dP_{1,E}}{d\tau_{1,BT}} > 0$. This implies, using (151), that $\frac{dP_{1,BT}}{d\tau_{1,BT}} < 0$. Using (150) we then have $\frac{df_{1,BT}^I}{d\tau_{1,BT}} < 0$, and using (141) we have $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} > 0$. Then, from (149) we find $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, which implies using (143) that $\frac{df_0^I}{d\tau_{1,BT}} > 0$. But then (140) implies $\frac{dP_0}{d\tau_{1,BT}} < 0$ and (148) 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 $\frac{df_{1,BT}^I}{d\tau_{1,BT}} \leq 0$. Suppose that the opposite holds. Then, (141) implies $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} < 0$, and using (55) we get $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$. But then (143) implies $\frac{df_0^I}{d\tau_{1,BT}} < 0$, (140) implies $\frac{dP_0}{d\tau_{1,BT}} > 0$, and (148) implies $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, a contradiction. Hence, $\frac{df_{1,BT}^I}{d\tau_{1,BT}} \leq 0$.

Then, suppose that $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} > 0$. From (149) we have $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, from (143) we have $\frac{df_0^I}{d\tau_{1,BT}} > 0$, from (140) we have $\frac{dP_0}{d\tau_{1,BT}} < 0$ and from (148) we have $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$, a contradiction. Therefore, $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} \leq 0$

For the next step, suppose that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$. Then, using (143) we have $\frac{df_0^I}{d\tau_{1,BT}} < 0$, using (140) we have $\frac{dP_0}{d\tau_{1,BT}} > 0$, and using (148) 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 (140), this implies that $\frac{df_0^I}{d\tau_{1,BT}} > 0$. From (148), 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

$$\frac{W}{P_0} = f_0^I \tag{152}$$

$$\frac{W}{P_{1,BT}} = C + f_{1,BT}^I + f_{1,BT}^E \tag{153}$$

$$q\frac{W}{P_{1,E}} = C \tag{154}$$

$$(1-q)\frac{W}{P_{1,NE}} = \bar{f}_0^I - f_0^I + \bar{f}_1^E \tag{155}$$

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

$$-\frac{W}{(P_0)^2}\frac{dP_0}{d\tau_{1,BT}} = \frac{df_0^I}{d\tau_{1,BT}} \tag{156}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} + \frac{df_{1,BT}^I}{d\tau_{1,BT}} + \frac{df_{1,BT}^E}{d\tau_{1,BT}} \tag{157}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} \tag{158}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\tau_{1,BT}} = -\frac{df_0^I}{d\tau_{1,BT}} + \frac{d\bar{f}_1^E}{d\tau_{1,BT}} \tag{159}$$

Optimal quantities are now given by

$$f_0^I = \frac{\kappa_1}{2-p_{BT}}P_0 - \frac{(1-p_{BT})\kappa_1}{2-p_{BT}}P_{1,NE} + \frac{1-p_{BT}}{2-p_{BT}}\bar{f}_0^I \tag{160}$$

$$\bar{f}_1^E = \frac{(1-p_{BT})(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-p_{BT})(1-\bar{\tau}_0)\kappa_2}P_{1,NE} \tag{161}$$

$$f_{1,BT}^I = f_{1,BT}^E = \kappa_1(1-\tau_{1,BT})P_{1,BT} \tag{162}$$

$$C = \delta\Big[p_{BT}P_{1,BT} + (1-p_{BT})P_{1,E}\Big] \tag{163}$$

which implies

$$\frac{df_0^I}{d\tau_{1,BT}} = \frac{\kappa_1}{2-p_{BT}}\frac{dP_0}{d\tau_{1,BT}} - \frac{(1-p_{BT})\kappa_1}{2-p_{BT}}\frac{dP_{1,NE}}{d\tau_{1,BT}} \tag{164}$$

$$\frac{d\bar{f}_1^E}{d\tau_{1,BT}} = \frac{(1-p_{BT})(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-p_{BT})(1-\bar{\tau}_0)\kappa_2}\frac{dP_{1,NE}}{d\tau_{1,BT}} \tag{165}$$

$$\frac{df_{1,BT}^I}{dd\tau_{1,BT}} = \frac{df_{1,BT}^E}{dd\tau_{1,BT}} = \kappa_1\Big[-P_{1,BT} + (1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}}\Big] \tag{166}$$

$$\frac{dC}{d\tau_{1,BT}} = \delta\Big[p_{BT}\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p_{BT})\frac{dP_{1,E}}{d\tau_{1,BT}}\Big] \tag{167}$$

