Climate Transition Risks and the Energy Sector *

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Abstract

We study how three climate transition risks—and uncertainty about their implementation—affect energy prices and energy-sector firm valuations: restrictions on fossil-fuel capacity, future carbon taxes, and technological breakthroughs that allow renewables to serve all sectors. The model distinguishes incumbents with developed reserves, entrants that must invest in exploration and drilling, and renewable producers. We show that these risks are interdependent but have distinct effects on investment, valuations, and prices, with optimal carbon taxes concentrated in breakthrough states because technological progress lowers policy costs. Empirically, we find support for heterogeneous effects on energy prices, firms' drilling permit submissions, and energy-sector stock returns.

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

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Through the burning of fossil fuels, energy production accounts for about three-quarters of global greenhouse gas emissions (Ritchie and Roser, 2020), making the energy sector a central focus of climate policy. To encourage a transition away from fossil fuels, policymakers employ a range of tools, including carbon prices, R&D subsidies for renewable energy, and restrictions on new fossil fuel capacity. This paper studies how these policies—and uncertainty about their implementation—shape the dynamics of prices, investment, production, and firm valuations across the energy sector. We find that the different policies, while often grouped together as 'climate transition risks,' can have meaningfully different implications for these outcomes, and should therefore be distinguished from one another. At the same time, we show that the different transition risks are tightly linked: we should expect carbon pricing to be implemented in precisely those states of the world that also bring technological innovation, since innovation lowers the cost of switching to greener energy production and thereby the welfare losses from carbon pricing.

We build a two-period model of the energy sector, where the periods can be thought of as roughly a decade apart. We model two types of fossil fuel firms: (i) incumbents with developed reserves that can be extracted at low marginal cost either today or tomorrow, and (ii) new entrants that must 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 solar park—to produce emission-free energy at zero marginal cost tomorrow. With current technologies, renewables cannot fully power the economy: their output 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 are hard to electrify. As a result, with current technologies, some share of future economy-wide energy demand must be met by fossil fuel firms, regardless of how much renewable capacity is built.

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 firms' investment and production behavior, on energy prices, and on valuations across the various parts of the energy sector.

Key Mechanisms. While the paper calibrates and solves the full model in which all transition risks appear jointly, the mechanisms are clearest when thinking through the risks independently. First, consider a time-0 restriction on *new* fossil fuel capacity. The restriction affects new entrants, limiting their ability to install capacity. This drop in investment capacity at time 0 reduces future supply, raising time-1 energy prices. Anticipating these higher future prices, incumbents delay extraction of their reserves, shifting production toward time 1. By withholding supply today, this inter-temporal inventory management also raises time-0 prices.[2] Valuation effects are heterogeneous: incumbents and renewable firms benefit from higher prices and reduced competition, while fossil fuel entrants lose because their ability to invest is constrained.[3]

Second, we analyze the effects of uncertain future carbon taxes, modeled as a period-1 tax τ on fossil fuel revenues that is implemented with probability π_T. The incumbent's key decision is

[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.

[2] This generates a form of what the ECB's Isabel Schnabel (2022) termed "fossilflation."

[3] Incidentally, our model highlights how measures aimed at *reducing* restrictions on new oil supply—including those proposed by the second 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 22, 2024).

how much of its developed reserves to extract and sell today (period 0) versus carry as inventory for potential extraction tomorrow (period 1). Crucially, firms are not obliged to fully extract their inventory: if the after-tax price in a given period-1 state would not cover the extraction cost, the incumbent can optimally leave some reserves "stranded" in the ground in those states. The value of carrying inventory into period 1 thus depends on the post-tax price the incumbent expects to receive in each period-1 state, not just the expected price across all states.

The option to leave reserves stranded in high-tax states shapes how the incumbent allocates extraction over time, and thus how current prices and valuations respond to changes in the expected carbon tax. This produces two regimes, distinguished by the expected level of the tax in the tax-state. At low initial tax rates, the incumbent expects to extract its full inventory in both the tax and non-tax states of the world. Increases in the expected tax therefore reduce expected revenue in period 1, and the incumbent accelerates extraction—a version of the "green paradox" (Sinn, 2008), in which the prospect of future climate policy accelerates near-term fossil fuel use. The anticipation of lower period-1 post-tax revenues also discourages capacity investments by the entrant. The combined drop in entrant and incumbent supply raises period-1 prices. Both incumbent and new entrant fossil fuel producers see their valuations decline as expected profits fall, while renewable valuations rise as fossil energy becomes less competitive.

At higher tax rates, the incumbent may leave some reserves stranded in the tax state: beyond a threshold $\tau > \tau_{\text{strand}}$, the after-tax price in the tax state falls below the marginal cost of extracting the full reserves, making it optimal to leave some reserves in the ground rather than extracting them at a loss. Given uncertainty about whether the tax is imposed at all, these reserves still retain option value ex ante, since extraction remains profitable in the no-tax state. Perhaps surprisingly, in the region $\tau > \tau_{\text{strand}}$, further increases in the expected tax can thus lead the incumbent to carry *more* reserves into period 1 rather than extracting them today, which leads to higher period-0 prices—a reversal of the "green paradox" logic described above. The intuition is that the *marginal* unit is already stranded in the taxed state—its value there cannot fall below zero as tax rates increase further—while reduced entrant investment raises the price in the no-tax state, the only state in which the marginal unit of reserves is still sold. Even though the marginal unit's value can therefore rise with expected taxes, incumbent valuations continue to fall, as higher taxes keep eroding the value of the *inframarginal* units still extracted in the tax state. Valuations for entrants also fall, while those of renewable firms increase.

Third, we consider the possibility of a technological breakthrough in renewable energy. Renewable firms invest today to supply clean energy tomorrow. With probability π_{BT}, a breakthrough allows renewables to satisfy demand from all sectors of the economy; otherwise, under current technology, renewables are only able to supply a share of the economy. Higher π_{BT} increases renewable investment, lowers breakthrough-state prices, reduces entrant fossil fuel investment, and induces incumbents to extract more today. Renewable firms' valuations rise, while fossil fuel firms' valuations decline, particularly for entrants. As with carbon taxes, uncertainty can generate a real-options channel: if renewable capacity is sufficiently large, incumbents may choose to strand reserves in the breakthrough state. In that region, marginal inventory decisions depend only on prices in the non-breakthrough state, so higher π_{BT} can raise current prices and inventories. However, a higher breakthrough probability also makes the non-breakthrough state less likely, so that the overall effect on the inventory management decisions of incumbents—and thus on today's prices and quantities—can be ambiguous.

Endogenous Link Between Transition Risks. We next explore how these mechanisms interact once they operate jointly. Before studying the full model solution, we derive an important result that helps us reduce the dimensionality of the problem, and gives us insights about the link between transition risks. The key insight is that these transition risks are, to varying degrees, endogenous (we take the policy choices to be fully endogenous and the technological innovation to be exogenous, though with a probability that is affected via the choice of R&D). We derive the following result: optimality of policy implies that high-carbon-tax states are likely to coin-

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

cide with "technological breakthrough" states in which renewable firms can supply substantial amounts of energy. This is because carbon taxes in those states can reduce emissions without substantial negative effects on energy prices and economic activity. Since the distortions from carbon taxes are lower if there is a cheap green technology with which to replace fossil fuels, technological innovation also increases the incentives of policymakers to introduce carbon taxes. This insight has important implications for real-world analysis of transition risks. For example, in the design of climate stress tests, scenarios where large carbon taxes (e.g., in net-zero scenarios) occur jointly with technological innovation that softens their negative consequences appear more plausible than scenarios where large carbon taxes are assumed to occur despite potentially disastrous economic losses (see Acharya et al., 2023a).

Full Model. Armed with this insight, we then solve and illustratively calibrate the full model focusing on only two states of the world: one with technological breakthroughs *and* high carbon taxes, and one without breakthroughs and low taxes. The unified framework confirms the mechanisms identified above and shows that transition risks widen energy price differences between sectors able to use renewables and those reliant on fossil fuels, driven by greater renewable investment and lower fossil fuel supply.

Our model yields several testable predictions (summarized in Table 1). News increasing the probability of carbon taxes or technological breakthroughs lowers fossil fuel valuations—especially for entrants—and raises renewable valuations. Restrictions on new fossil fuel development reduce entrant valuations but may increase incumbent valuations. While restrictions on new capacity unambiguously raise energy prices, carbon tax and technological breakthrough news can have ambiguous price effects.

Empirical Results. We empirically test these implications by studying the reactions of oil futures prices, equity valuations in different energy sub-sectors, and drilling permit activity of oil and gas producers 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, a large language model 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 Index, which captures news about carbon pricing policies and the regulatory or financial costs of 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, as well as 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.

We then study how energy prices, drilling permit activity, and stock returns of energy firms respond 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 (see Section 4.2 for formal definitions of proved developed vs. undeveloped reserves). Firms with higher developed ratios—such as Exxon, Chevron, ConocoPhillips, 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 deciding whether to invest in future oil capacity. We identify renewable firms using the holding firms of the Invesco Solar ETF and the First Trust Global Wind Energy ETF, which include companies in the solar and wind energy industries, respectively. Examples of these firms include First Solar, Altus Power, and Arcosa Towers.

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.

Beyond financial market reactions, we explore whether transition risk news also affects real investment decisions. Using well-level drilling permit data from Enverus, we show that innovations in all three transition risk indices predict a decline in the number of new drilling permits filed by oil and gas firms over the following weeks. The cumulative effects are statistically significant for all three indices, with the renewable breakthrough index producing the strongest and most persistent response. These results suggest that transition risk news is associated not just with financial market movements but also with real investment decisions by fossil fuel firms, consistent with the model's prediction.

Finally, we find that oil futures prices decrease during months with news about possible renewable energy breakthroughs and increase in months with news about higher costs of carbon emissions, consistent with our model. However, news about tightening oil capacity is associated with a decrease in oil futures prices, contrary to the model's prediction. That said, oil futures prices are also driven by macroeconomic factors beyond transition risk news, making these estimates noisier.

Related Literature. Our paper belongs to the growing literature on climate finance, with a particular focus on the implications for energy firms (see Giglio et al., 2021; 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 can 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 (2024) 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 "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. We interpret the valuation of stranded assets through the lens of real options, along the lines of Brennan and Schwartz (1985) and Paddock et al. (1988). More recently, Flora and Tankov (2023) use a real-options approach to evaluate assets and potential investment projects under uncertainty about a climate transition. Similar to the mechanism highlighted by our paper, Ryan (2012) argues that environmental restrictions can increase the cost of entry and increase market concentration, focusing on the cement industry. Finally, we focus on the effects of various transition risks on the energy sector, abstracting from possible general equilibrium effects that are investigated by Barnett (2024), Cai and Lontzek (2019), and Barnett et al. (2024).

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 in green and non-green sectors.

Last but not the least, 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. (2023b), 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 Model Setup

In this section, we describe the full structure of our model, focusing on the economic environment, the agents, and all the various transition risks we analyze.

General Setup. 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 three types of representative producers. The first is an "incumbent" fossil fuel firm with developed reserves that can be extracted today or tomorrow. The second is a "new entrant" fossil fuel company that needs to invest today to build production capacity to extract tomorrow. Finally, there is a "renewable" energy firm that also must invest in capacity today to potentially supply green energy in the future. Energy supply at date zero is therefore entirely driven by the incumbent fossil fuel firm's extraction decisions.

We analyze two possible policy instruments affecting the fossil fuel sector. The first is the imposition of time-0 restrictions on new fossil fuel production capacity by entrants, modeled as a tax rate $\bar{\tau}_0$ on new capacity. 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 companies. The second is the introduction of a carbon tax at time 1, τ_1, on energy production coming from fossil fuel sources. Because we assume that capacity restrictions are imposed at date 0, there is no uncertainty about their implementation. Period-1 carbon taxes, on the other hand, will only be imposed with probability π_T. We denote with T (Tax) the set of all period-1 states of the world in which the carbon tax is introduced, and with NT (No-Tax) the states of the world with no tax.

Finally, we assume that the renewable firm will be able to supply energy in period 1 only if a "breakthrough" in renewable technologies occurs[4]. We let BT (Breakthrough Technology) denote the set of states where such a breakthrough occurs, and CT (Current Technology) be the set of states where there is no breakthrough. This captures the fact that current renewable technologies cannot yet 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). For simplicity, we assume that in the absence of a technological breakthrough, renewable firms are unable to supply any energy.[5]

We thus have four possible states in period 1, characterized by whether each of these risks materializes or not, which can be collected in the following state space

$$S = \{(BT, T), (CT, T), (BT, NT), (CT, NT)\}.$$

For now, we can think of these four states as separate. Before presenting the full solution to the model in Section 3, however, we will show that under optimal policy, we can derive a link between the two types of transition risks and reduce the dimensionality of this state space.

Incumbent fossil fuel firm. We now describe the problems of the various agents in the economy, starting with the incumbent fossil fuel firm. At time 0, the incumbent 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 has a cost of $\frac{1}{2\kappa_1}f^2$, with $\kappa_1 > 0$. Taking as given the price of energy in the two periods, and across the different states in period 1, $(P_0, \{P_{1,s}\}_{s\in S})$, and the carbon tax implemented in each state in period 1, $\{\tau_{1,s}\}_{s\in S}$, the incumbent firm chooses production quantities $(f_0^I, \{f_{1,s}^I\}_{s\in S})$ that solve

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

where the period-1 continuation value $V_{1,s}^I$ in each state $s \in S$ is equal to

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

Note that the incumbent does not invest into new capacity—its only decision is the intertemporal problem of when to extract and sell the fossil fuel.

Entrant fossil fuel firm. The other fossil fuel producer in the economy is a representative entrant firm (superscript E) that has no existing production capacity, and has to choose how much new capacity to install to be used in period 1.[6] Installing an amount of new capacity

[4] We later relax this assumption and allow the renewable firm to serve a fraction q of demand if the breakthrough does not occur.

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

[6] 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.

$\bar{f}_1^E$ has a cost $\frac{1}{2(1-\bar{\tau}_0)\kappa_2}(\bar{f}_1^E)^2$, with $\kappa_2 > 0$. The tax rate $\bar{\tau}_0 \in (0,1)$ captures the extent of restrictions on capacity expansion. The entrant's production costs in period 1 are the same as the incumbent firm's costs. 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:

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

where the period-1 continuation value $V_{1,s}^E$ is equal to

$$V_{1,s}^E = \max_{0 \leq f_{1,s}^E \leq \bar{f}_1^E} \; P_{1,s} f_{1,s}^E - \frac{1}{2\kappa_1}(f_{1,s}^E)^2. \tag{4}$$

Renewable energy firm. The renewable energy firm must invest in production capacity today to potentially supply energy in the future. We assume that installing an amount of production capacity C has a convex cost $\frac{1}{2\delta}C^2$, where $\delta > 0$. 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 purchasing fuels to operate). However, this will only be possible in states where the technological breakthrough has occurred, in which the renewable firm will always choose to employ its full production capacity. The renewable firm maximizes expected profits, taking as given the price of energy in the future states. The firm's problem is therefore:

$$\max_{C \geq 0} \; -\frac{1}{2\delta}C^2 + E[C_s P_{1,s}], \tag{5}$$

where $C_s = 0$ for $s \in \{(CT, NT), (CT, T)\}$ and $C_s = C$ for $s \in \{(BT, NT), (BT, T)\}$.

Equilibrium. We close the model by introducing a unit mass of consumers with 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 given price P is equal to $\frac{W}{P}$, yielding the following market clearing conditions:

$$\frac{W}{P_0} = f_0^I \tag{6}$$

$$\frac{W}{P_{1,s}} = f_{1,s}^I + f_{1,s}^E + C_s, \quad s \in S. \tag{7}$$

The definition of equilibrium is standard and specified formally in Appendix A.1. 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 implies that, absent any transition risk realizations, the incumbent firm expects to extract its full remaining reserves at the period-1 price, setting up an interesting trade-off between extracting today or tomorrow.

2 Model Analysis

In this section, we individually analyze each of the three transition risks that we study in our general model to clearly isolate their implications for energy prices and firm valuations. We begin with 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 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.

Next, we examine optimal carbon taxes in our framework, and find that high carbon taxes are likely to be implemented in the same future states of the world where the green transition occurs. This allows us to considerably simplify our subsequent analysis by restricting the state space in period 1 to two states only. Using this simplification, we then analyze the full model that incorporates all three climate transition risks jointly while fully endogenizing prices. We solve this model numerically to provide testable implications, and highlight that all intuitions developed in the simpler cases carry through.