Suppose first that $\frac{dP_0}{d\tau_{1,BT}} < 0$. Using (156), this implies that $\frac{df_0^I}{d\tau_{1,BT}} > 0$. From (164), it then follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$. This implies, from (159), that $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} > 0$. But then, from (165), 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 (156), this implies that $\frac{df_0^I}{d\tau_{1,BT}} < 0$. From (164), it then follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$. Then, from (159), this $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} < 0$. But it then follows from (165) 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 $\frac{df_0^I}{d\tau_{1,BT}} = \frac{d\bar{f}_1^E}{d\tau_{1,BT}} = \frac{dP_{1,NE}}{d\tau_{1,BT}} = 0$

□

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

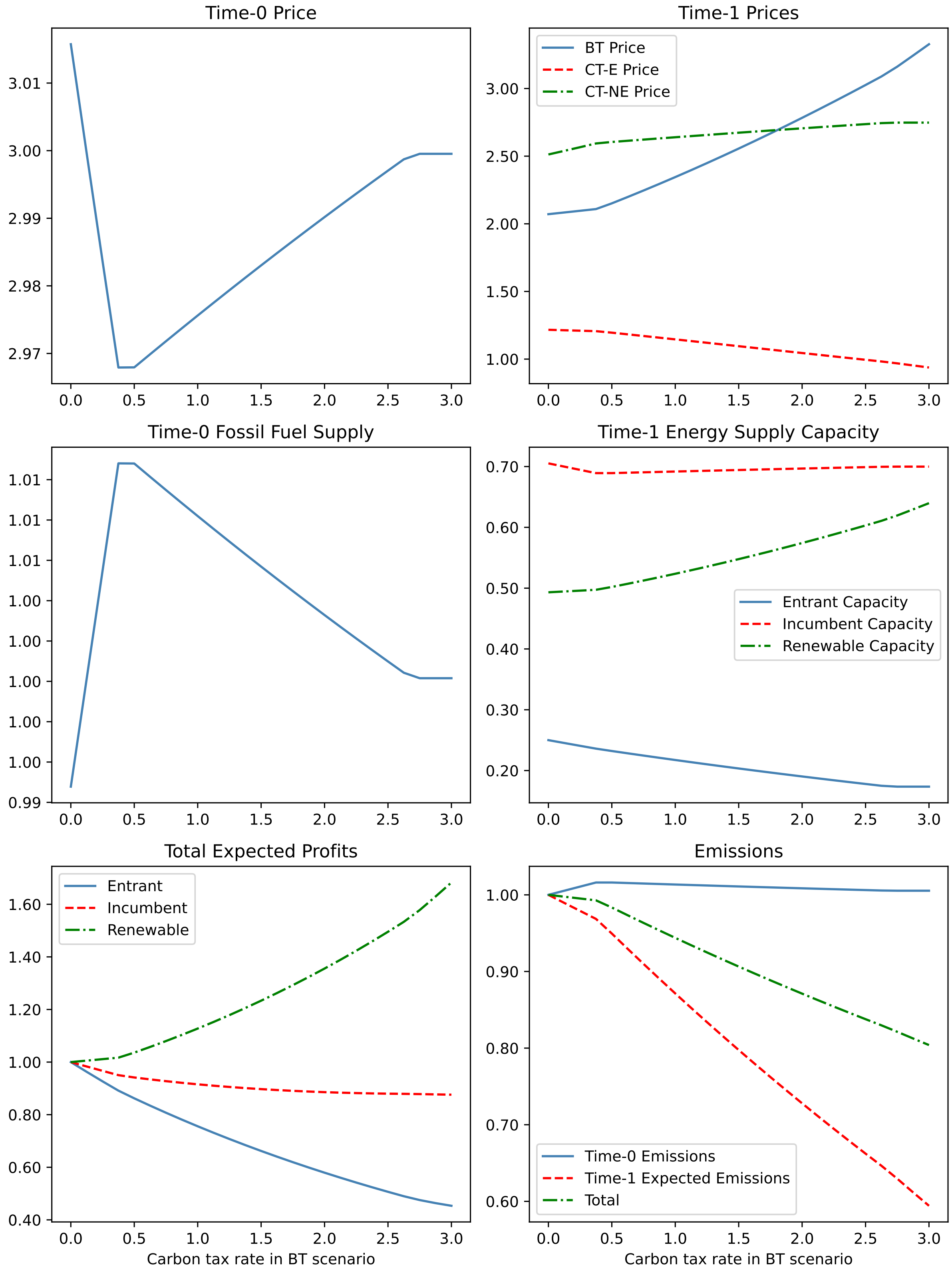


Figure 7: Equilibrium effects of changes in BT tax rate. Note that profits for each producer are normalized by their profits for $p_{BT} = 0$, whereas emissions are normalized for each period and total by the corresponding value for $p_{BT} = 1$. BT scenario probability is fixed at $p_{BT} = 0.5$.

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.

Appendix D Additional Data Details

D.1 Measuring Climate Transition Risks By GPT

We construct several indices measuring climate transition risks outlined in our model by applying state-of-the-art large language models (LLMs) to news articles published in the New York Times (NYT). LLMs are a type of artificial intelligence (AI) models 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 and architectural innovations. We employ GPT-4o Mini, one of the most advanced LLMs pre-trained by OpenAI.[16]

D.1.1 Pre-processing

We obtained historical NYT news articles through LexisNexis, covering a 12-year period from 2012 to 2023. We first need to identify news articles relevant to the climate transition risks we are measuring, which are restrictions on new fossil fuel production capacity, 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.[17]

D.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 prompts 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. We separate our queries by transition risk type to minimize context-switching and potential model performance degradation. For each transition risk, we pose questions across multiple topics, including some not directly analyzed but provided guidance to GPT.[18] For each topic, we pose four questions. The first question assesses the

---

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

[17] 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 > 0.97), 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).

[18] In our theoretical analysis, we focus on breakthrough probability p_{BT}. To avoid GPT classifying articles about cost of production of renewable energy δ as related to probability of renewable breakthrough, we explicitly included policies subsidizing or supporting renewable energy production as a topic. In our oil capacity prompt, we include subtopics like permit availability, financing availability, and compliance standards to guide GPT's interpretation of factors affecting the maximum production capacity of fossil fuels companies.

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 policy regarding that topic. 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 producers.

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': '(choice id)'};
{'Question6': '(choice id)'};
{'Question7': '(choice id)'};
{'Question8': '(choice id)'};
{'Question9': 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)};
{'Question10': Provide detailed explanations on Question5 to Question8, 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 - If answered "No", skip Question2,3,4 (answer (c) in Question2, (e) in Question3, and (e) in Question4).

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 the fossil fuel industry?
(a) Most Significant Impact[19]
(b) Highly Significant Impact[20]
(c) Moderate Impact[21]
(d) Minimal Impact[22]
(e) No Impact[23]

Question5: Does this article discuss regulatory or financial cost of carbon emissions in U.S., or factors related to regulatory or financial cost of carbon emissions in U.S.?

(a) Yes
(b) No - If answered ”No”, skip Question6,7,8 (answer (c) in Question6, (e) in Question7, and (e) in Question8).

Question6: 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 regulatory or financial cost of carbon emissions in U.S..

Question7: How likely is the change you indicated in Question6?
(a) Extremely Likely
(b) Very Likely
(c) Somewhat Likely
(d) Slightly Likely
(e) Neutral - if answered Neutral in Question6.

Question8: How significant do you anticipate the impact of this news about regulatory or financial cost of carbon emissions in U.S. will be on the market prices and operational strategies of companies in the fossil fuel industry?
(a) Most Significant Impact[18]
(b) Highly Significant Impact[19]
(c) Moderate Impact[20]
(d) Minimal Impact[21]
(e) No Impact[22]

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’: ’(choice id)’};
{’Question6’: ’(choice id)’};
{’Question7’: ’(choice id)’};
{’Question8’: ’(choice id)’};
{’Question9’: ’(choice id)’};
{’Question10’: ’(choice id)’};
{’Question11’: 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)};
{’Question12’: Provide detailed explanations on Question5 to Question6, 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)};
{’Question13’: Provide detailed explanations on Question7 to Question10, 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 renewable energy or battery storage technology breakthroughs, or factors related to renewable energy or battery storage technology breakthroughs?
(a) Yes

(b) No - If answered ”No”, skip Question2,3,4 (answer (c) in Question2, (e) in Question3, and (e) in Question4).

Question2: Does this article indicate an increase or decrease in renewable energy or battery storage technology breakthrough probabilities?
(a) Increase
(b) Decrease
(c) Neutral - The article does not provide specific details or evidence regarding renewable energy or battery storage technology breakthrough probabilities.

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 renewable energy or battery storage technology breakthroughs will be on the market prices and operational strategies of companies in fossil fuel industry?
(a) Most Significant Impact[18]
(b) Highly Significant Impact[19]
(c) Moderate Impact[20]
(d) Minimal Impact[21]
(e) No Impact[22]

Question5: Does this article discuss actual or realized technology breakthroughs (not just plans and investments) on renewable energy or battery storage?
(a) Yes
(b) No - If answered ”No”, skip Question6 (answer (e) in Question6).