2.1 Effects of Drilling Restrictions

We first focus on a case in which (i) no carbon tax is implemented in period 1 with certainty, and (ii) there is no possibility of a technological breakthrough that would allow for energy provision by renewable firms. The state space in period 1 is thus the singleton $S = \{(CT, NT)\}$. These assumptions allow us to clearly isolate the effect of date-0 drilling restrictions on firm valuations and energy prices. We derive the following result.

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 for this result is that restrictions on the development of new fossil fuel capacity only directly affect the entrant firm: 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 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 increase. Therefore, Proposition 1 predicts that news about increased drilling restrictions should have a negative effect on the stock prices for oil and gas firms with little existing capacity—those firms who still need to invest to develop reserves—while firms with large developed reserves can even see their stock market valuations increase due to reduced competition from entrants.

While we will formally test these predictions in Section 4, it is worth highlighting that they align closely with recent discussions about the potential effects of the Trump administration's expected *easing* of constraints on future oil-capacity expansion (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 highlight how restrictions on new drilling can affect incumbents and new firms differentially in ways consistent with our theoretical framework.

2.2 Effects of carbon taxes without uncertainty

The second source of transition risk we consider is the possible introduction of a carbon tax. To establish a benchmark, we first study the effects of a tax τ_1 that is implemented with certainty in period 1, so that fossil fuel producers only earn $(1 - \tau_1)P_1$ from selling an additional unit of energy in that period. We continue to assume that there will be no technological breakthrough in period 1, so the state space is now given by the singleton $S = \{(CT, T)\}$: current technology with carbon taxes. 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 result highlights that if fossil fuel firms expect the future introduction of carbon taxes with certainty, 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. This result is 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 nuanced ways.

2.3 Effects of uncertain carbon taxes

We now consider a carbon tax that is implemented only with some probability in the future. Specifically, now the state space in period 1 is given by $S = \{(CT, NT), (CT, T)\}$. Both states keep the current technology, but they differ by whether the tax is implemented (T) or not (NT). For simplicity, therefore, we let $NT = (CT, NT)$ and $T = (CT, T)$, and we denote with π_T the probability that state T realizes, in which case a carbon tax τ_1 is introduced on fossil fuel revenues. Demand for energy is the same across the two states. 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 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 be microfounded from 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). This assumption is supported by direct 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 tax rate τ_1 implemented with some probability is ambiguous. In particular:*

- *For low enough values of the tax rate, further 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 (that is, fossil fuel is never stranded). In that case, the optimal period-0 fossil fuel supply by the incumbent is:

$$f_0^I = \frac{\bar{f}_0}{2} + \frac{\kappa_1}{2}\Big[P_0 - \pi_T(1-\tau_1)P_{1,T} - (1-\pi_T)P_{1,NT}\Big], \tag{8}$$

while optimal capacity installation by the entrant is:

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\Big[\pi_T(1-\tau_1)P_{1,T} + (1-\pi_T)P_{1,NT}\Big]. \tag{9}$$

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 incumbent's 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 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 by Assumption 2, it is the incumbent (who has larger initial reserves, and therefore a higher marginal cost of extraction for its last unit) 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 9), 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:

$$f_0^I = \frac{1-\pi_T}{2-\pi_T}\bar{f}_0 + \frac{\kappa_1}{2-\pi_T}\Big[P_0 - (1-\pi_T)P_{1,NT}\Big]. \tag{10}$$

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 incumbent's *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* effects on the incumbent's period-0 extraction decision. Specifically, since higher taxes continue to induce the new entrant to reduce investment (see equation 9), they raise the 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. This mechanism continues to be in place until the tax rate becomes so high that further fossil fuel production becomes unprofitable for the incumbent as well.

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 be 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 non-monotonicity, which effectively reverses the "green paradox" effect at high levels of expected carbon taxes τ in state T.[7]

As highlighted by Assumption 2, our result relies on the incumbent having a larger cost of fully exhausting its reserves in period 1, which happens if $\bar{f}_0$ is sufficiently large. The level of initial reserves of the incumbent is therefore the key parameter that yields our nonmonotone response of the energy price to the tax rate, with higher $\bar{f}_0$ increasing the marginal cost of extracting the last unit of reserves, and thus lowering the threshold τ_{strand}.[8]

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.

We focused our discussion on the effects of changes in the tax rate on the date-0 energy price (that is, the level of the tax *conditional* on the tax being implemented). Alternatively, one could investigate the price response to changes in the tax probability, π_T. If the incumbent has no stranded assets in state T, then the effect of changes in the tax probability is the same as the effect of changes in the tax rate, namely $\frac{dP_0}{d\pi_T} < 0$. The intuition is that the incumbent still takes into account the lower P_T price for its marginal inventory decisions, and hence increasing its probability makes the future value of inventory lower, thus inducing an increase in current energy supply. If instead there are stranded assets in the T state, then the effect of changes in π_T on P_0 is generally ambiguous. On the one hand, the same mechanism that drives the tax rate result is in place, namely that a higher tax probability reduces investment from the entrant firm, thus increasing the energy price in the NT state and inducing the incumbent to reduce current energy supply, which increases P_0. On the other hand, an increase in π_T also makes the NT state less likely, which has the effect of reducing the incumbent's incentive to carry inventory in the future, thus raising current energy supply and while reducing P_0. The overall effect of an increase in π_T on the date-0 price is therefore ambiguous. However, for high enough levels of the tax probability π_T the second effect prevails, so that $\frac{dP_0}{d\pi_T} < 0$ even in the stranded assets case.

Modeling alternative 1: Linear Demand. In Appendix D.1, we show that the previous

[7]Note that for Proposition 3 we don't need the assumption that the carbon tax is exactly equal to zero in the NT state. The same result would continue to hold in the presence of a lower tax in the NT state, as long as part of the incumbent's assets are stranded in the T state only.

[8]We provide an analytic expression for τ_{strand} in Appendix D.1 using a model with linear demand.

results continue to hold if we assume an exogenously given energy demand that is linear in the price. This alternative formulation allows us to derive closed-form analytical expressions for the date-0 energy price and its derivatives, which can then be analyzed explicitly. We also derive an explicit expression for the tax threshold τ_{strand} after which the date-0 energy price becomes increasing in the tax rate, and show how it is decreasing in the level of initial reserves of the incumbent, $\bar{f}_0$. As highlighted above, large initial reserves mean that the marginal cost of fully extracting them becomes higher, so that it can become optimal for the incumbent to leave some of its assets stranded if the tax rate is high enough. While linear demand yields some analytical tractability, we do not use linear demand in our main model to be consistent with the welfare analysis of section 2.6, where we assume a standard utility function such as CRRA.

Modeling alternative 2: Stochastic Demand. Our baseline model assumes identical energy demand across period-1 states. We now allow demand to differ across states, and to correlate with transition risk realizations, in essence linking supply and demand shocks. In Appendix D.2, we show that our results continue to hold whenever energy demand is negatively correlated with the tax rate, i.e., when demand is lower in the T state. If instead the tax falls on a state where demand is sufficiently high, the post-tax price there may exceed the NT price. The T state then becomes the more attractive one for fossil fuel companies, so raising its probability could lead the incumbent to build inventory and push up the date-0 price. Assets may also become stranded in the NT state rather than the T state (though due to low demand), reversing the effect analyzed in Proposition 3. In short, if carbon taxes are positively correlated with energy demand, this could counteract our mechanism. However, Section 2.6 shows that carbon taxes are harder to implement precisely where energy prices are high, due to reduced supply from both fossil fuels and green firms. The more realistic case is therefore a tax imposed in lower-demand states, where energy prices are lower, leaving our implications intact.

2.4 Technological breakthroughs and a green energy transition

We now consider a different dimension of uncertainty, related to the possibility of a technological breakthrough that facilitates transitioning to an economy where clean producers can reliably satisfy the economy's full energy demand. For simplicity, we assume a world with no carbon taxes to assess this technological breakthrough scenario. The state space in period 1 is thus given by $S = \{(CT, NT), (BT, NT)\}$, distinguished by whether we have current technology (CT) or a breakthrough technology (BT). For simplicity, we let $CT = (CT, NT)$ and $BT = (BT, NT)$, and denote the probability that the BT state occurs by π_{BT}. That state is characterized by a supply of energy by the renewable firm, which is able to produce at zero marginal cost using capacity installed at time 0. We derive the following result:

Proposition 4. *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,* $\frac{dP_0}{d\pi_{BT}} < 0$.

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 generally ambiguous. However, we have $\frac{dP_0}{d\pi_{BT}} < 0$ *as* $\pi_{BT} \to 1$.

The Breakthrough Technology state features lower profits for fossil fuel firms because of the competition from the renewable sector. If the energy price difference across states is small—for example, due to limited capacity investment by renewable firms—then it is optimal 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 (8) in the case of carbon taxes. As π_{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. And given that the probability of that state is increasing, 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 π_{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: as in the high-carbon-tax case (equation 10), some reserves will be stranded in the BT state and the incumbent's marginal inventory decisions no longer depend on the BT price. Instead, they are based on the price in the CT state—the only state the incumbent is expecting to sell its marginal unit of inventory—weighted by the probability of that state: $(1-\pi_{BT})P_{1,CT}$.

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

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

2.5 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 reverse: worsening expectations related to future transition risk realizations can sometimes induce fossil fuel firms to reduce current energy supply, thus causing an increase in energy prices. For this to happen, there needs to be some *uncertainty* related to the realization of climate transition risks: there should be some states of the world with transition risk realizations characterized by low profits for fossil fuel companies, which 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 low-profit states should leave assets stranded for some firms, giving a positive value to the real option of not fully extracting the oil.

2.6 Optimal carbon tax policy

In the previous sections, we separated the discussion of a possible technological breakthrough in green energy production from the discussion of the possible introduction of carbon taxes. We now show that these two sources of transition risk are, in fact, closely related. In particular, policymakers will be more willing to impose high carbon taxes in states of the world where reliable clean energy is available, so that states of the world with technological breakthroughs and states with high taxes are likely to coincide.

Let us first consider uncertainty about the technological breakthrough alone, with a state-specific carbon tax that is different in the two scenarios. As before, we denote the two states by BT and CT for simplicity. We assume that fossil fuel emissions, $f_{1,s}$ in each state $s \in \{BT, CT\}$, entail a social cost $\frac{\lambda}{2} f_{1,s}^2$, with $\lambda > 0$. As before, there is a unit mass of consumers with preferences over energy consumption represented by a concave utility function u. Let $e_{1,s}$ denote total energy consumption. We can therefore define social welfare in each state as

$$W_{1,s} = u(e_{1,s}) - \frac{\lambda}{2} f_{1,s}^2. \tag{11}$$

In our analysis, we assume CRRA utility with parameter $\gamma > 1$. A benevolent social planner chooses a carbon tax in each state in order to maximize social welfare:

$$\max_{\tau_{1,s} \in [0,1]} W_{1,s}. \tag{12}$$

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 sets the period-1 tax after the technological state is realized, rather than committing in period 0 to a tax that maximizes expected ex-ante welfare. We make this assumption because a tax that is optimal ex ante need not remain optimal ex post: once the uncertainty about the technological state is resolved, the planner has an incentive to deviate from any previously announced policy. Agents anticipate this time-consistency problem and expect taxes to be chosen optimally in each state. The resulting optimal taxes correspond to a subgame perfect equilibrium. We derive the following result about the optimal carbon tax:

Proposition 5. *It is always optimal for the social planner to have less fossil fuel production in the BT state compared to the CT state. When carbon taxes are implemented in both states, it is optimal to impose a higher carbon tax in the BT state: $\tau^*_{1,BT} > \tau^*_{1,CT}$. 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 lower energy prices resulting from the provision of clean energy by the renewable sector. As a result, 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. In that state, large carbon taxes substantially increase energy prices and harm consumers. It follows that a lower carbon tax is optimally implemented in the CT state.[9]

Level of Optimal Carbon Tax vs. Breakthrough Probability. We now analyze how the level of the optimal carbon tax in the BT state varies with the ex-ante breakthrough probability π_{BT}. Let $e_{1,BT}$ denote energy consumption and $f_{1,BT}$ total fossil-fuel supply in the BT state. Because production capacities ($\bar{f}_0 - f_0^I$, $\bar{f}_1^E$, and C) are chosen at date 0, they are predetermined when the date-1 state realizes and the tax is set. Assuming an interior solution, the planner chooses $\tau^\star_{1,BT}$ so that:

$$u'(e_{1,BT}) \frac{de_{1,BT}}{d\tau_{1,BT}} = \lambda f_{1,BT} \frac{df_{1,BT}}{d\tau_{1,BT}}.$$

In equilibrium, $e_{1,BT} = C + f_{1,BT}$, and since C is fixed at date 1, any tax-induced change in consumption must come one-for-one from fossil-fuel supply, $de_{1,BT}/d\tau_{1,BT} = df_{1,BT}/d\tau_{1,BT}$. The first-order condition therefore reduces to

$$u'(e_{1,BT}) = \lambda f_{1,BT}. \tag{13}$$

Equation (13) equates the marginal cost and the marginal benefit of taxation: the last unit of fossil energy displaced by the tax costs consumers its marginal utility, $u'(e_{1,BT})$, and avoids the marginal emission damage, $\lambda f_{1,BT}$. At the optimum, the two coincide.

[9] 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.

To see how $\tau^{\star}_{1,BT}$ responds to the breakthrough probability, consider an increase in π_{BT} holding the tax fixed. A higher π_{BT} raises the supply of green energy and reduces fossil fuel supply. In equilibrium, the energy price in the BT state is lower, and energy consumption is higher. Since $e_{1,BT}$ rises and $f_{1,BT}$ falls, both sides of equation (13) therefore decline: marginal utility falls because energy is more abundant ($u'' < 0$), and marginal emission costs fall because fewer fossil fuels are burned ($\lambda > 0$). Therefore, the optimality condition no longer holds. The direction in which the planner adjusts the tax depends on which side falls by more. Since a higher carbon tax reduces fossil-fuel supply, raises the price, and lowers consumption ($df_{1,BT}/d\tau_{1,BT} < 0$ and $de_{1,BT}/d\tau_{1,BT} < 0$), raising the tax increases the left side of equation (13) and decreases the right side. Hence, if the increase in π_{BT} leaves $u'(e_{1,BT}) < \lambda f_{1,BT}$—that is, marginal utility has fallen by more than marginal damage—restoring equation (13) requires a higher tax; if instead $u'(e_{1,BT}) > \lambda f_{1,BT}$, it requires a lower tax.

The economic intuition is as follows. If the breakthrough delivers a large expansion of green energy, consumption rises substantially and the utility cost of displacing the remaining fossil fuel is small; the planner then optimally raises the tax to curb emissions further, at a small consumption cost. If instead the additional green supply barely offsets the decline in fossil-fuel supply, energy remains scarce and expensive; the planner then optimally lowers the tax to reduce the energy price, accepting the welfare loss from higher emissions.

We showed in the previous sections that increases in the breakthrough probability are generally associated with higher fossil fuel production and emissions at date-0 (the "green paradox"). Expectations about future carbon taxes, on the other hand, can induce an increase in the date-0 energy price, due to the lower fossil fuel supply coming from the incumbent firm through its inventory decisions. Therefore, the green paradox result associated with a higher breakthrough probability can be attenuated if the increase in breakthrough probability induces the planner to increase the optimally imposed carbon tax in the BT state, and if this increase is strong enough to leave some of the incumbent's assets stranded in that state. By the argument above, the optimal tax rises with π_{BT} when the marginal utility cost of taxation falls below the marginal gain from reducing emissions. In our model, this can occur when consumers' utility is highly curved (high γ under CRRA preferences), so that the rise in consumption driven by green energy supply sharply depresses marginal utility. It follows that under this scenario, the optimal policy response can counteract the green paradox result, and even reverse it if the increase in CT state profits more than compensates the lower probability of that state, so that the incumbent firm aggressively reduces date-0 energy supply to increase its inventory.