Question6: How significant do you anticipate the impact of this news about actual or realized technology breakthroughs on renewable energy or battery storage will be on the market prices and operational strategies of companies in the fossil fuel industry?
(a) Most Significant Impact[18]
(b) Highly Significant Impact[19]
(c) Moderate Impact[20]
(d) Minimal Impact[21]
(e) No Impact[22]

Question7: Does this article discuss policies that subsidize or support the production of renewable energy, or factors related to policies that subsidize or support the production of renewable energy?
(a) Yes
(b) No - If answered ”No”, skip Question8,9,10 (answer (c) in Question8, (e) in Question9, and (e) in Question10).

Question8: Does this article indicate tightening or loosening policies that subsidize or support the production of renewable energy?
(a) Tightening
(b) Loosening
(c) Neutral - The article does not provide specific details or evidence regarding changes in policies that subsidize or support the production of renewable energy.

Question9: How likely is the change you indicated in Question8?
(a) Extremely Likely
(b) Very Likely
(c) Somewhat Likely
(d) Slightly Likely

(e) Neutral - if answered Neutral in Question8.

Question10: How significant do you anticipate the impact of this news about policies that subsidize or support the production of renewable energy will be on the market prices and operational strategies of companies in the fossil fuel industry?
(a) Most Significant Impact[18]
(b) Highly Significant Impact[19]
(c) Moderate Impact[20]
(d) Minimal Impact[21]
(e) No Impact[22]

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’: ’(choice id)’};
{’Question6’: ’(choice id)’};
{’Question7’: ’(choice id)’};
{’Question8’: ’(choice id)’};
{’Question9’: ’(choice id)’};
{’Question10’: ’(choice id)’};
{’Question11’: ’(choice id)’};
{’Question12’: ’(choice id)’};
{’Question13’: ’(choice id)’};
{’Question14’: ’(choice id)’};
{’Question15’: ’(choice id)’};
{’Question16’: ’(choice id)’};
{’Question17’: 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)};
{’Question18’: Provide detailed explanations on Question5 to Question8, 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)};
{’Question19’: Provide detailed explanations on Question9 to Question12, 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)};
{’Question20’: Provide detailed explanations on Question13 to Question16, identifying specific parts of the

---

[19] 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 fossil fuel producers 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.

[20] This news will have a large impact on fossil fuel producers. 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.

[21] 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.

[22] This news is unlikely to have a substantial impact on fossil fuel producers. 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.

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

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 policies or regulations which directly affect the ability of fossil fuel companies to expand their maximum production capacity?
(a) Yes
(b) No - If answered ”No”, skip Question2,3,4 (answer (c) in Question2, (e) in Question3, and (e) in Question4).

Question2: Does this article indicate policies or regulations which expand or restrict the ability of fossil fuel companies to expand their production capacity?
(a) Restriction
(b) Expansion
(c) Neutral - The article does not provide specific details or evidence regarding the ability of fossil fuel companies to expand their production capacity.

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 regulations impacting fossil fuel production capacity will be on the market prices and operational strategies of fossil fuel companies? Please also include news not related to the United States.
(a) Most Significant Impact[24]
(b) Highly Significant Impact[25]
(c) Moderate Impact[26]
(d) Minimal Impact[27]
(e) No Impact[28]

Question5: Does this article discuss licensing and permit regulations for fossil fuel production, like transportation and export permit availability, or oil and gas lease access? Please also include news not related to the United States.
(a) Yes
(b) No - If answered ”No”, skip Question6,7,8 (answer (c) in Question6, (e) in Question7, and (e) in Question8).

Question6: 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 regulatory or financial cost of carbon emissions in U.S..

Question7: How likely is the change you indicated in Question6?
(a) Extremely Likely
(b) Very Likely
(c) Somewhat Likely
(d) Slightly Likely
(e) Neutral - if answered Neutral in Question6.

Question8: How significant do you anticipate the impact of this news about regulatory or financial cost of carbon emissions in U.S. will be on the market prices and operational strategies of companies in the fossil fuel industry?
(a) Most Significant Impact[23]
(b) Highly Significant Impact[24]

(c) Moderate Impact[25]
(d) Minimal Impact[26]
(e) No Impact[27]

Question9: Does this article discuss policies or regulations which directly impact the availability of financing for fossil fuel infrastructure, or factors affecting it, such as shifts in bank funding policies or shareholder activism? Please also include news not related to the United States.
(a) Yes
(b) No - If answered ”No”, skip Question10,11,12 (answer (c) in Question10, (e) in Question11, and (e) in Question12).

Question10: Does this article indicate policies or regulations that expand or restrict fossil fuel infrastructure financing availability? Please also include news not related to the United States.
(a) Restriction
(b) Expansion
(c) Neutral - The article does not provide specific details or evidence regarding fossil fuel infrastructure financing availability.

Question11: How likely is the change you indicated in Question10?
(a) Extremely Likely
(b) Very Likely
(c) Somewhat Likely
(d) Slightly Likely
(e) Neutral - if answered Neutral in Question10.

Question12: How significant do you anticipate the impact of this news about infrastructure financing availability will be on the market prices and operational strategies of fossil fuel companies? Please also include news not related to the United States.
(a) Most Significant Impact[23]
(b) Highly Significant Impact[24]
(c) Moderate Impact[25]
(d) Minimal Impact[26]
(e) No Impact[27]

Question13: Does this article discuss policies or regulation directly affecting the compliance requirements of fossil fuel infrastructure, including factors like oil well emissions standards or offshore drilling safety requirements? Please also include news not related to the United States. (Not company policy)
(a) Yes
(b) No - If answered ”No”, skip Question14,15,16 (answer (c) in Question14, (e) in Question15, and (e) in Question16).

Question14: Does this article indicate policies or regulations that increase or reduce fossil fuel infrastructure compliance requirements? Please also include news not related to the United States.
(a) Restriction
(b) Expansion
(c) Neutral - The article does not provide specific details or evidence regarding fossil fuel infrastructure compliance requirements.

Question15: How likely is the change you indicated in Question14?
(a) Extremely Likely
(b) Very Likely
(c) Somewhat Likely
(d) Slightly Likely
(e) Neutral - if answered Neutral in Question14.

Question16: How significant do you anticipate the impact of this news about compliance requirements will be on the market prices and operational strategies of fossil fuel companies? Please also include news not related to the United States.

(a) Most Significant Impact[23]
(b) Highly Significant Impact[24]
(c) Moderate Impact[25]
(d) Minimal Impact[26]
(e) No Impact[27]

We analyzed a total of 33,960 news articles, filtered by the above keywords over our 12-year sample period. The five topics included in our index construction are:

- 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-4o Mini 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.

---

[24] 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.

[25] 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.

[26] 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.

[27] 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.

[28] 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-4o Mini				
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 a significant new plan by President Obama to regulate carbon emissions from power plants, indicating a tightening of U.S. carbon pricing policy. The regulations aim to curb emissions, which will likely lead to increased costs for fossil fuel producers, particularly coal. The mention of potential job losses in the coal industry and the need for states to adopt cleaner energy options further supports this tightening stance.
Trump Stymies California Climate Efforts Even as State Burns	Yes	Loosening	Extremely Likely	Highly Significant Impact	The article discusses U.S. carbon pricing policy indirectly through California's efforts to maintain stricter emissions standards against the Trump administration's rollbacks. The administration's actions, including revoking California's authority under the Clean Air Act, indicate a loosening of carbon pricing policy. This is significant as it undermines California's leadership in climate policy, which could lead to broader implications for carbon pricing nationally. The likelihood of this change affecting the fossil fuel industry is high due to California's economic influence.
Parachutist's Record Fall: Over 25 Miles in 15 Minutes	No	Neutral	Neutral	No Impact	The article does not discuss U.S. carbon pricing policy or related factors, focusing instead on Alan Eustace's record-breaking jump. It highlights his technical achievements and personal motivations rather than any policy implications. Therefore, the responses reflect a neutral stance regarding carbon pricing policy.

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

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

	Responses from GPT-4o Mini				
Headline	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 the regulatory cost of carbon emissions due to the new limits imposed on coal and gas plants. The requirement for technology like carbon capture and sequestration adds financial burdens to coal operators. This regulatory change is likely to have a highly significant impact on fossil fuel producers, as they may need to invest heavily in compliance technologies and potentially alter their operational strategies to adapt to the new standards, leading to considerable market fluctuations.
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 pollution regulations. This change is deemed extremely likely, as the Trump administration is expected to simplify compliance for automakers, reducing their financial burden. The impact on fossil fuel producers is considered highly significant, as the relaxation of these standards may lead to increased emissions and potentially lower operational costs for fossil fuel companies, prompting them to adjust their strategies accordingly.
A Hot Spot for River Otters? The Latrine	No	Neutral	Neutral	No Impact	Similarly, the article does not address regulatory or financial costs of carbon emissions in the U.S. It centers on ecological research rather than economic or regulatory frameworks, resulting in 'No' for Question5 and a neutral stance in Questions 6-8, indicating no impact on the fossil fuel industry.