2.7 Carbon taxes and renewable technologies

The argument in the previous section suggests that it is optimal for the social planner to implement higher carbon taxes and have fossil fuel stranded assets in the same future states of the world where the breakthrough in renewable technologies occurs. This is due to the fact that it would be less socially costly to implement policies aimed at limiting fossil fuel emissions in a state where there is large energy supply from renewable firms. Therefore, in order to analyze both the effects of carbon taxes and breakthrough technologies on the energy sector, we can simplify our analysis by assuming that carbon taxes are only imposed when the technological breakthrough occurs, so that the relevant state space for period 1 becomes

$$S = \{(BT, T), (CT, NT)\}.$$

That is, it is sufficient to focus on two future states of the world only: one where the technological breakthrough occurs and carbon taxes are implemented, and another where there is no green energy supply and no carbon taxes. We will therefore base the rest of our analysis on this assumption, and denote for simplicity the two states by BT and CT respectively, since the technological breakthrough is the main determinant of the adoption of carbon taxes. Finally,

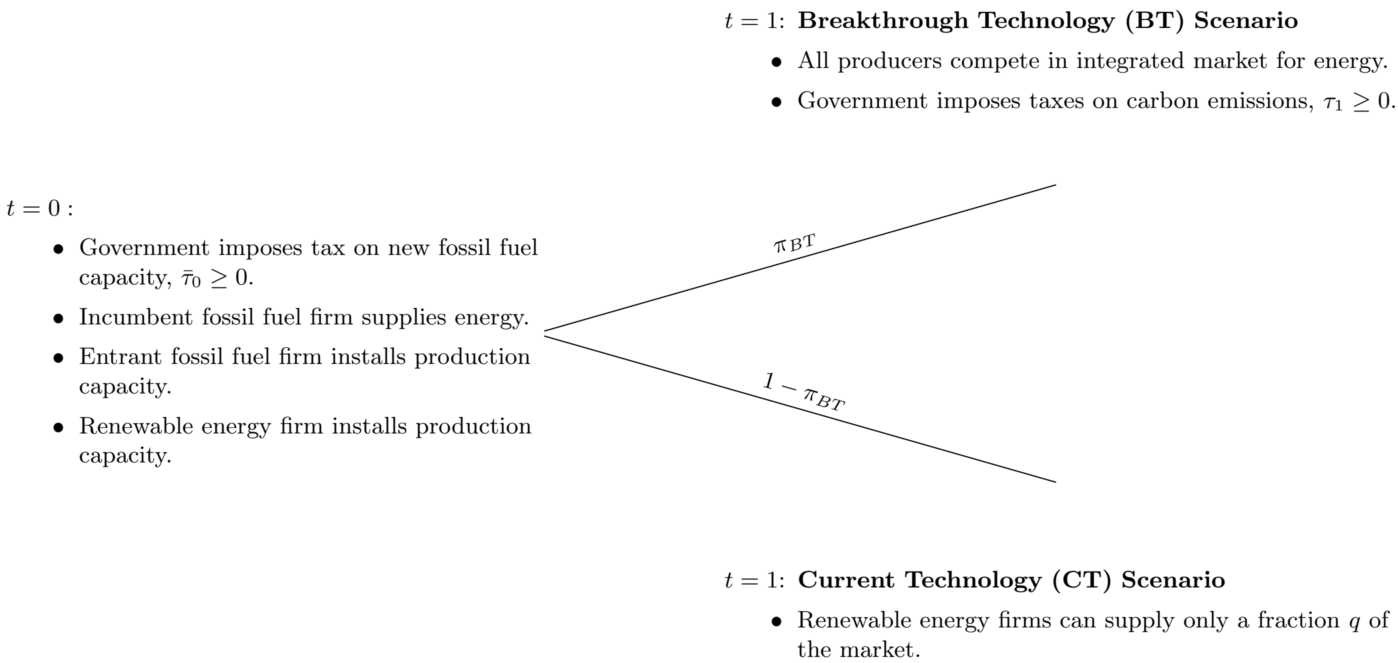


Figure 1: Timeline of the model.

we let π_{BT} be the probability that the BT state occurs. Figure 1 shows the timeline of our full model under this two-state assumption, with an overview of all the actions performed by the various firms in the two periods.

3 Solution of the full model

In this section, we solve the full model that jointly incorporates the three transition risks. We show that the previous results continue to hold in this more general model, and use numerical examples to illustrate how additional outcomes vary with each transition risk.

3.1 Summary of Setup

The model setup was presented in Section 1, and includes the three types of transition risks that we have so far considered separately: drilling restrictions, uncertain carbon taxes, and the probability of a technological breakthrough in renewable technologies. The main difference relative to the original setup is that we assume that carbon taxes are implemented only if the technological breakthrough occurs, as implied by the optimal policy result of the previous section. Therefore, the model features only two states of the world, $S = \{(BT, T), (CT, NT)\}$. The timeline of the model is summarized in Figure 1. All the details of the full model and the solution are reported in Appendix A.

One difference from the simpler models 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 ($0 < q < 1$). 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. In particular, fossil fuel firms will only supply energy to the NE market in equilibrium, thus creating a degree of segmentation between the two markets.

3.2 Main Results

We first show that the key results that we derived in Section 2 continue to hold. In particular, we have the following proposition.

Proposition 6. *In the general model, the period-0 price of energy is affected by the various transition risks as follows:*

- *An increase in the tax on new fossil fuel production capacity, $\bar{\tau}_0$, increases the period-0 price of energy.*
- *An increase in the probability of a technological breakthrough in renewable energy, π_{BT}, generally decreases the period-0 price of energy, although the sign of the response can be ambiguous.*[10]
- *For low enough carbon taxes, $\tau_{1,BT}$, further increases in the tax rate reduce the period-0 energy price. For high enough carbon taxes, further increases in the tax rate increase the energy price.*

We now use the model to illustrate through numerical examples how the various transition risks affect all the endogenous variables, in order to better understand the economic mechanisms that drive the response of energy prices. All 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. Each set of comparative statics on the full model in this section is accompanied by a figure that plots how the different outcomes change as the parameter changes. In the text, we focus on the main results only, highlighting any additional predictions relative to the simpler models described in the previous sections.

3.2.1 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 2 shows how energy prices and other quantities vary with this policy instrument for a model calibration that fixes the probability of a technological breakthrough at $\pi_{BT} = 0.5$. The figure (similarly to all following figures) has six panels, all reporting the parameter of interest on the x-axis. Panel A reports the period-0 energy price; Panel B the period-1 energy prices in the various states of the world; Panel C reports the supply of fossil fuel by the incumbent in period 0; Panel D the period-1 capacity of each energy firm; Panel E expected profits of the different firms; and Panel F carbon emissions in period 0 and period 1.

The results confirm the forces highlighted in Section 2.1: the reduction in investment by new entrants raises the period-1 price and reduces the incumbent's incentive to extract in period 0, thereby increasing the period-0 price. In the full model, we have separate electrifiable and non-electrifiable markets at period 1 under current technologies. The calibration shows that prices increase in markets that depend on fossil fuel supply, whereas the prices in the electrifiable market actually decrease (Panel B). This is because, in response to higher expected prices in the BT scenario, renewable firms increase their period-1 capacity (Panel D), which leads to a lower price in the *CT-E* market, where they would be the only energy supplier.

Panel B highlights that transition risks can have rich implications for energy prices in different states of the world. Importantly, at higher levels of the tax, the price gap between electrifiable and non-electrifiable markets in the *CT* state increases. This divergence may have

[10] The same discussion as in Section 2.4 applies. We verify numerically using the full model that the period-0 energy price is generally decreasing in the probability of a technological breakthrough for most parameter values.

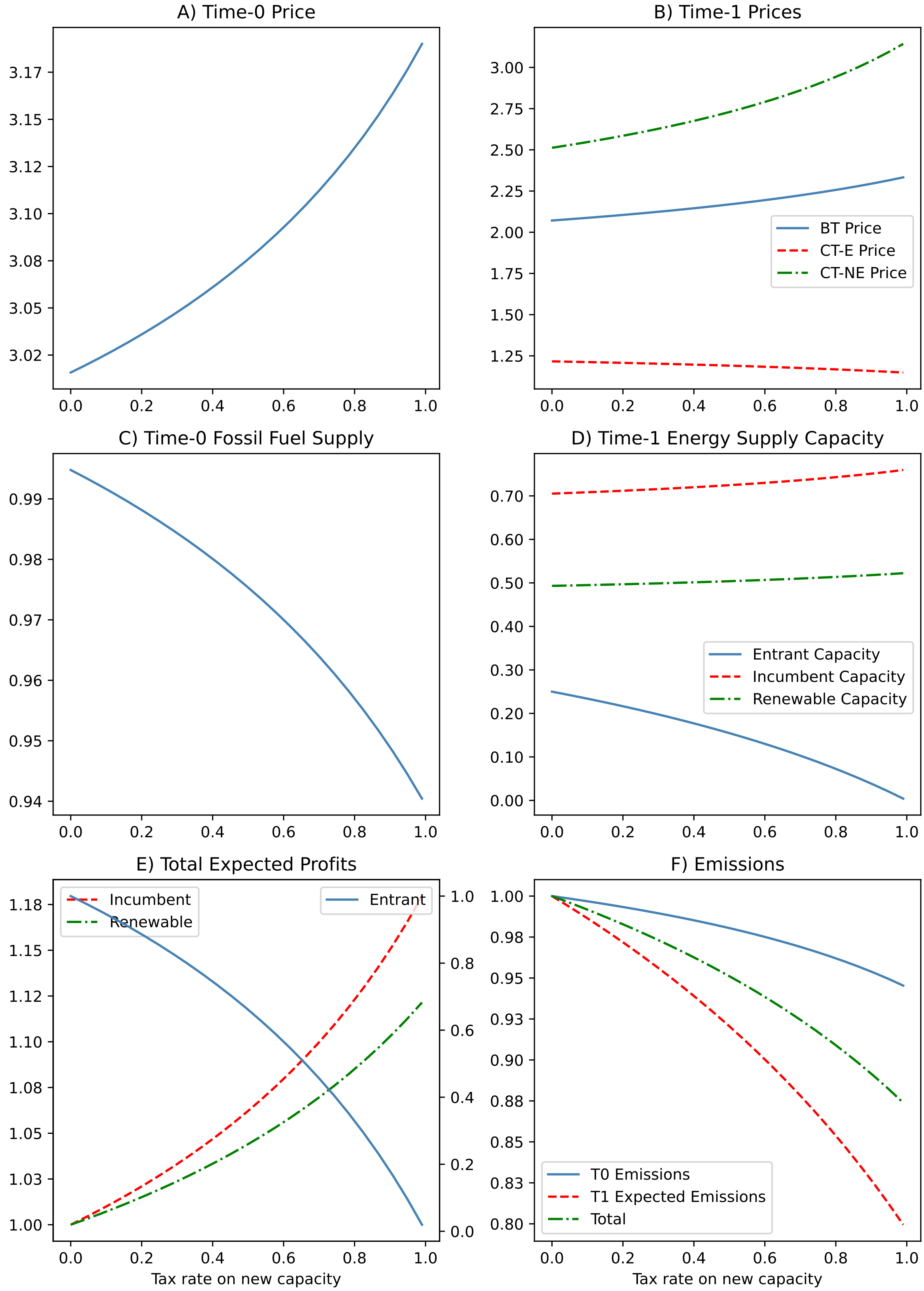


Figure 2: **Equilibrium effects of changes in the tax rate on new production capacity.** Note that profits for each producer are normalized by their profits for $\bar{\tau}_0 = 0$, and emissions are normalized for each period and total by the corresponding value for $\bar{\tau}_0 = 0$. Profits for the entrant fossil fuel firm in Panel E are shown on the right axis. BT scenario probability is fixed at $\pi_{BT} = 0.5$.

important implications for the composition of economic activity in the absence of a technological breakthrough, as different firms and sectors may end up facing different costs depending on their ability to electrify (and thus on their access to cheap renewable energy). It may also 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 renewable energy production).

We can also use the full model to track emissions, the key target of transition policies, as a function of the tax on new capacity. Panel F shows that higher taxes on new fossil fuel production capacity reduce emissions in both periods 0 and 1.

3.3 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 π_{BT}. We assume throughout this simulation that carbon taxes ($\tau_{1,BT}$) and production capacity taxes ($\bar{\tau}_0$) are zero. Figure 3 shows how outcomes change as π_{BT} increases. This comparative static is similar to the one in Section 2.4, though with some additional implications.

The figure shows that the key results continue to hold: as the probability of the Breakthrough Technology scenario increases, the renewable firm increases its installed capacity (Panel D), while both fossil fuel firms anticipate that 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 period-1 inventory and extracts more at period 0, leading to the green paradox (increase in period-0 emissions, visible in Panel F). On the flip side, *expected* period-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.

There are also additional implications for the price across markets in the CT state (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: as before, absent a breakthrough, the lower oil and gas capacity is particularly costly for firms who continue to rely on fossil fuels.

Expected profits (and hence valuations) of both types of fossil fuel firms decline as π_{BT} increases, with larger negative effects on the valuations of new entrants (Panel E). By contrast, renewable firms experience an increase in their valuations, as their future expected profits increase with the technological breakthrough becoming more likely.

3.4 Analysis of Changes in the Tax on Fossil Fuel Emissions

Finally, we turn to an analysis of the effects of changes in the tax on carbon emissions in the BT state (taxes are always zero in the CT state).[11] Figure 4 shows how the 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 ($\pi_{BT} = 0.5$).

Just as described in Section 2.3, there is a non-monotonicity of the period-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 2.3, this non-monotonicity is due to the uncertainty about whether the tax will be implemented, and a calculation by incumbents that it may be worth increasing period-1 inventory to profit in states of the world where the

[11] 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.

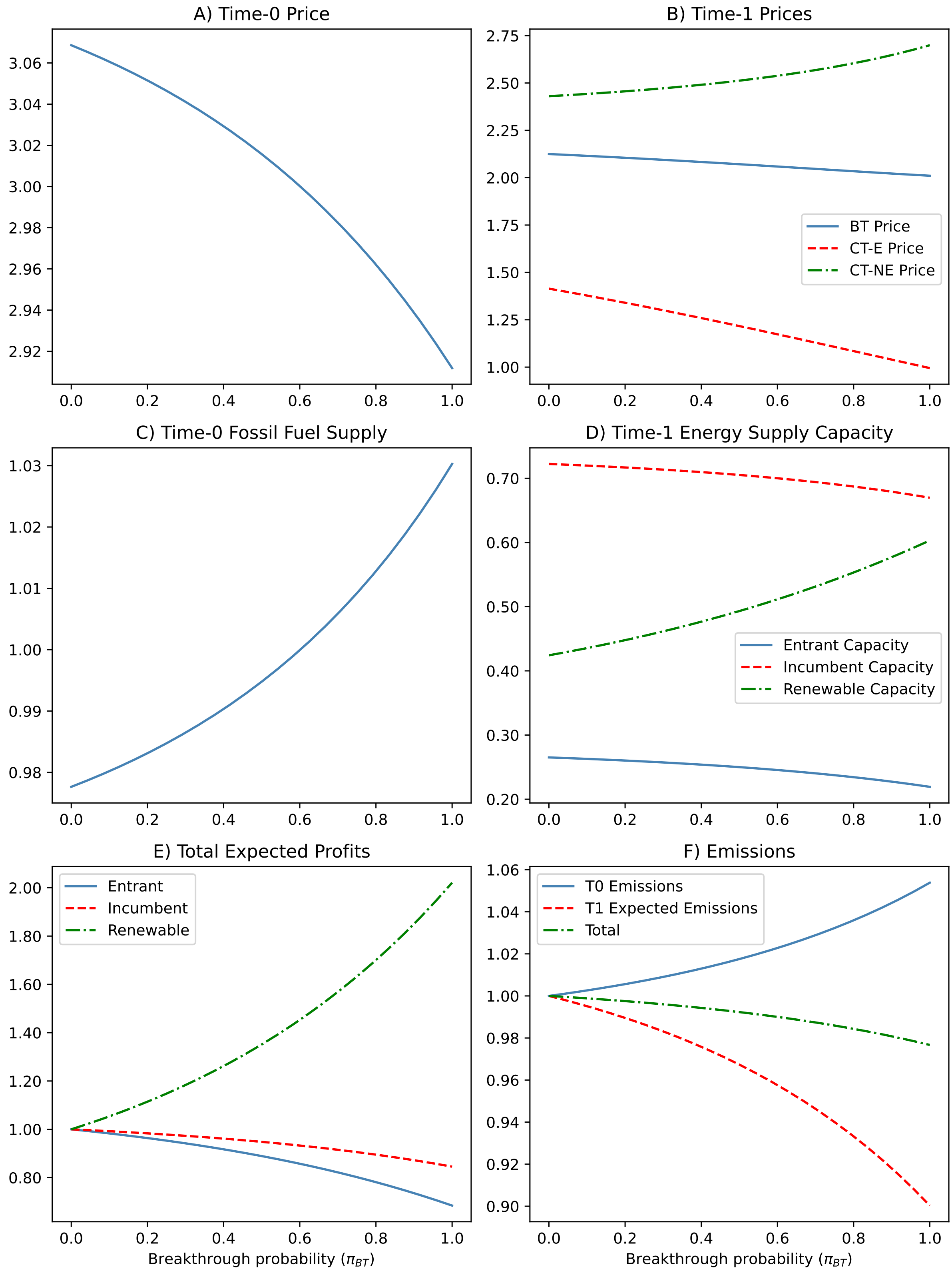


Figure 3: **Equilibrium effects of changes in the probability of a technological breakthrough, π_{BT}.** Note that profits for each producer are normalized by their profits when $\pi_{BT} = 0$, and emissions are normalized for each period and in total by the corresponding value for $\pi_{BT} = 0$.

carbon tax is not enacted and oil is scarce and valuable, even at the cost of having stranded oil if the tax is enacted (the stranded oil in the BT state gives a real option to the incumbent).