Note: Sample responses from GPT-4o Mini 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-4o Mini				
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 new solar technology that aims to enhance the energy content of natural gas, indicating a breakthrough in renewable energy. The process could reduce natural gas usage and greenhouse gas emissions by 20%, which is significant for renewable energy advancements. The mention of federal stimulus funding also highlights governmental support for such innovations.
Chinese Solar Panel Giant Is Tainted by Bankruptcy	Yes	Decrease	Extremely Likely	Highly Significant Impact	The article discusses the collapse of Suntech Power, a major player in the solar industry, indicating a significant downturn in the renewable energy sector. The bankruptcy reflects a decrease in the viability of solar manufacturing, particularly for Chinese companies, due to overcapacity and tariffs. This suggests a decrease in breakthrough probabilities for renewable energy technologies as financial instability hampers innovation and growth.
Dwarf Planet Lacks Atmosphere, Glimpse Suggests	No	Neutral	Neutral	No Impact	The article does not discuss renewable energy or battery storage technology breakthroughs, focusing instead on the scientific findings related to the dwarf planet Makemake. Therefore, it is marked as 'No' for Question1, leading to a neutral stance in subsequent questions regarding renewable energy impacts.

Note: Sample responses from GPT-4o Mini 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-4o Mini		
Headline	Discussed Actual BT?	Importance	Explanation
Batteries That Make Use of Solar Power, Even in the Dark	Yes	Highly Significant Impact	The article details the actual implementation of battery storage technology, which is already operational on Beatty's farm. This technology allows for better energy management and increased revenue, indicating a highly significant impact on fossil fuel market dynamics as renewable energy becomes more competitive. The potential for battery storage to stabilize energy supply further emphasizes its importance in the transition to renewable energy.
Wind Farms See Promise in Platforms That Float	Yes	Highly Significant Impact	The article details actual technology breakthroughs, such as the successful testing of floating platforms at the University of Maine. These advancements are expected to reduce costs and improve the viability of offshore wind energy, which could significantly impact fossil fuel market prices as renewable energy becomes more competitive. The anticipated commercial deployment of these technologies suggests a highly significant impact on fossil fuel operational strategies.
What if Highways Were Electric? Germany Is Testing the Idea.	Yes	Highly Significant Impact	The article mentions that the eHighway project is already operational, with trucks using the system, indicating a realized technology breakthrough. This could lead to a highly significant impact on fossil fuel market prices as companies may need to adapt to a changing landscape where electric-powered trucks become more prevalent, thus affecting their long-term operational strategies.

Note: Sample responses from GPT-4o Mini 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-4o Mini				
Headline	Relevance	Direction	Strength	Importance	Explanation
Banks Pull Back on Funding Coal	Yes	Restriction	Extremely Likely	Extremely Significant Impact	The article discusses significant restrictions on coal financing, with major banks like JPMorgan Chase, Bank of America, and Citigroup halting funding for new coal projects. This shift indicates a permanent downward trend in coal production capacity, as banks view lending to coal companies as increasingly risky. The impact on market prices is expected to be significant due to the potential for extreme fluctuations and the need for companies to alter their operational strategies.
Trump Revives Keystone Pipeline Rejected by Obama	Yes	Expansion	Extremely Likely	Highly 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, the administration is facilitating increased oil transport and production, indicating a clear policy shift towards expansion.
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' ability to expand production capacity. The proposed regulations aim to limit methane emissions, indicating a restriction on operations that could lead to increased costs and compliance burdens for these companies. This is significant as it represents a shift from previous policies and aims to address climate change more aggressively.

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

D.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 the stock market's response 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.

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

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 D.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, together with the oil capacity news index, with labels indicating related events.

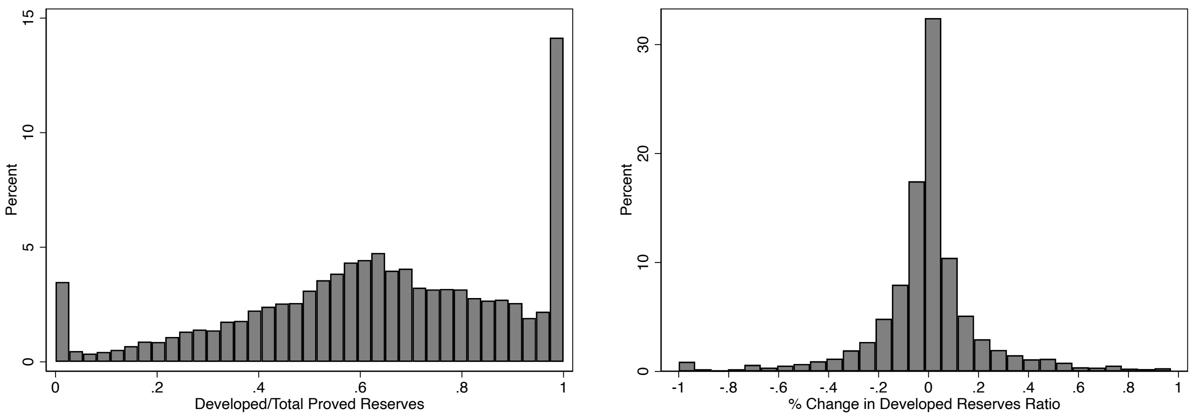
D.2 Classification of energy companies and returns data cleaning