To clarify this mechanism, Figure 5 plots the fraction of the incumbent's 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 4, in this range we see that the carbon tax induces higher period-0 energy supply and lower period-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 5). As discussed in Section 2.3, at that point, further increases in the tax have no additional 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 4). 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 period-0 extraction and a higher period-0 price (Panels A and C).

Relative to these mechanisms, already present in the simple model of Section 2.3, the full model adds the behavior of renewable energy firms. The increase in carbon taxes induces renewable firms to increase their period-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 affect the price in the CT scenario and the incumbent's incentive to increase its inventory. This corresponds to the rightmost region of Figure 4, where the response of period-0 price and fossil fuel supply to the carbon tax becomes flat.

Panel E of Figure 4 also shows that news about future carbon taxes has 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.

3.5 Tax Revenues and Breakthrough Technology

In our model, we assume that the breakthrough probability is fixed and independent of the future carbon tax rate. This is a simplifying assumption, as it might be argued that expectations about future carbon taxes might increase the probability of a technological breakthrough, for instance if tax revenues are used for green subsidies or if they incentivize private firms to invest in renewable energy research. Appendix D.3 extends our current framework and allows the breakthrough probability π_{BT} to increase as the expected tax rates increase. Since increases in the breakthrough probability can have the opposite effect on energy prices than increases in tax rates, the effect of the tax rates on the period-0 energy price can be dampened and even reversed if the increase in π_{BT} is strong enough.

An interesting exception is represented by the case where the increase in the carbon tax rate, $\tau_{1,BT}$, causes a decrease in the marginal cost of current renewable capacity, rather than an increase in the probability of developing new breakthrough technologies. In this case, if the incumbent firm has stranded assets in the BT state, the effect of an increase in the tax rate on the period-0 price is actually amplified. The intuition is that an increase in renewable efficiency

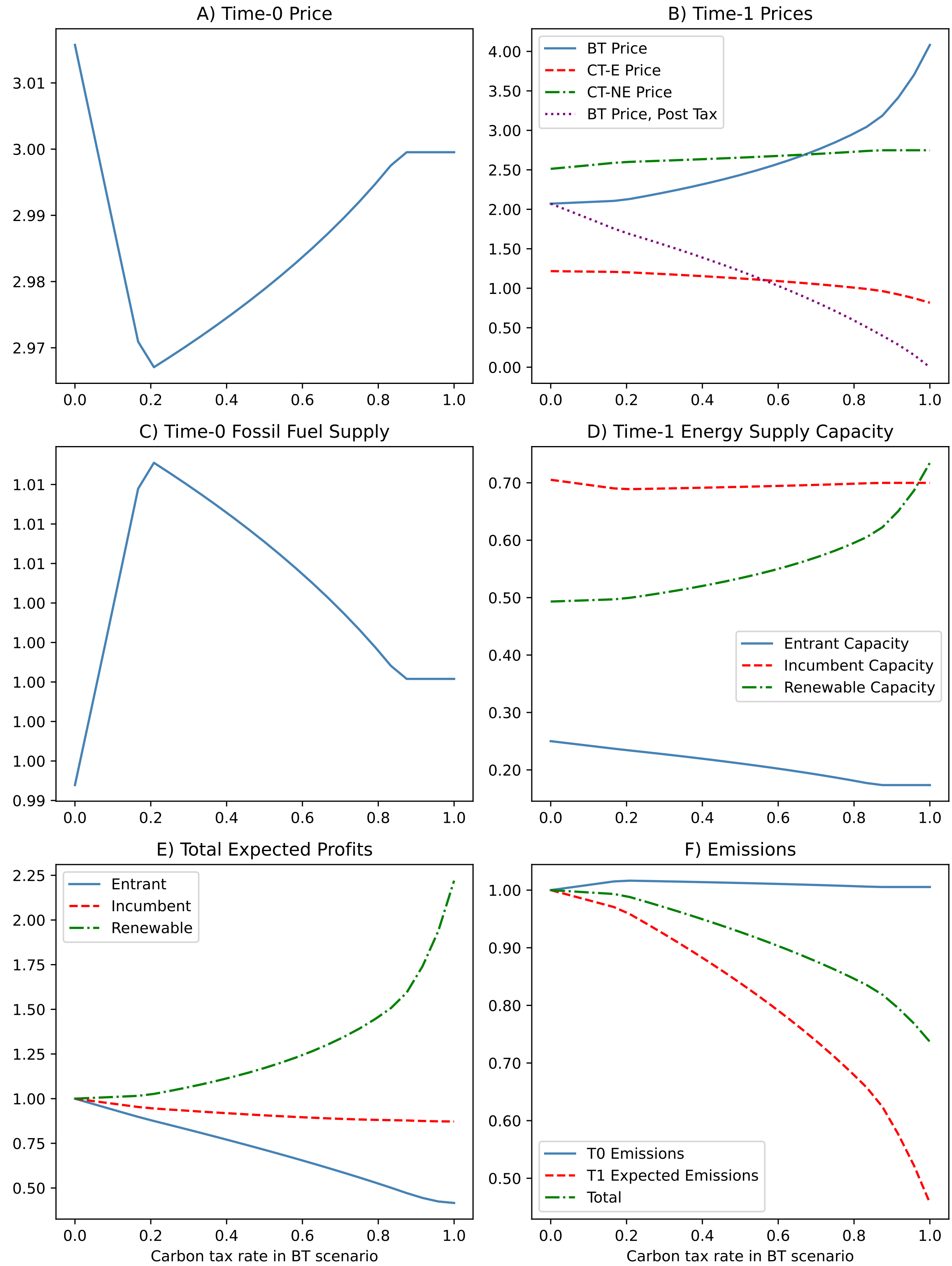


Figure 4: **Equilibrium effects of changes in** ***BT*** **carbon tax rate.** Note that profits for each producer are normalized by their profits for $\tau_{1,BT} = 0$, and emissions are normalized for each period and total by the corresponding value for $\tau_{1,BT} = 0$. BT scenario probability is fixed at $\pi_{BT} = 0.5$.

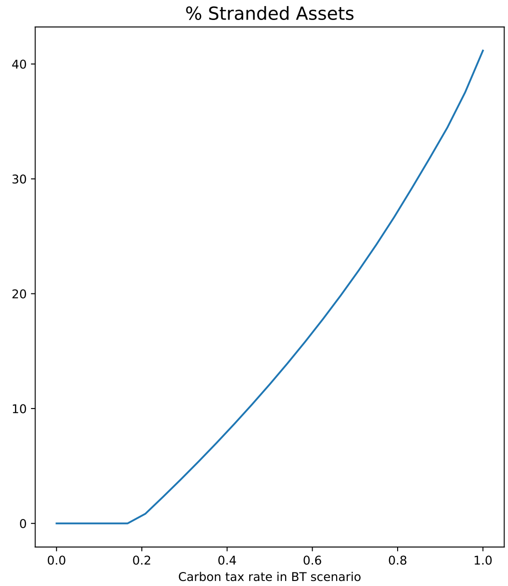


Figure 5: Fossil fuel stranded assets in the BT scenario as a function of the tax rate in the BT scenario. BT scenario probability is fixed at $\pi_{BT} = 0.5$.

that does not affect the breakthrough probability makes the BT state worse for fossil fuel firms, without changing its likelihood. It is therefore equivalent to the carbon tax rate being increased in that state only, which, as explained in the previous sections, directly affects only the marginal decision of the entrant firm to install new capacity, and thus induces the incumbent to reduce current energy supply and carry more production capacity in the future.

4 Empirical Analysis

We now test the main empirical implications of the model. We begin by studying how expectations about climate transition risk realizations affect the valuations of energy firms, distinguishing between renewable firms and fossil fuel firms, which we position on a continuum from entrants to incumbents according to their fraction of developed reserves. We then examine whether these shocks translate into real investment responses by analyzing drilling permit submissions at the well level, and finally assess their impact on oil prices.

To operationalize the empirical analysis, we follow Engle et al. (2020) and others to study how financial markets and firm investment decisions 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).

4.1 Climate Transition News Indices

We build our climate transition news indices by analyzing news coverage in the NYT using GPT-4o Mini, a large language model created by OpenAI.[12] We begin by summarizing how we construct these climate news indices, and provide additional details in Appendix E.

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: "Business Financial", "National", "Foreign", "Metropolitan", "Science", "Climate", "U.S.", "Editorial", and "Business". This excludes sections such as "Travel" and "Opinion" to better capture direct news such as policy announcements. From these articles, we select those containing at least one of the following keywords

[12] We verify that our results are robust to the choice of language model by replicating the main analysis using Google's Gemini 2.5 Flash-Lite model; see Appendix E.5.2.

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 33,965 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, to assess whether the risk is increasing or decreasing, and to quantify the importance of the content. The prompts are provided in Appendix E. 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.

A potential concern is that large language models may have been trained on information that post-dates the publication of the articles we classify, allowing parametric knowledge of future events to influence scores. We mitigate this in two ways. First, each article is scored in isolation and its score is aggregated into the index for its publication week; we never carry text across weeks, which prevents cross-period contamination. Second, following Engelberg et al. (2025), we re-run the classification on a neutered version of the corpus that removes identifying information (dates, locations, names) before processing; the resulting indices yield essentially unchanged empirical results. Additional details are in Appendix E.5.1.

A second potential concern arises from the fact that the first type of transition risk aims to identify "carbon pricing policy" news. In interpreting these news terms, we map them into an increase in the carbon tax in the model, which happens in the BT state. It is however plausible that some articles that imply a change in the *probability* of a carbon tax being implemented might also be identified. In the model, news about the two shares many (but not all) implications, and in theory it would be useful to be able to fully distinguish the two. That turns out to be very difficult to do in practice, even with more advanced LLMs, because the articles themselves tend to not make this distinction clear. Given that our second question directly targets the transition probability (and that probability is the same as the carbon tax probability within the model), for the remainder of the section we maintain the interpretation that carbon policy news relates to the level of carbon prices.

The GPT processing step assigns each article a transition risk score for each risk category. The score is the product of three components: (1) a direction indicator, equal to $+1$ (-1) if the article indicates increasing (decreasing) transition risk, and 0 if the article is irrelevant to that risk category; (2) a binary indicator equal to one if the identified change in transition risk is sufficiently strong; and (3) a binary indicator equal to one if the news is likely to affect the market prices or operational strategies of fossil fuel producers. Appendix E provides further details on the classification criteria. Within each of the three transition risk categories, we aggregate the scores by taking the sum across all articles in a week,[13] creating the *NYT-Emission Cost News Index*, the *NYT-Renewable Breakthrough News Index*, and the *NYT-Oil Capacity News Index.*

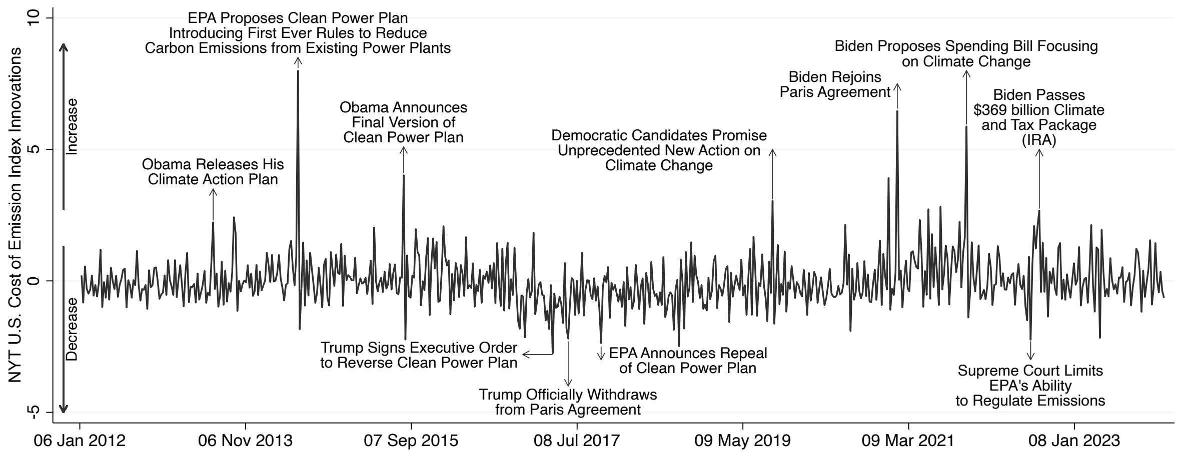
We then estimate an AR(1) model for each news index k using weekly data. We focus on AR(1) innovations because we are interested in the unexpected component of the news, though the low persistence of the news series means that results are similar if we include the index directly instead of the innovations. We scale the residuals by their sample standard deviation to make magnitudes comparable across transition news indices.

Figure 6 plots the time series of the innovations of the three news indices, 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 innovations of *NYT-Emission Cost News Index* spike 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 inno-

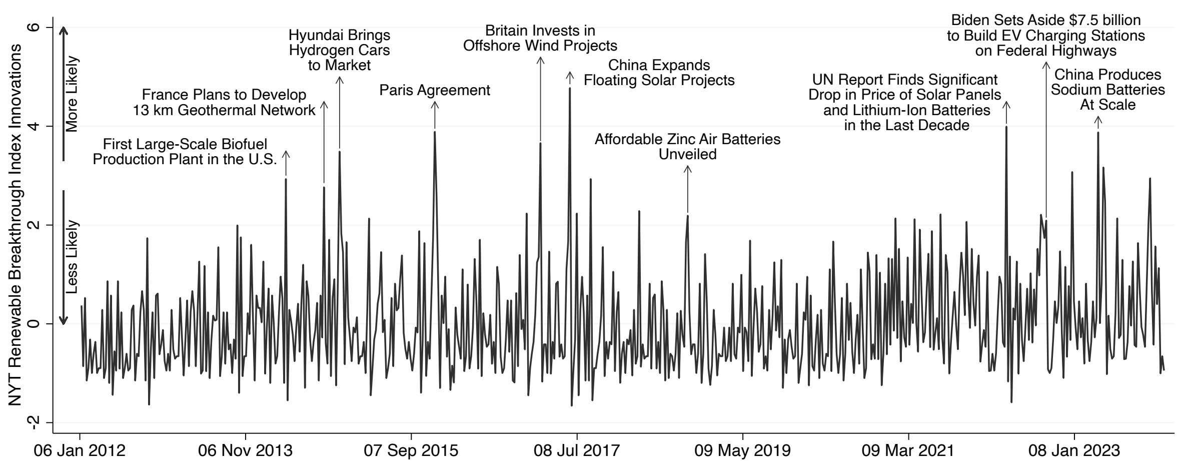
[13]We include news from Saturday and Sunday in the following week since this news would only be reflected in Monday stock prices once the market opens.

Figure 6: Time-Series of NYT News Index Innovations

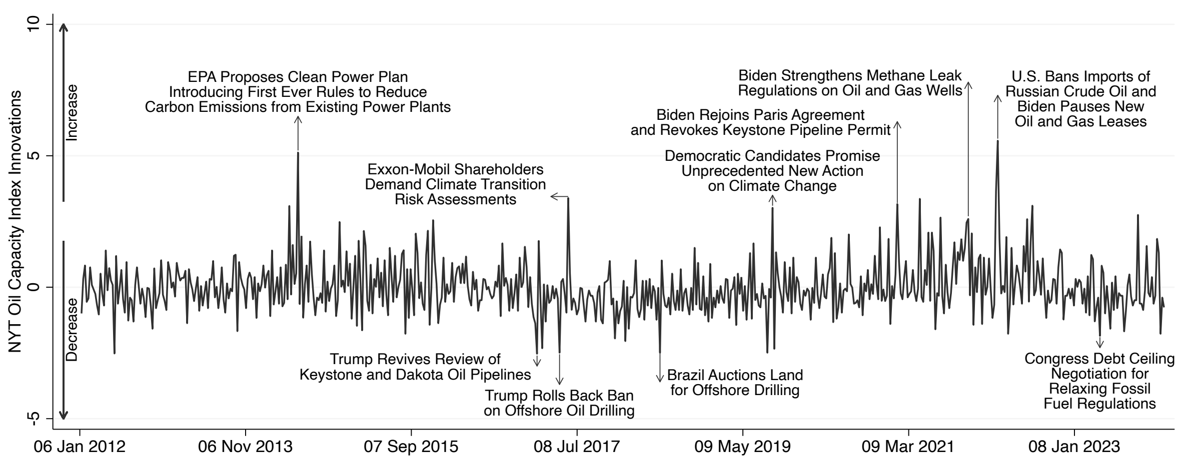
(a) NYT-Emission Cost News



(b) NYT-Renewable Breakthrough News



(c) NYT-Oil Capacity News



Note: Panel (a) shows the standardized innovations of 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 the cost of emissions and renewable energy supports. IRA: Inflation Reduction Act.

vations of *NYT-Oil Capacity News Index* spike (in both directions) around regulations which influence fossil fuel production, like 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 innovations of the *NYT-Renewable Breakthrough News Index* are markedly right-skewed: large positive surprises cluster around announcements of 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 standardized innovations of 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 standardized innovations of 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. Since each of our indices captures only one dimension of transition risk, we also report the correlation of their sum with existing measures. Notably, the sum of our three indices achieves a correlation with the Faccini et al. (2023) climate policy index comparable to that of the other existing indices, suggesting that our measures collectively span a similar domain of policy-driven transition risk.[14] Armed with these high-frequency indices of transition risk, we now move to the empirical tests of the implications of our model.

Table 2: Standardized Innovations Index Correlations

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) NYT-EmissionCostNews	1.00						
(2) NYT-RenewableBTNews	0.16	1.00					
(3) NYT-OilCapacityNews	0.43	0.20	1.00				
(4) NYT-AllTransitionRiskNews	0.74	0.63	0.76	1.00			
(5) Bua-TransitionRisk	0.06	0.06	0.09	0.10	1.00		
(6) Faccini-ClimatePolicy	0.31	0.17	0.29	0.36	0.10	1.00	
(7) Ardia-MediaClimateChangeConcern	0.08	0.13	0.20	0.20	0.03	0.38	1.00

4.2 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 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 E). 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 barrels 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. Chevron's 10-K statement, for example, describes:

[14]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.

> *"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 (see the histogram of developed ratios in Appendix E.2).

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 industries, respectively. This helps us identify 19 companies listed on U.S. stock exchanges, which we categorize as renewable companies.[15]

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

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

where $R_{i,t}$ is the market-hedged return of stock i in week t,[16] 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 standardized AR(1) innovations from this time-series model as $\nu_{k,t}$. 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 news 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 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 in the 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 0.25 ppt higher return for renewable companies in that week. Renewable energy firms also outperform upon news about restrictions on new oil capacity, though these estimates are not statistically significant.

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 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.[17]

One caveat is that we cannot empirically distinguish whether the price changes we observe are driven by cash-flow news, as the model predicts, or by discount-rate news. This distinction is notoriously difficult to draw, particularly at the firm level and at the high frequencies our analysis requires (see, e.g., Vuolteenaho (2002) for a lower-frequency firm-level decomposition, and Campbell et al. (2023) for a high-frequency exercise conducted only at the aggregate level).

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

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

[17]While the responses across the three columns are more similar than the model's sharpest cross-channel predictions imply, the results still clearly support the broad mechanism: renewables gain, entrants are hurt most, and incumbents are more insulated.

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**	-0.0075***	-0.0038*
	(0.0026)	(0.0019)	(0.0022)
Fossil Fuel Company × Index AR(1) Innovation × Developed Ratio	0.0092**	0.0107***	0.0068**
	(0.0038)	(0.0029)	(0.0034)
Renewable × Index AR(1) Innovation	0.0025**	0.0026***	0.0015
	(0.0011)	(0.0007)	(0.0009)
Company FE	Yes	Yes	Yes
Remove Market from Stock Returns	Yes	Yes	Yes
R^2	0.006	0.006	0.006
Observations	51003	51003	51003

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. Regressions (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).

Our results are consistent with the cash-flow channel, but we cannot rule out a contribution from discount rates.

Appendix E.5 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 use the oil developed reserves ratio rather than the total developed reserves ratio.

4.3 Well Permits and Investment Response

The preceding analysis documented how transition risk news affects the stock prices of fossil fuel and renewable firms. A natural question is whether this news also translates into real changes in firms' behavior. To address this, we study drilling permits—a forward-looking measure of investment in new oil and gas wells. Because permits are typically filed before construction and drilling begin, they provide a timely indicator of firms' responses to evolving expectations about transition risk. In addition, the decision to delay or cancel the filing of a permit can be taken quickly in response to events.

We obtain well-level permit data from Enverus (formerly DrillingInfo), a commercial data provider that aggregates oil and gas records across North America and is widely used in empirical studies of the oil and gas industry (see e.g., Herrnstadt et al., 2024; Décaire, 2025; Seleznev and Selezneva, 2025).[18] Our sample spans 2012–2023, matching the period covered by our news-based transition risk indices. Each record reports the permit submission date, well location, and the name of the operating firm responsible for the well. We match operators to our Compustat sample of publicly traded oil and gas firms.[19] We then aggregate permits to the firm-week level, counting the number of permits submitted each week by each matched firm. This yields a

[18] Enverus serves as a trusted data provider for various federal agencies involved in environmental and energy reporting, with its datasets being utilized in studies by agencies such as the U.S. Environmental Protection Agency (EPA) and the U.S. Energy Information Administration (EIA).

[19] The raw Enverus dataset also includes Canadian wells, but none fall within our 2012–2023 sample window, so our analysis effectively covers only U.S. permits.

firm-week panel of permitting activity, which we use as our primary measure of real investment decisions by oil and gas producers. Appendix E.4 provides further details on the construction of this dataset and the permit submission process.

Specification. We estimate the following panel regression to study how permitting activity responds to transition risk news:

$$Permits_{i,t} = \alpha_{i,k} + \sum_{l=0}^{6} \beta_{l,k}\nu_{k,t-l} + \gamma_k Permits_{i,t-1} + \epsilon_{i,k,t}, \tag{15}$$

where $Permits_{i,t}$ is the number of permits submitted by firm i during week t and $\nu_{k,t-l}$ is the standardized AR(1) innovation of news index k in week $t-l$; standardizing ensures comparability across indices and allows coefficients to be interpreted as the effect of a one–standard-deviation news shock. We include contemporaneous and up to six weekly lags of the news innovations to capture both immediate and delayed responses of permitting activity to transition risk news. $\alpha_{i,k}$ denotes firm fixed effects, which absorb time-invariant heterogeneity in baseline permitting rates across firms. We also include the lagged number of permits $Permits_{i,t-1}$ to account for persistence in permitting activity.

Results. Table 4 reports the results of regression (15). The coefficients on $\nu_{k,t-l}$ are uniformly negative across all lags and all three indices, just as predicted by the model.

Table 4: Well Permits and NYT Index

	Emission Cost (1)	Renewable Breakthrough (2)	Oil Capacity (3)
0 Week Lagged Index AR(1) Innovation	-0.1154	-0.1563*	-0.0985
	(0.0857)	(0.0831)	(0.0761)
1 Week Lagged Index AR(1) Innovation	-0.1203	-0.1471**	-0.1356*
	(0.0910)	(0.0694)	(0.0794)
2 Week Lagged Index AR(1) Innovation	-0.1785*	-0.2021**	-0.2021**
	(0.1043)	(0.0837)	(0.0954)
3 Week Lagged Index AR(1) Innovation	-0.1829	-0.1415	-0.1861
	(0.1141)	(0.0964)	(0.1286)
4 Week Lagged Index AR(1) Innovation	-0.1206*	-0.2512***	-0.1173*
	(0.0683)	(0.0873)	(0.0689)
5 Week Lagged Index AR(1) Innovation	-0.0848	-0.1138	-0.1400
	(0.1100)	(0.0938)	(0.1173)
6 Week Lagged Index AR(1) Innovation	-0.0672	-0.1706**	-0.0765
	(0.0700)	(0.0712)	(0.0726)
1 Week Lagged Permits Submitted	0.3219***	0.3208***	0.3217***
	(0.0579)	(0.0572)	(0.0579)
Firm FE	Yes	Yes	Yes
Cumulative effect p-value	0.033	0.0011	0.025
Observations	27,996	27,996	27,996

Note: Regression (1) shows coefficients from a firm-level weekly panel regression of permits submitted on contemporaneous and lagged (0–6 weeks) standardized AR(1) innovations of the *NYT-Emission Cost News Index*, together with one lag of the dependent variable to capture persistence in permitting activity. Regressions (2) and (3) instead use standardized innovations from the *NYT-Renewable Breakthrough News Index* and the *NYT-Oil Capacity News Index*, respectively. All regressions include firm fixed effects. The cumulative effect p-value tests whether the sum of all lag coefficients is zero. Standard errors are in parentheses and are clustered at the firm and week level. Significance levels: * (p<0.10), ** (p<0.05), *** (p<0.01).

A one-standard-deviation increase in *NYT-Emission Cost News Index* innovations yields a decline in permits filed over the following six weeks, with the cumulative effect significant at the 5% level. A one-standard-deviation increase in *NYT-Renewable Breakthrough News Index* innovations produces a stronger and more persistent decline, with individually significant coefficients at multiple lag horizons and a cumulative effect significant at the 1% level. A one-standard-deviation increase in *NYT-Oil Capacity News Index* innovations similarly reduces permitting activity, with the cumulative effect significant at the 5% level. The coefficient on lagged permitting is strongly positive, consistent with substantial persistence in drilling activity. Overall, these findings suggest that transition risk news not only moves financial valuations but also leads firms to reduce new drilling activity, with the effect building gradually over several weeks.

4.4 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. This is essentially a time-series macroeconomic analysis, where isolating the effects of transition risk from other confounding events (e.g., geopolitical events) is complicated. 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, which exploited a panel structure across firms. We employ the following specification:

$$f_t^h = \alpha + \beta_1 \nu_t^{\text{EC}} + \beta_2 \nu_t^{\text{BT}} + \beta_3 \nu_t^{\text{OC}} + Controls_t + \epsilon_t,$$

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.[20]

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 then compute three equal-weighted average returns of futures of different maturities: one for short-term maturities averaging all 1-month to 12-month futures, and 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. While these constructions smooth contract-level noise, it is important to note that even the longest futures contract (60 months) captures only near-term horizons relative to the decades-long interval between date 0 and date 1 in the model.

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 the percentage change in zero-coupon treasury yields by Liu and Wu (2021).[21] We also control for the stock market excess returns and an additional demand factor, OECD liquid fuel consumption change from EIA. The data spans a 12-year period between 2012 and 2023. See Appendix Table 14 for a detailed overview of the data and its sources. Table 5 shows the results of the regression, with each column corresponding to a different dependent variable.

[20]We also run the same regression at the weekly frequency (holding key control variables constant throughout the month). Those estimates are generally imprecise and do not cleanly reproduce the monthly pattern.

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

Table 5: 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	0.0128**	0.0101**	0.0116**
	(0.0061)	(0.0044)	(0.0051)
Index AR(1) Innovation - Renewable Breakthrough	-0.0135**	-0.0115***	-0.0120**
	(0.0056)	(0.0042)	(0.0047)
Index AR(1) Innovation - Oil Capacity	-0.0124*	-0.0077*	-0.0076
	(0.0063)	(0.0040)	(0.0051)
Controls	Yes	Yes	Yes
p-value Emission Cost = Renewable Breakthrough	0.0040	0.0011	0.0013
p-value Emission Cost = Oil Capacity	0.016	0.018	0.030
p-value Renewable Breakthrough = Oil Capacity	0.90	0.51	0.56
R^2	0.486	0.473	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, 36, 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 prices 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 on building new capacity. The observed relationship between oil futures prices and innovations in the *NYT-Oil Capacity News Index* instead is negative, although this result is not robust to excluding the four-month period around the sharp dislocation in WTI futures prices at the onset of the pandemic, as shown in Appendix Table 25.

5 Conclusion

We explore how different climate transition risks can affect the price of energy and the valuation of energy firms. Our analysis delivers three 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. Our rich theoretical model provides economic intuition for the various economic forces at play. Second, building on the previous insight, we show theoretically and find empirically 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. Finally, we show that the different types of transition risks are linked together by optimal climate transition policy—most notably, carbon taxes are much more likely to be implemented in states of the world where alternative green energy sources exist, which lowers the distortions from imposing the carbon tax. Overall, our theoretical and empirical analysis shows that a full understanding of the impact of transition risks requires distinguishing between the types of energy firms, the types of transition risks, and the way endogenous policy relates them to one another.

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, one could consider subsidies to the renewable sector as an additional policy instrument to endogenize the link between (carbon) taxes and renewables breakthrough, 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 microfound the endogeneity of the transition probability with respect to the tax policy, by formalizing 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., 2023b). Finally, while we focused in our empirical work on energy prices, stock prices of energy subsectors, and the investment response of oil and gas producers through drilling permits, additional model implications for inventories and production are also worthy of empirical scrutiny.

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Appendix A Details on Full Model

A.1 Model Setup

A.1.1 Consumers and Demand for Energy

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

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

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

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

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

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

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

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

$$\max_{C\geq 0} \; -\frac{1}{2\delta}C^2 + C\left[\pi_{BT}P_{1,BT} + (1-\pi_{BT})P_{1,E}\right] \tag{16}$$

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

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

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 from 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 2.6, a social planner would choose 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:

$$\max_{f_0^I} \; f_0^I P_0 - \frac{1}{2\kappa_1}(f_0^I)^2 + E[V_f^I] \tag{17}$$

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

$$V_f^{I,BT} = \max_{f_{1,BT}^I} \; (1-\tau_{1,BT})P_{1,BT}f_{1,BT}^I - \frac{1}{2\kappa_1}(f_{1,BT}^I)^2, \tag{18}$$

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

$$V_f^{I,CT} = \max_{f_{1,E}^I, f_{1,NE}^I} \; P_{1,E}f_{1,E}^I + P_{1,NE}f_{1,NE}^I - \frac{1}{2\kappa_1}(f_{1,E}^I + f_{1,NE}^I)^2, \tag{19}$$

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

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 potentially produce 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 $0 \leq \bar{\tau}_0 < 1$ 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:

$$\max_{\bar{f}_1^E} \; -\frac{1}{2(1-\bar{\tau}_0)\kappa_2}(\bar{f}_1^E)^2 + E[V_f^E] \tag{20}$$

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 π_{BT}, given by

$$V_f^{E,BT} = \max_{f_{1,BT}^E} (1 - \tau_{1,BT}) P_{1,BT} f_{1,BT}^E - \frac{1}{2\kappa_1} (f_{1,BT}^E)^2, \tag{21}$$

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

$$V_f^{E,CT} = \max_{f_{1,E}^E, f_{1,NE}^E} P_{1,E} f_{1,E}^E + P_{1,NE} f_{1,NE}^E - \frac{1}{2\kappa_1} (f_{1,E}^E + f_{1,NE}^E)^2, \tag{22}$$

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

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:

$$\frac{W}{P_0} = f_0^I, \tag{23}$$

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

$$q\frac{W}{P_{1,E}} = C + f_{1,E}^I + f_{1,E}^E, \text{ and} \tag{25}$$

$$(1-q)\frac{W}{P_{1,NE}} = f_{1,NE}^I + f_{1,NE}^E. \tag{26}$$

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 their 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

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

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

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

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

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

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

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

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

which gives the following interior solution

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

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

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

which gives the following interior solution

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

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

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

which gives the following interior solution

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

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

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

which gives the following interior solution

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

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

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

which gives the following interior solution

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

3. Production constraint always binding: this gives

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

which gives the following interior solution

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

Note that since in equilibrium fossil fuel firms will only supply in the CT market with the highest price, it has to be that $P_{1,NE} \geq P_{1,E}$. 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 (26), the price 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 $f_1^I = \kappa_1(1-\tau_1)P_1$. 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

$$f_0^I = \frac{\kappa_1}{2}\Big[P_0 - (1-\tau_1)P_1\Big] + \frac{\bar{f}_0^I}{2} \tag{27}$$

$$f_1^I = \frac{\bar{f}_0^I}{2} - \frac{\kappa_1}{2}\Big[P_0 - (1-\tau_1)P_1\Big] \tag{28}$$