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. We also dropped observations with stock price < \$1 if it was preceded by a month of stock prices < \$1.

To obtain our continuous classification of existing production capacity, we compute a proved developed reserves ratio by dividing the combined amount of proved *developed* reserves for oil, natural gas, and natural gas liquids in barrel of oil equivalents (BOE) by the combined amount of *total* proved reserves for these resources in BOE.[29] 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 infrastructure to develop a large fraction of the reserves that they own, and are more similar to entrants in our model.

We obtain the proved developed reserves and total proved reserves from the Industry Specific Annual section of Compustat where available. Otherwise, we manually looked up reserves values in the SEC's EDGAR database to input 116 instances of companies missing yearly reserves data in the Compustat database. We also carried forward this value for a maximum of 2 years, to account for when companies change their year-end definition and delay filing their 10-K reports. 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 panel shows the distribution of ratios of developed/total reserves (reported annually). The right panel instead reports 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:

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

where $\mathrm{Idx}_{k,t}$ 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.

D.3 Oil Futures Price

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

---

[29] Barrel of oil equivalents (BOE) allows to aggregate oil, natural gas and natural gas liquids reserves by the amount of energy they produce.

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.

D.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, signal strength, and responses from the importance question. Table 11 presents versions for other scaling methods: direction only, direction scaled by signal strength, and direction scaled only by importance. The results are consistent across scaling methods.

We obtained our results in Table 3 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 amount of *developed* reserves for oil and the amount of *total* proved reserves for oil, obtained from Compustat and the SEC's EDGAR database. We find that our results are directionally consistent across all regression specifications, with varying levels of statistical significance.

We compare our results with regression results using other measures of transition risk introduced in Ardia et al. (2023), Faccini et al. (2023), and Bua et al. (2024) and the same stock price and oil futures price regression specifications as in Tables 3 and 4. For the stock price regression, the results are largely statistically insignificant. The results which are statistically significant agree with our empirical results, except Bua's Transition News measure interacted with a renewable dummy. For the oil price regression, only Ardia's Media Climate Change Concern (MCCC) Index was statistically significant, with a large positive coefficient, showing that as climate change concern increases, oil futures prices also increase.

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)
Fossil Fuel Company × Index AR(1) Innovation	-0.0062**	-0.0053**	-0.0059**	-0.0081***	-0.0079***	-0.0080***	-0.0047**	-0.0044**	-0.0047**
	(0.0024)	(0.0025)	(0.0025)	(0.0019)	(0.0021)	(0.0019)	(0.0022)	(0.0022)	(0.0022)
Fossil Fuel Company × Index AR(1) Innovation × Developed Ratio	0.0100***	0.0092**	0.0098***	0.0121***	0.0118***	0.0119***	0.0076**	0.0073**	0.0076**
	(0.0035)	(0.0037)	(0.0036)	(0.0029)	(0.0032)	(0.0029)	(0.0034)	(0.0034)	(0.0034)
Renewable × Index AR(1) Innovation	0.0023**	0.0026**	0.0023**	0.0027***	0.0027***	0.0026***	0.0012	0.0012	0.0012
	(0.0010)	(0.0011)	(0.0010)	(0.0007)	(0.0007)	(0.0007)	(0.0009)	(0.0009)	(0.0009)
Company FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Remove Market from Stock Returns	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Specification	Dir	Dir×Str	Dir×Imp	Dir	Dir×Str	Dir×Imp	Dir	Dir×Str	Dir×Imp
R^2	0.607	0.606	0.606	0.629	0.626	0.626	0.586	0.585	0.586
Observations	50851	50851	50851	50851	50851	50851	50851	50851	50851