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

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

Substituting optimal quantities into market clearing conditions, we have

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

$$\frac{W}{P_1} = \frac{\bar{f}_0^I}{2} - \frac{\kappa_1}{2}\Big[P_0 - (1-\tau_1)P_1\Big] + \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}(1-\tau_1)P_1 \tag{31}$$

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

$$\frac{df_0^I}{d\bar{\tau}_0} = \frac{\kappa_1}{2}\left[\frac{dP_0}{d\bar{\tau}_0} - (1-\tau_1)\frac{dP_1}{d\bar{\tau}_0}\right] \tag{32}$$

$$\frac{df_1^I}{d\bar{\tau}_0} = -\frac{df_0^I}{d\bar{\tau}_0} \tag{33}$$

$$\frac{d\bar{f}_1^E}{d\bar{\tau}_0} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}(1-\tau_1)\frac{dP_1}{d\bar{\tau}_0} - \frac{\kappa_1^2\kappa_2}{[\kappa_1 + (1-\bar{\tau}_0)\kappa_2]^2}(1-\tau_1)P_1 \tag{34}$$

and from market clearing conditions we have that

$$-\frac{W}{P_0^2}\frac{dP_0}{d\bar{\tau}_0} = \frac{df_0^I}{d\bar{\tau}_0} \tag{35}$$

$$-\frac{W}{P_1^2}\frac{dP_1}{d\bar{\tau}_0} = -\frac{df_0^I}{d\bar{\tau}_0} + \frac{d\bar{f}_1^E}{d\bar{\tau}_0} \tag{36}$$

We proceed by contradiction. Suppose that $\frac{dP_0}{d\bar{\tau}_0} < 0$. Then (35) implies that $\frac{df_0^I}{d\bar{\tau}_0} > 0$. From (32) we then get $\frac{dP_1}{d\bar{\tau}_0} < 0$ which implies, using (34), that $\frac{d\bar{f}_1^E}{d\bar{\tau}_0} < 0$, and using (36) 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

$$\frac{d\Pi^E}{d\bar{\tau}_0} = \frac{1-\tau_1}{2}\left[\frac{d\bar{f}_1^E}{d\bar{\tau}_0}P_1 + \bar{f}_1^E\frac{dP_1}{d\bar{\tau}_0}\right] \tag{37}$$

Using (36), we have

$$\frac{W}{P_1^2}\frac{dP_1}{d\bar{\tau}_0} + \frac{d\bar{f}_1^E}{d\bar{\tau}_0} < 0 \tag{38}$$

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

$$\frac{d\Pi^I}{d\bar{\tau}_0} = \frac{dP_0}{d\bar{\tau}_0}\left[\frac{\kappa_1}{2}(P_0 - (1-\tau_1)P_1) + \frac{1}{2}\bar{f}_0^I\right] + \frac{1-\tau_1}{2}\frac{dP_1}{d\bar{\tau}_0}\left[\bar{f}_0^I - \kappa_1(P_0 - (1-\tau_1)P_1)\right] \tag{39}$$

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

$$\frac{df_0^I}{d\tau_1} = \frac{\kappa_1}{2}\left[\frac{dP_0}{d\tau_1} - (1-\tau_1)\frac{dP_1}{d\tau_1} + P_1\right] \tag{40}$$

$$\frac{d\bar{f}_1^E}{d\tau_1} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[(1-\tau_1)\frac{dP_1}{d\tau_1} - P_1\right] \tag{41}$$

while market clearing conditions give

$$-\frac{W}{P_0^2}\frac{dP_0}{d\tau_1} = \frac{df_0^I}{d\tau_1} \tag{42}$$

$$-\frac{W}{P_1^2}\frac{dP_1}{d\tau_1} = -\frac{df_0^I}{d\tau_1} + \frac{d\bar{f}_1^E}{d\tau_1} \tag{43}$$

Suppose again by contradiction that $\frac{dP_0}{d\tau_1} > 0$, which immediately implies using (42) that $\frac{df_0^I}{d\tau_1} < 0$. Then, (40) 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 (41), $\frac{d\bar{f}_1^E}{d\tau_1} > 0$. But then, (43) 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

$$\frac{d\Pi_1^E}{d\tau_1} = \frac{1}{2}\left[\frac{d\bar{f}_1^E}{d\tau_1}(1-\tau_1)P_1 + \bar{f}_1^E\left((1-\tau_1)\frac{dP_1}{d\tau_1} - P_1\right)\right] \tag{44}$$

which is negative, given $\frac{d\bar{f}_1^E}{d\tau_1} < 0$ and (41). Finally, profits for the incumbent change according to

$$\frac{d\Pi_1^I}{d\tau_1} = -\frac{1}{2}f_0^I\frac{df_0^I}{d\tau_1} + (\bar{f}_0 - f_0^I)\left((1-\tau_1)\frac{dP_1}{d\tau_1} - P_1\right) + 2\frac{df_0^I}{d\tau_1}\left[\frac{1}{\kappa_1}(\bar{f}_0^I - f_0^I) - (1-\tau_1)P_1\right] \tag{45}$$

$$\frac{d\Pi_1^I}{d\tau_1} = f_0^I\frac{dP_0}{d\tau_1} + (\bar{f}_0 - f_0^I)\left((1-\tau_1)\frac{dP_1}{d\tau_1} - P_1\right) \tag{46}$$

which is also negative, since $f_0^I < \bar{f}_0^I$ and $\frac{dP_0}{d\tau_1} < 0$ and using (41). □

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

$$\max_{0\le f_0^I \le \bar{f}_0^I} \; f_0^I P_0 - \frac{1}{2\kappa_1}(f_0^I)^2 + E[V_1^I] \tag{47}$$

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

$$V_{1,T}^I = \max_{0\le f_{1,T}^I \le \bar{f}_0^I - f_0^I} \; (1-\tau_1)P_{1,T}f_{1,T}^I - \frac{1}{2\kappa_1}(f_{1,T}^I)^2, \tag{48}$$

and

$$V_{1,NT}^I = \max_{0\le f_{1,NT}^I \le \bar{f}_0^I - f_0^I} \; P_{1,NT}f_{1,NT}^I - \frac{1}{2\kappa_1}(f_{1,NT}^I)^2, \tag{49}$$

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

$$f_0^I = \frac{\bar{f}_0^I}{2} + \frac{\kappa_1}{2}\left[P_0 - \pi_T(1-\tau_1)P_{1,T} - (1-\pi_T)P_{1,NT}\right] \tag{50}$$

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

$$f_0^I = \frac{1-\pi_T}{2-\pi_T}\bar{f}_0^I + \frac{\kappa_1}{2-\pi_T}\left[P_0 - (1-\pi_T)P_{1,NT}\right] \tag{51}$$

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

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

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[\pi_T(1-\tau_1)P_{1,T} + (1-\pi_T)P_{1,NT}\right] \tag{52}$$

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

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\pi_T)(1-\bar{\tau}_0)\kappa_2}(1-\pi_T)P_{1,NT} \tag{53}$$

Finally, market clearing conditions are now given by

$$\frac{W}{P_0} = f_0^I \tag{54}$$

$$\frac{W}{P_{1,T}} = f_{1,T}^I + f_{1,T}^E \tag{55}$$

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

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

$$\frac{df_0^I}{d\tau_1} = \frac{\kappa_1}{2}\left[\frac{dP_0}{d\tau_1} - \pi_T(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} + \pi_T P_{1,T} - (1-\pi_T)\frac{dP_{1,NT}}{d\tau_1}\right] \tag{57}$$

$$\frac{d\bar{f}_1^E}{d\tau_1} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[\pi_T(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} - \pi_T P_{1,T} + (1-\pi_T)\frac{dP_{1,NT}}{d\tau_1}\right] \tag{58}$$

and

$$-\frac{W}{P_0^2}\frac{dP_0}{d\tau_1} = \frac{df_0^I}{d\tau_1} \tag{59}$$

$$-\frac{W}{P_{1,T}^2}\frac{dP_{1,T}}{d\tau_1} = -\frac{df_0^I}{d\tau_1} + \frac{d\bar{f}_1^E}{d\tau_1} \tag{60}$$

$$-\frac{W}{P_{1,NT}^2}\frac{dP_{1,NT}}{d\tau_1} = -\frac{df_0^I}{d\tau_1} + \frac{d\bar{f}_1^E}{d\tau_1} \tag{61}$$

Suppose by contradiction that $\frac{dP_0}{d\tau_1} > 0$. Then, using (59), we have $\frac{df_0^I}{d\tau_1} < 0$. It follows from (57) that

$$-\pi_T(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} + \pi_T P_{1,T} - (1-\pi_T)\frac{dP_{1,NT}}{d\tau_1} < 0 \tag{62}$$

which in turn implies, using (58), that $\frac{d\bar{f}_1^E}{d\tau_1} > 0$. But then it follows from (60) and (61) that $\frac{dP_{1,T}}{d\tau_1} < 0$ and $\frac{dP_{1,NT}}{d\tau_1} < 0$, which contradicts (62). 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

$$\frac{df_0^I}{d\tau_1} = \frac{\kappa_1}{2-\pi_T}\left[\frac{dP_0}{d\tau_1} - (1-\pi_T)\frac{dP_{1,NT}}{d\tau_1}\right] \tag{63}$$

$$\frac{df_{1,T}^I}{d\tau_1} = \kappa_1\left[(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} - P_{1,T}\right] \tag{64}$$

and using market clearing in the T state

$$-\frac{W}{P_{1,T}^2}\frac{dP_{1,T}}{d\tau_1} = \frac{df_{1,T}^I}{d\tau_1} + \frac{d\bar{f}_1^E}{d\tau_1} \tag{65}$$

Suppose now that $\frac{dP_0}{d\tau_1} < 0$. Using (59), we have $\frac{df_0^I}{d\tau_1} > 0$ which implies, using (63), that $\frac{dP_{1,NT}}{d\tau_1} < 0$. But then, using (61), we have that $\frac{d\bar{f}_1^E}{d\tau_1} > 0$ which implies, using (58), that $\frac{dP_{1,T}}{d\tau_1} > 0$. From (65) we then get $\frac{df_{1,T}^I}{d\tau_1} < 0$ which implies, using (64), that

$$(1-\tau_1)\frac{dP_{1,T}}{d\tau_1} - P_{1,T} < 0 \tag{66}$$

But this, using (58), 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 (65) and $\frac{df_{1,T}^I}{d\tau_1} = 0$ from (64), 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 of the two fossil fuel producers are the same as in the previous section, with the two states now being $T = BT$ and $NT = CT$. We allow for a carbon tax in the BT state, but set it equal to zero for now. Market clearing conditions in the two states in period 1 are now given by

$$\frac{W}{P_0} = f_0^I \tag{67}$$

$$\frac{W}{P_{1,BT}} = C + f_{1,BT}^I + f_{1,BT}^E \tag{68}$$

$$\frac{W}{P_{1,CT}} = f_{1,CT}^I + f_{1,CT}^E \tag{69}$$

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

$$\frac{df_0^I}{d\pi_{BT}} = \frac{\kappa_1}{2}\left[\frac{dP_0}{d\pi_{BT}} - (1-\tau_{1,BT})\left(P_{1,BT} + \pi_{BT}\frac{dP_{1,BT}}{d\pi_{BT}}\right) - (1-\pi_{BT})\frac{dP_{1,CT}}{d\pi_{BT}} + P_{1,CT}\right] \tag{70}$$

$$\frac{d\bar{f}_1^E}{d\pi_{BT}} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[(1-\tau_{1,BT})\left(P_{1,BT} + \pi_{BT}\frac{dP_{1,BT}}{d\pi_{BT}}\right) + (1-\pi_{BT})\frac{dP_{1,CT}}{d\pi_{BT}} - P_{1,CT}\right] \tag{71}$$

$$\frac{dC}{d\pi_{BT}} = \delta\left(P_{1,BT} + \pi_{BT}\frac{dP_{1,BT}}{d\pi_{BT}}\right) \tag{72}$$

and

$$-\frac{W}{P_0^2}\frac{dP_0}{d\pi_{BT}} = \frac{df_0^I}{d\pi_{BT}} \tag{73}$$

$$-\frac{W}{P_{1,BT}^2}\frac{dP_{1,BT}}{d\pi_{BT}} = \frac{dC}{d\pi_{BT}} - \frac{df_0^I}{d\pi_{BT}} + \frac{d\bar{f}_1^E}{d\pi_{BT}} \tag{74}$$

$$-\frac{W}{P_{1,CT}^2}\frac{dP_{1,CT}}{d\pi_{BT}} = -\frac{df_0^I}{d\pi_{BT}} + \frac{d\bar{f}_1^E}{d\pi_{BT}} \tag{75}$$

As usual, we prove the proposition by contradiction. Suppose that $\frac{dP_0}{d\pi_{BT}} > 0$. Using (73), this implies that $\frac{df_0^I}{d\pi_{BT}} < 0$. It then follows from (70) that

$$-(1-\tau_{1,BT})\left(P_{1,BT} + \pi_{BT}\frac{dP_{1,BT}}{d\pi_{BT}}\right) - (1-\pi_{BT})\frac{dP_{1,CT}}{d\pi_{BT}} + P_{1,CT} < 0 \tag{76}$$

which immediately implies, using (71), that $\frac{d\bar{f}_1^E}{d\pi_{BT}} > 0$. Using (75), we then have $\frac{dP_{1,CT}}{d\pi_{BT}} < 0$, which implies, using (76), that

$$P_{1,BT} + \pi_{BT}\frac{dP_{1,BT}}{d\pi_{BT}} > 0 \tag{77}$$

which immediately implies, using (72) and (74), that $\frac{dC}{d\pi_{BT}} > 0$ and $\frac{dP_{1,BT}}{d\pi_{BT}} < 0$. 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 (70), that $\frac{df_0^I}{d\pi_{BT}} > 0$, which is a contradiction. Therefore, it must be $\frac{dP_0}{d\pi_{BT}} \leq 0$. Following the same steps, we get the same contradiction if $\frac{dP_0}{d\pi_{BT}} = 0$, so that it must be $\frac{dP_0}{d\pi_{BT}} < 0$.

Consider now the case where the production constraint for the incumbent fossil fuel producer is only binding in the CT state. Under assumption (2), the entrant's production constraint is still binding in both states. We now have

$$\frac{df_0}{d\pi_{BT}} = \frac{1}{(2-\pi_{BT})^2}\left[\kappa_1\Big(P_0-(1-\pi_{BT})P_{1,CT}\Big)-\bar{f}_0\right]+\frac{\kappa_1}{2-\pi_{BT}}\left[\frac{dP_0}{d\pi_{BT}}-(1-\pi_{BT})\frac{dP_{1,CT}}{d\pi_{BT}}+P_{1,CT}\right] \quad (78)$$

$$\frac{df^I_{1,BT}}{d\pi_{BT}} = (1-\tau_{1,BT})\kappa_1\frac{dP_{1,BT}}{d\pi_{BT}} \quad (79)$$

and

$$-\frac{W}{P^2_{1,BT}}\frac{dP_{1,BT}}{d\pi_{BT}} = \frac{dC}{d\pi_{BT}} + \frac{df^I_{1,BT}}{d\pi_{BT}} + \frac{d\bar{f}_1}{d\pi_{BT}} \quad (80)$$

Note that the first term in bracket on the right hand side of equation (78) is negative, using the expression for the optimal f_0 and the fact that $f_0 < \bar{f}_0$. We first show that $\frac{dC}{d\pi_{BT}} \geq 0$. Suppose that the opposite holds, which immediately implies from (72) that

$$P_{1,BT} + \pi_{BT}\frac{dP_{1,BT}}{d\pi_{BT}} < 0 \quad (81)$$

and consequently $\frac{dP_{1,BT}}{d\pi_{BT}} < 0$. It then follows from (79) that $\frac{df^I_{1,BT}}{d\pi_{BT}} < 0$, and using (80) it follows that $\frac{d\bar{f}_1}{d\pi_{BT}} > 0$. Then, from (81) and (71) we get

$$(1-\pi_{BT})\frac{dP_{1,CT}}{d\pi_{BT}} - P_{1,CT} > 0 \quad (82)$$

and consequently $\frac{dP_{1,CT}}{d\pi_{BT}} > 0$. It then follows from (75) that $\frac{df_0}{d\pi_{BT}} > 0$ and from (73) that $\frac{dP_0}{d\pi_{BT}} < 0$. But then, (78) implies that $-(1-\pi_{BT})\frac{dP_{1,CT}}{d\pi_{BT}} + P_{1,CT} > 0$, which contradicts (82). Therefore, it must be $\frac{dC}{d\pi_{BT}} \geq 0$, which immediately implies that

$$P_{1,BT} + \pi_{BT}\frac{dP_{1,BT}}{d\pi_{BT}} \geq 0 \quad (83)$$

We now show that it must be $\frac{d\bar{f}_1}{d\pi_{BT}} \leq 0$. Suppose that the opposite holds. Then, from (79) and (80), it must be that $\frac{dP_{1,BT}}{d\pi_{BT}} < 0$. It then follows, from (71) and (83), and noting that $(1-\tau_1)P_{1,BT} < P_{1,CT}$, that (82) holds, and consequently $\frac{dP_{1,CT}}{d\pi_{BT}} > 0$. But from (75), it must be $\frac{df_0}{d\pi_{BT}} > 0$, which immediately implies, using (73), that $\frac{dP_0}{d\pi_{BT}} < 0$. But then (78) implies that $-(1-\pi_{BT})\frac{dP_{1,CT}}{d\pi_{BT}} + P_{1,CT} > 0$, which contradicts (82). Therefore, it must be $\frac{d\bar{f}_1}{d\pi_{BT}} \leq 0$, which immediately implies, using (71) and (83), that

$$(1-\pi_{BT})\frac{dP_{1,CT}}{d\pi_{BT}} - P_{1,CT} \leq 0 \quad (84)$$

Suppose now that $\frac{dP_{1,CT}}{d\pi_{BT}} < 0$. Then it follows immediately from $\frac{d\bar{f}_1}{d\pi_{BT}} \leq 0$, (75) and (73) that $\frac{df_0}{d\pi_{BT}} < 0$ and $\frac{dP_0}{d\pi_{BT}} > 0$. But note that, using (78) and the expression for the optimal f^I_0, we have

$$\frac{df_0}{d\pi_{BT}} - \frac{\kappa_1}{2-\pi_{BT}}\frac{dP_0}{d\pi_{BT}} = \frac{1}{2-\pi_{BT}}\left[\kappa_1 P_{1,CT} - (\bar{f}_0 - f_0)\right] - \kappa_1\frac{(1-\pi_{BT})}{2-\pi_{BT}}\frac{dP_{1,CT}}{d\pi_{BT}} \quad (85)$$

The left-hand side of (85) 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 (85) is positive, which is a contradiction. It follows that it must be $\frac{dP_{1,CT}}{d\pi_{BT}} \geq 0$.

These conditions do not allow to pin down with certainty the sign of $\frac{dP_0}{d\pi_{BT}}$. In particular, we can see from (85) that the first term is positive, while the second is negative. However, as $\pi_{BT} \to 1$, the second term goes to zero and only the positive term remains, which gives $\frac{df_0}{d\pi_{BT}} > 0$ and $\frac{dP_0}{d\pi_{BT}} < 0$.

We show how the various firms' profits move with π_{BT} in the proof of Proposition 6 using the more general model.

□

Proof of Proposition 5

We consider the planner's problem to set the optimal tax in each state, taking as given the production capacities of each producer. Let $e_{1,s}$ and $f_{1,s}$ be energy consumption and fossil fuel production from both producers in each state. Given market clearing conditions and the welfare functions, the planner's first order conditions in the two states are given by

$$u'(C + f_{1,BT}) = \lambda f_{1,BT}$$

and

$$u'(f_{1,CT}) = \lambda f_{1,CT}$$

Combining the two conditions, we get

$$\frac{f_{1,CT}}{f_{1,BT}} = \frac{u'(f_{1,CT})}{u'(C + f_{1,BT})} > \frac{u'(f_{1,CT})}{u'(f_{1,BT})}$$

where the inequality follows from the concavity of u whenever $C > 0$. Suppose now that $f_{1,BT} > f_{1,CT}$. Then, we would have

$$1 > \frac{f_{1,CT}}{f_{1,BT}} > \frac{u'(f_{1,CT})}{u'(f_{1,BT})} > 1$$

which is a contradiction. Therefore, it is always optimal for the planner to have less fossil fuel emissions in the BT state compared to the CT state.

Let us now solve for the optimal tax explicitly with CRRA preferences. Let us consider the CT state first. Considering interior solutions for both fossil fuel producers, optimal quantities are given by

$$f^I_{1,CT} = f^E_{1,CT} = (1 - \tau_{1,CT})\kappa_1 P_{1,CT} \tag{86}$$

Plugging these quantities into the market clearing condition (69) we obtain the following expression for the equilibrium price

$$P_{1,CT} = \sqrt{\frac{W}{2\kappa_1(1 - \tau_{1,CT})}} \tag{87}$$

The first order condition for the planner's problem is

$$\left[2\kappa_1(1 - \tau_{1,CT})P_{1,CT}\right]^{-\gamma} = \lambda 2\kappa_1(1 - \tau_{1,CT})P_{1,CT} \tag{88}$$

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

$$\tau^*_{1,CT} = 1 - \frac{1}{\lambda^{\frac{2}{1+\gamma}} 2W\kappa_1} \tag{89}$$

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

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

$$f^I_{1,BT} = f^E_{1,BT} = (1 - \tau_{1,BT})\kappa_1 P_{1,BT} \tag{90}$$

Using market clearing condition (68), the equilibrium price is now given by

$$P_{1,BT} = \frac{\sqrt{C^2 + 8\kappa_1(1 - \tau_{1,BT})W} - C}{4\kappa_1(1 - \tau_{1,BT})} \tag{91}$$

The optimality condition for the planner is now

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

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

$$\left[2\lambda\kappa_1(1 - \tau_{1,BT})W\right]^{\frac{1}{1-\gamma}} - \left[\frac{1}{\lambda(2\kappa_1 W)^\gamma(1 - \tau_{1,BT})^\gamma}\right]^{\frac{1}{1-\gamma}} = C > 0 \tag{93}$$

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

$$\tau^*_{1,BT} > 1 - \frac{1}{\lambda^{\frac{2}{1+\gamma}} 2W\kappa_1} = \tau^*_{1,CT} \tag{94}$$

Finally, note that the left-hand side of (93) is decreasing in λ and increasing in $\tau_{1,BT}$. Therefore, as λ increases, the optimal tax rate that satisfies (93) also has to increase. □

B.1 Proof of Proposition 6: Effects of Drilling Restrictions

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

$$-\frac{W}{(P_0)^2}\frac{dP_0}{d\bar{\tau}_0} = \frac{df_0^I}{d\bar{\tau}_0} \tag{95}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\bar{\tau}_0} = \frac{dC}{d\bar{\tau}_0} - \frac{df_0^I}{d\bar{\tau}_0} + \frac{d\bar{f}_1^E}{d\bar{\tau}_0} \tag{96}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\bar{\tau}_0} = \frac{dC}{d\bar{\tau}_0} \tag{97}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\bar{\tau}_0} = -\frac{df_0^I}{d\bar{\tau}_0} + \frac{d\bar{f}_1^E}{d\bar{\tau}_0} \tag{98}$$

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

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[\pi_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-\pi_{BT})P_{1,NE}\right] \tag{99}$$

$$f_0^I = \frac{1}{2}\bar{f}_0^I + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\left[\pi_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-\pi_{BT})P_{1,NE}\right] \tag{100}$$

$$C = \delta\left[\pi_{BT}P_{1,BT} + (1-\pi_{BT})P_{1,E}\right] \tag{101}$$

which implies

$$\begin{aligned}\frac{d\bar{f}_1^E}{d\bar{\tau}_0} &= -\frac{\kappa_1^2\kappa_2}{[\kappa_1 + (1-\bar{\tau}_0)\kappa_2]^2}\left[\pi_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-\pi_{BT})P_{1,NE}\right] \\ &\quad + \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\left[\pi_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\bar{\tau}_0} + (1-\pi_{BT})\frac{dP_{1,NE}}{d\bar{\tau}_0}\right]\end{aligned} \tag{102}$$

$$\frac{df_0^I}{d\bar{\tau}_0} = \frac{\kappa_1}{2}\frac{dP_0}{d\bar{\tau}_0} - \frac{\kappa_1}{2}\left[\pi_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\bar{\tau}_0} + (1-\pi_{BT})\frac{dP_{1,NE}}{d\bar{\tau}_0}\right] \tag{103}$$

$$\frac{dC}{d\bar{\tau}_0} = \delta\left[\pi_{BT}\frac{dP_{1,BT}}{d\bar{\tau}_0} + (1-\pi_{BT})\frac{dP_{1,E}}{d\bar{\tau}_0}\right] \tag{104}$$

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 (95), this implies $\frac{df_0^I}{d\bar{\tau}_0} > 0$. It follows from (103) that

$$\pi_{BT}\frac{dP_{1,BT}}{d\bar{\tau}_0} + (1-\pi_{BT})\frac{dP_{1,NE}}{d\bar{\tau}_0} < 0 \tag{105}$$

which implies, using (102) that $\frac{d\bar{f}_1^E}{d\bar{\tau}_0} < 0$. From (98), it then follows that $\frac{dP_{1,NE}}{d\bar{\tau}_0} > 0$, which implies, using (105), that $\frac{dP_{1,BT}}{d\bar{\tau}_0} < 0$. From (96), we then have $\frac{dC}{d\bar{\tau}_0} > 0$, which implies, from (97), that $\frac{dP_{1,E}}{d\bar{\tau}_0} < 0$. But then, (104) 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 6: 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

$$\frac{W}{P_0} = f_0^I \tag{106}$$

$$\frac{W}{P_{1,BT}} = C + \bar{f}_0^I - f_0^I + \bar{f}_1^E \tag{107}$$

$$q\frac{W}{P_{1,E}} = C \tag{108}$$

$$(1-q)\frac{W}{P_{1,NE}} = \bar{f}_0^I - f_0^I + \bar{f}_1^E \tag{109}$$

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

$$-\frac{W}{(P_0)^2}\frac{dP_0}{d\pi_{BT}} = \frac{df_0^I}{d\pi_{BT}} \tag{110}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\pi_{BT}} = \frac{dC}{d\pi_{BT}} - \frac{df_0^I}{d\pi_{BT}} + \frac{d\bar{f}_1^E}{d\pi_{BT}} \tag{111}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\pi_{BT}} = \frac{dC}{d\pi_{BT}} \tag{112}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\pi_{BT}} = -\frac{df_0^I}{d\pi_{BT}} + \frac{d\bar{f}_1^E}{d\pi_{BT}} \tag{113}$$

Moreover, optimal quantities are given by

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

$$f_0^I = \frac{1}{2}\bar{f}_0^I + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\Big[\pi_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-\pi_{BT})P_{1,NE}\Big] \tag{115}$$

$$C = \delta\Big[\pi_{BT}P_{1,BT} + (1-\pi_{BT})P_{1,E}\Big] \tag{116}$$

which implies

$$\frac{d\bar{f}_1^E}{d\pi_{BT}} = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[(1-\tau_{1,BT})P_{1,BT} - P_{1,NE} + \pi_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\pi_{BT}} + (1-\pi_{BT})\frac{dP_{1,NE}}{d\pi_{BT}}\Big] \tag{117}$$

$$\frac{df_0^I}{d\pi_{BT}} = \frac{\kappa_1}{2}\frac{dP_0}{d\pi_{BT}} - \frac{\kappa_1}{2}\Big[(1-\tau_{1,BT})P_{1,BT} - P_{1,NE} + \pi_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\pi_{BT}} + (1-\pi_{BT})\frac{dP_{1,NE}}{d\pi_{BT}}\Big] \tag{118}$$

$$\frac{dC}{d\pi_{BT}} = \delta\Big[P_{1,BT} - P_{1,E} + \pi_{BT}\frac{dP_{1,BT}}{d\pi_{BT}} + (1-\pi_{BT})\frac{dP_{1,E}}{d\pi_{BT}}\Big] \tag{119}$$

Let us show that we have $\frac{dP_0}{d\pi_{BT}} \leq 0$. By contradiction, suppose $\frac{dP_0}{d\pi_{BT}} > 0$. Then, (110) implies $\frac{df_0^I}{d\pi_{BT}} < 0$. But then, using (118), we have

$$(1-\tau_{1,BT})P_{1,BT} - P_{1,NE} + \pi_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\pi_{BT}} + (1-\pi_{BT})\frac{dP_{1,NE}}{d\pi_{BT}} > 0 \tag{120}$$

It then follows from (117) that $\frac{d\bar{f}_1^E}{d\pi_{BT}} > 0$, which implies, using (113), that $\frac{dP_{1,NE}}{d\pi_{BT}} < 0$. Now, note that market clearing conditions and $P_{1,E} \leq P_{1,NE}$ imply that $P_{1,BT} < P_{1,NE}$. Using (120), it then follows that $\frac{dP_{1,BT}}{d\pi_{BT}} > 0$, which in turn implies, using (111), that $\frac{dC}{d\pi_{BT}} < 0$. But then, (112) implies that $\frac{dP_{1,E}}{d\pi_{BT}} > 0$, which in turn implies, using (119), that $\frac{dC}{d\pi_{BT}} > 0$. This is a contradiction, so we must have $\frac{dP_0}{d\pi_{BT}} \leq 0$. Assuming then $\frac{dP_0}{d\pi_{BT}} = 0$ and following the previous steps yields immediately a contradiction, hence it must be $\frac{dP_0}{d\pi_{BT}} < 0$.

We also show that $\frac{d\bar{f}_1^E}{d\pi_{BT}} < 0$ and $\frac{dC}{d\pi_{BT}} \geq 0$. From (110), we immediately have $\frac{df_0^I}{d\pi_{BT}} > 0$. Using (118), we have

$$(1-\tau_{1,BT})P_{1,BT} - P_{1,NE} + \pi_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\pi_{BT}} + (1-\pi_{BT})\frac{dP_{1,NE}}{d\pi_{BT}} < 0 \tag{121}$$

which immediately implies from (117) that $\frac{d\bar{f}_1^E}{d\pi_{BT}} < 0$. Using (113) we then have $\frac{dP_{1,NE}}{d\pi_{BT}} > 0$. Finally, suppose that $\frac{dC}{d\pi_{BT}} < 0$. It then follows from (111) that $\frac{dP_{1,BT}}{d\pi_{BT}} > 0$. But this contradicts (121), showing that it must be $\frac{dC}{d\pi_{BT}} \geq 0$.

Note that if demand is different in the two states in period 1, then it is not always true that the previous result holds. In particular, if demand in the BT state is higher than in the CT state, then it is not obvious that $P_{1,BT} < P_{1,NE}$, as this would depend on the level of green energy supply C. Indeed, if we had $P_{1,BT} > P_{1,NE}$ because of a higher demand, then the BT state would be more attractive to the incumbent firm, thus increasing the probability π_{BT} would induce it to increase its inventory reserves, causing the date-0 energy price to increase with π_{BT}.

Finally, following the same steps as in the proof of Proposition 4, 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

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

which implies that total expected profits in period 0 are

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

It follows that

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

The result that $\frac{d\Pi_0^E}{d\pi_{BT}} \leq 0$ follows immediately from (117) and $\frac{d\bar{f}_1^E}{d\pi_{BT}} < 0$.

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

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

We showed before that $\frac{dP_0}{d\pi_{BT}} \leq 0$. 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

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

using

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

we have

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

Therefore, this implies

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

and our result follows immediately from (119) and $\frac{dC}{d\pi_{BT}} \geq 0$.