Note: This is a robustness table of Table 3. Regressions (1)-(3) 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 (4)-(6) instead show coefficients of regressing stock returns on AR(1) innovations of NYT-Renewable Breakthrough News Index, and regressions (7)-(9) 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 removed observations with stock price < \$1 if it was preceded by a month of stock prices < \$1. We focus on the most frequent sections: "business financial", "national", "foreign", "metropolitan", "science", "climate", "us", "editorial", "business", excluding sections such as "travel" and "opinion" to better capture direct news such as new policy announcements. We focus on energy firms in these regressions. The news indices were constructed by scaling direction based on the signal strength and the news's importance to market prices and oil industry operation strategies. This table includes several scaling methods: direction only ((1), (4) and (7)); direction scaling by signal strength ((2), (5) and (8)); and direction scaling by importance ((3), (6) and (9)). 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	-0.0072***	-0.0030	-0.0055***	-0.0069***	-0.0058***	-0.0066***	-0.0038	-0.0031*	-0.0038**
	(0.0023)	(0.0023)	(0.0018)	(0.0022)	(0.0020)	(0.0019)	(0.0025)	(0.0018)	(0.0018)
Fossil Fuel Company × Index AR(1) Innovation × Developed Ratio	0.0112***	0.0058*	0.0094***	0.0097***	0.0086***	0.0097***	0.0079**	0.0051*	0.0061**
	(0.0034)	(0.0034)	(0.0027)	(0.0035)	(0.0032)	(0.0029)	(0.0037)	(0.0028)	(0.0027)
Renewable × Index AR(1) Innovation	0.0028***	0.0029**	0.0026**	0.0023***	0.0022***	0.0027***	0.0017*	0.0013	0.0012
	(0.0011)	(0.0011)	(0.0011)	(0.0008)	(0.0007)	(0.0007)	(0.0009)	(0.0010)	(0.0009)
Company FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Section Filtering	No	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Remove Market 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	0.621	0.617	0.617	0.610	0.622	0.622	0.602	0.597	0.585
Observations	50851	45808	50557	50851	45808	50557	50851	45808	50557

Note: This is a robustness table of Table 3. 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 focus on the most frequent sections: "business financial", "national", "foreign", "metropolitan", "science", "climate", "us", "editorial", "business", excluding sections such as "travel" and "opinion" to better capture direct news such as new policy announcements. We focus on energy firms in these regressions and removed observations with stock price $< \$1$ if it was preceded by a month of stock prices $< \$1$. 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 amount of developed reserves for oil and the 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).

Table 13: Stock Returns and Other Indices

	Bua	Faccini	Ardia
	(1)	(2)	(3)
Fossil Fuel Company × Index AR(1) Innovation	-0.0041**	-0.0003	0.0023
	(0.0018)	(0.0028)	(0.0030)
Fossil Fuel Company × Index AR(1) Innovation × Developed Ratio	0.0035	0.0008	-0.0034
	(0.0028)	(0.0041)	(0.0047)
Renewable × Index AR(1) Innovation	-0.0025***	0.0039***	0.0008
	(0.0007)	(0.0010)	(0.0007)
Company FE	Yes	Yes	Yes
Remove Market from Stock Returns	Yes	Yes	Yes
R^2	0.610	0.614	2.862
Observations	50851	49082	29687

Note: This is a robustness table of Table 3. Regression (1) shows coefficients of regressing stock returns on AR(1) innovations of Bua et al. (2024) Transition Risk 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. Regressions (2) and (3) instead show coefficients of regressing stock returns on the AR(1) innovations of the Faccini et al. (2023) Climate Policy Index and AR(1) innovations of the Ardia et al. (2023) Media Climate Change Concern 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 removed observations with stock price < \$1 if it was preceded by a month of stock prices < \$1. We focus on the most frequent sections: "business financial", "national", "foreign", "metropolitan", "science", "climate", "us", "editorial", "business", excluding sections such as "travel" and "opinion" to better capture direct news such as new policy announcements. 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 14: Oil Futures Price and Other Indices

	Monthly Level		
	Avg 1-12m (1)	Avg 13-60m (2)	Avg 1-60m (3)
Index AR(1) Innovation - Bua Transition Risk Index	-0.0017 (0.0055)	0.0009 (0.0038)	-0.0004 (0.0043)
Controls	Yes	Yes	Yes
R^2	0.45	0.42	0.48
Observations	143	143	143
	(1)	(2)	(3)
Index AR(1) Innovation - Faccini Climate Policy	0.0063 (0.0071)	0.0030 (0.0049)	0.0042 (0.0051)
Controls	Yes	Yes	Yes
R^2	0.47	0.44	0.49
Observations	137	137	137
	(1)	(2)	(3)
Index AR(1) Innovation - Ardia Media Climate Change Concern	0.0197*** (0.0057)	0.0144*** (0.0040)	0.0179*** (0.0050)
Controls	Yes	Yes	Yes
R^2	0.47	0.46	0.49
Observations	77	77	77

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).