□

B.3 Proof of Proposition 6: 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

$$-\frac{W}{(P_0)^2}\frac{dP_0}{d\tau_{1,BT}} = \frac{df_0^I}{d\tau_{1,BT}} \tag{122}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} - \frac{df_0^I}{d\tau_{1,BT}} + \frac{d\bar{f}_1^E}{d\tau_{1,BT}} \tag{123}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} \tag{124}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\tau_{1,BT}} = -\frac{df_0^I}{d\tau_{1,BT}} + \frac{d\bar{f}_1^E}{d\tau_{1,BT}} \tag{125}$$

Optimal quantities are now given by

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\Big[\pi_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-\pi_{BT})P_{1,NE}\Big] \tag{126}$$

$$f_0^I = \frac{1}{2}\bar{f}_0^I + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\Big[\pi_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-\pi_{BT})P_{1,NE}\Big] \tag{127}$$

$$C = \delta\Big[\pi_{BT}P_{1,BT} + (1-\pi_{BT})P_{1,E}\Big] \tag{128}$$

which implies that we have

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

$$\frac{df_0^I}{d\tau_{1,BT}} = \frac{\kappa_1}{2}\frac{dP_0}{d\tau_{1,BT}} - \frac{\kappa_1}{2}\Big[-\pi_{BT}P_{1,BT} + \pi_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-\pi_{BT})\frac{dP_{1,NE}}{d\tau_{1,BT}}\Big] \tag{130}$$

$$\frac{dC}{d\tau_{1,BT}} = \delta\Big[\pi_{BT}\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-\pi_{BT})\frac{dP_{1,E}}{d\tau_{1,BT}}\Big] \tag{131}$$

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 (122), $\frac{df_0^I}{d\tau_{1,BT}} < 0$. It follows from (130) that

$$-\pi_{BT}P_{1,BT} + \pi_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-\pi_{BT})\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0 \tag{132}$$

which in turn implies, using (129), that $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} > 0$. Using (125), it follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$, which implies, using (132), that $\frac{dP_{1,BT}}{d\tau_{1,BT}} > 0$. It then follows from (123) that $\frac{dC}{d\tau_{1,BT}} < 0$ which in turn implies from (124) that $\frac{dP_{1,E}}{d\tau_{1,BT}} > 0$. But then, (131) 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 than 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

$$\frac{W}{P_0} = f_0^I \tag{133}$$

$$\frac{W}{P_{1,BT}} = C + f_{1,BT}^I + \bar{f}_1^E \tag{134}$$

$$q\frac{W}{P_{1,E}} = C \tag{135}$$

$$(1-q)\frac{W}{P_{1,NE}} = \bar{f}_0^I - f_0^I + \bar{f}_1^E \tag{136}$$

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

$$-\frac{W}{(P_0)^2}\frac{dP_0}{d\tau_{1,BT}} = \frac{df_0^I}{d\tau_{1,BT}} \tag{137}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} + \frac{df_{1,BT}^I}{d\tau_{1,BT}} + \frac{d\bar{f}_1^E}{d\tau_{1,BT}} \tag{138}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} \tag{139}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\tau_{1,BT}} = -\frac{df_0^I}{d\tau_{1,BT}} + \frac{d\bar{f}_1^E}{d\tau_{1,BT}} \tag{140}$$

Optimal quantities are given by

$$f_0^I = \frac{\kappa_1}{2-\pi_{BT}}P_0 - \frac{(1-\pi_{BT})\kappa_1}{2-\pi_{BT}}P_{1,NE} + \frac{1-\pi_{BT}}{2-\pi_{BT}}\bar{f}_0^I \tag{141}$$

$$\bar{f}_1^E = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\Bigg[\pi_{BT}(1-\tau_{1,BT})P_{1,BT} + (1-\pi_{BT})P_{1,NE}\Bigg] \tag{142}$$

$$f_{1,BT}^I = \kappa_1(1-\tau_{1,BT})P_{1,BT} \tag{143}$$

$$C = \delta\Bigg[\pi_{BT}P_{1,BT} + (1-\pi_{BT})P_{1,E}\Bigg] \tag{144}$$

which implies

$$\frac{df_0^I}{d\tau_{1,BT}} = \frac{\kappa_1}{2-\pi_{BT}}\frac{dP_0}{d\tau_{1,BT}} - \frac{(1-\pi_{BT})\kappa_1}{2-\pi_{BT}}\frac{dP_{1,NE}}{d\tau_{1,BT}} \tag{145}$$

$$\frac{d\bar{f}_1^E}{d\tau_{1,BT}} = \frac{(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\bar{\tau}_0)\kappa_2}\Bigg[-\pi_{BT}P_{1,BT} + \pi_{BT}(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-\pi_{BT})\frac{dP_{1,NE}}{d\tau_{1,BT}}\Bigg] \tag{146}$$

$$\frac{df_{1,BT}^I}{d\tau_{1,BT}} = \kappa_1\Bigg[-P_{1,BT} + (1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}}\Bigg] \tag{147}$$

$$\frac{dC}{d\tau_{1,BT}} = \delta\Bigg[\pi_{BT}\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-\pi_{BT})\frac{dP_{1,E}}{d\tau_{1,BT}}\Bigg] \tag{148}$$

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 (139) we have $\frac{dP_{1,E}}{d\tau_{1,BT}} > 0$. This implies, using (148), that $\frac{dP_{1,BT}}{d\tau_{1,BT}} < 0$. Using (147) we then have $\frac{df^I_{1,BT}}{d\tau_{1,BT}} < 0$, and using (138) we have $\frac{d\bar{f}^E_1}{d\tau_{1,BT}} > 0$. Then, from (146) we find $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, which implies using (140) that $\frac{df^I_0}{d\tau_{1,BT}} > 0$. But then (137) implies $\frac{dP_0}{d\tau_{1,BT}} < 0$ and (145) gives $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$, which is a contradiction. Therefore, it must be $\frac{dC}{d\tau_{1,BT}} \geq 0$, which in turn implies $\frac{dP_{1,E}}{d\tau_{1,BT}} \leq 0$ and $\frac{dP_{1,BT}}{d\tau_{1,BT}} \geq 0$ following the same steps.

We now show that $\frac{df^I_{1,BT}}{d\tau_{1,BT}} \leq 0$. Suppose that the opposite holds. Then, (138) implies $\frac{d\bar{f}^E_1}{d\tau_{1,BT}} < 0$, and using (146) we get $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$. But then (140) implies $\frac{df^I_0}{d\tau_{1,BT}} < 0$, (137) implies $\frac{dP_0}{d\tau_{1,BT}} > 0$, and (145) implies $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, a contradiction. Hence, $\frac{df^I_{1,BT}}{d\tau_{1,BT}} \leq 0$.

Then, suppose that $\frac{d\bar{f}^E_1}{d\tau_{1,BT}} > 0$. From (146) we have $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, from (140) we have $\frac{df^I_0}{d\tau_{1,BT}} > 0$, from (137) we have $\frac{dP_0}{d\tau_{1,BT}} < 0$ and from (145) we have $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$, a contradiction. Therefore, $\frac{d\bar{f}^E_1}{d\tau_{1,BT}} \leq 0$.

For the next step, suppose that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$. Then, using (140) we have $\frac{df^I_0}{d\tau_{1,BT}} < 0$, using (137) we have $\frac{dP_0}{d\tau_{1,BT}} > 0$, and using (145) 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 (137), this implies that $\frac{df^I_0}{d\tau_{1,BT}} > 0$. From (145), it then follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$, a contradiction. This proves that we must have $\frac{dP_0}{d\tau_{1,BT}} \geq 0$.

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

$$\frac{W}{P_0} = f^I_0 \tag{149}$$

$$\frac{W}{P_{1,BT}} = C + f^I_{1,BT} + f^E_{1,BT} \tag{150}$$

$$q\frac{W}{P_{1,E}} = C \tag{151}$$

$$(1-q)\frac{W}{P_{1,NE}} = \bar{f}^I_0 - f^I_0 + \bar{f}^E_1 \tag{152}$$

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

$$-\frac{W}{(P_0)^2}\frac{dP_0}{d\tau_{1,BT}} = \frac{df^I_0}{d\tau_{1,BT}} \tag{153}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} + \frac{df^I_{1,BT}}{d\tau_{1,BT}} + \frac{df^E_{1,BT}}{d\tau_{1,BT}} \tag{154}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} \tag{155}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\tau_{1,BT}} = -\frac{df^I_0}{d\tau_{1,BT}} + \frac{d\bar{f}^E_1}{d\tau_{1,BT}} \tag{156}$$

Optimal quantities are now given by

$$f^I_0 = \frac{\kappa_1}{2-\pi_{BT}}P_0 - \frac{(1-\pi_{BT})\kappa_1}{2-\pi_{BT}}P_{1,NE} + \frac{1-\pi_{BT}}{2-\pi_{BT}}\bar{f}^I_0 \tag{157}$$

$$\bar{f}^E_1 = \frac{(1-\pi_{BT})(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\pi_{BT})(1-\bar{\tau}_0)\kappa_2}P_{1,NE} \tag{158}$$

$$f^I_{1,BT} = f^E_{1,BT} = \kappa_1(1-\tau_{1,BT})P_{1,BT} \tag{159}$$

$$C = \delta\Big[\pi_{BT}P_{1,BT} + (1-\pi_{BT})P_{1,E}\Big] \tag{160}$$

which implies

$$\frac{df_0^I}{d\tau_{1,BT}} = \frac{\kappa_1}{2-\pi_{BT}}\frac{dP_0}{d\tau_{1,BT}} - \frac{(1-\pi_{BT})\kappa_1}{2-\pi_{BT}}\frac{dP_{1,NE}}{d\tau_{1,BT}} \tag{161}$$

$$\frac{d\bar{f}_1^E}{d\tau_{1,BT}} = \frac{(1-\pi_{BT})(1-\bar{\tau}_0)\kappa_1\kappa_2}{\kappa_1+(1-\pi_{BT})(1-\bar{\tau}_0)\kappa_2}\frac{dP_{1,NE}}{d\tau_{1,BT}} \tag{162}$$

$$\frac{df_{1,BT}^I}{dd\tau_{1,BT}} = \frac{df_{1,BT}^E}{dd\tau_{1,BT}} = \kappa_1\Big[-P_{1,BT}+(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}}\Big] \tag{163}$$

$$\frac{dC}{d\tau_{1,BT}} = \delta\Big[\pi_{BT}\frac{dP_{1,BT}}{d\tau_{1,BT}}+(1-\pi_{BT})\frac{dP_{1,E}}{d\tau_{1,BT}}\Big] \tag{164}$$

Suppose first that $\frac{dP_0}{d\tau_{1,BT}} < 0$. Using (153), this implies that $\frac{df_0^I}{d\tau_{1,BT}} > 0$. From (161), it then follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$. This implies, from (156), that $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} > 0$. But then, from (162), 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 (153), this implies that $\frac{df_0^I}{d\tau_{1,BT}} < 0$. From (161), it then follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$. Then, from (156), this implies $\frac{d\bar{f}_1^E}{d\tau_{1,BT}} < 0$. But it then follows from (162) 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 $\frac{df_0^I}{d\tau_{1,BT}} = \frac{d\bar{f}_1^E}{d\tau_{1,BT}} = \frac{dP_{1,NE}}{d\tau_{1,BT}} = 0$.

Note that the previous proof does not rely on the specific value of the demand function W in the two states. Therefore, even if demand in the BT state were higher, the previous result would continue to hold as long as the incumbent's assets are still stranded in that state, that is if $(1-\tau_{1,BT})P_{1,BT} < P_{1,NE}$.

□

Appendix C Carbon Tax on Production rather than on Sales

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

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

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

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

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

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

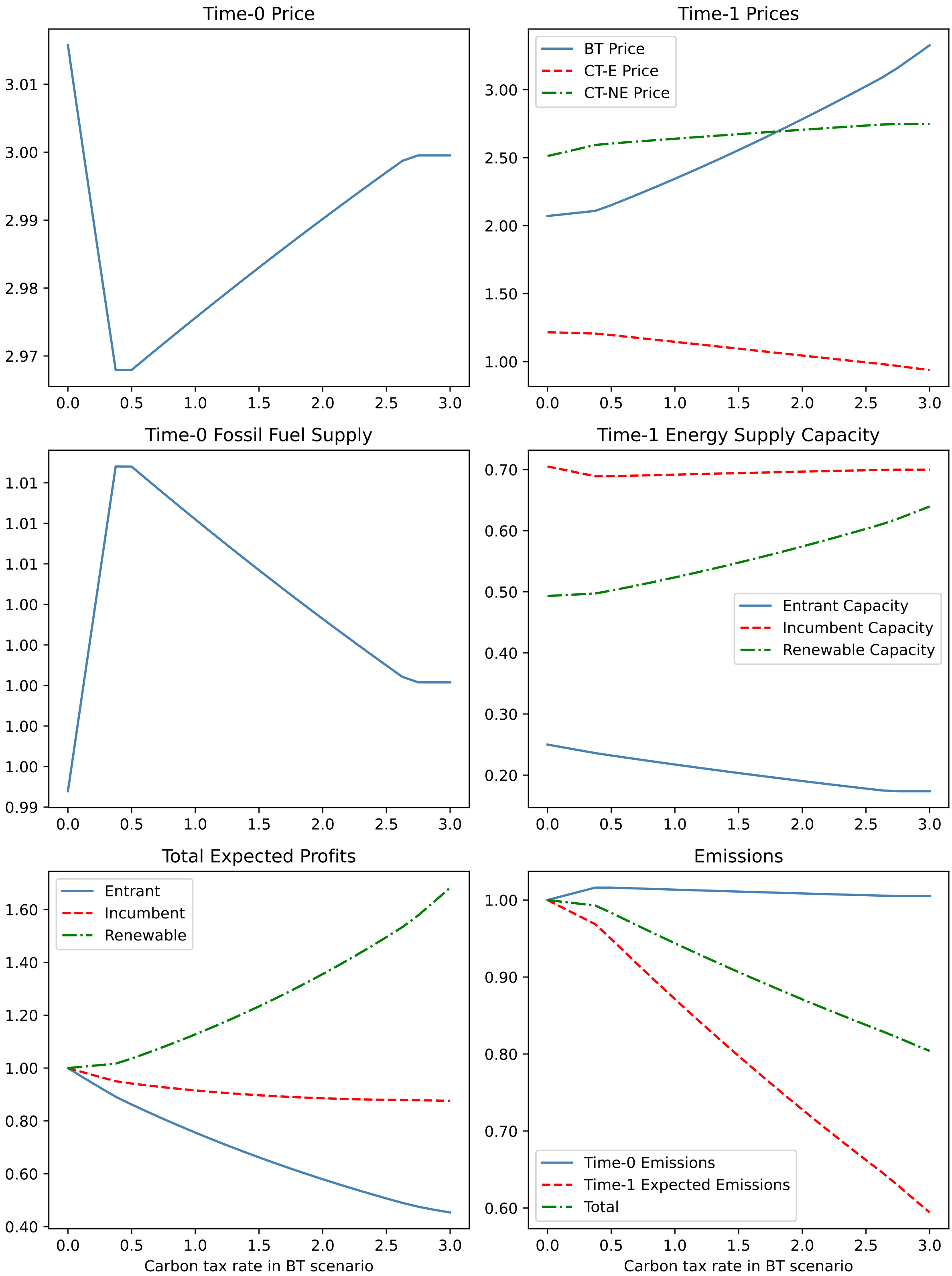


Figure 7: Equilibrium effects of changes in BT tax rate. Note that profits for each producer are normalized by their profits for $\tau_{1,BT} = 0$, whereas emissions are normalized for each period and total by the corresponding value for $\tau_{1,BT} = 1$. BT scenario probability is fixed at $\pi_{BT}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

Appendix D Modeling Alternatives

D.1 Model with linear demand

In this section, we consider the model without a renewable sector and assume that in each period and state, demand for energy is linear in the price, that is, $D = \alpha - \beta P$. For simplicity, we also assume that marginal costs of energy production and extraction are equal, and set them as $\kappa_1 = \kappa_2 = 1$. We show how this allows to obtain closed form expressions for the equilibrium energy price, and that the results of the effects of tax rates on energy prices in our main model remain unchanged.

D.1.1 Model with no tax uncertainty

The equilibrium conditions become

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

$$f_1^E = \frac{(1-\bar{\tau}_0)(1-\tau_1)}{2-\bar{\tau}_0}P_1$$

$$\alpha - \beta P_0 = f_0^I$$

$$\alpha - \beta P_1 = \bar{f}_0^I - f_0^I + f_1^E$$

After substituting the expressions for optimal quantities into market clearing conditions and combining them, we obtain

$$P_0 = \frac{(1-\bar{\tau}_0)(1-\tau_1) + (2-\bar{\tau}_0)(1-\tau_1+\beta)}{[(1-\bar{\tau}_0)(1-\tau_1) + \beta(2-\bar{\tau}_0)](1+2\beta) + (1-\tau_1)(2-\bar{\tau}_0)\beta}(2\alpha - \bar{f}_0^I)$$

Note that prices have to be positive in equilibrium, which thus requires $\alpha > \frac{1}{2}\bar{f}_0$. Taking derivatives with respect to the two tax rates, we obtain

$$\frac{dP_0}{d\tau_1} = -\frac{(2\alpha - \bar{f}_0^I)(1+\beta)\beta}{\left[\left(\beta + \frac{(1-\bar{\tau}_0)(1-\tau_1)}{2-\bar{\tau}_0}\right)(1+2\beta) + (1-\tau_1)\beta\right]^2} < 0$$

$$\frac{dP_0}{d\bar{\tau}_0} = \frac{(2\alpha - \bar{f}_0^I)(1+\beta)(1-\tau_1)^2}{\left[\left(\beta + \frac{(1-\bar{\tau}_0)(1-\tau_1)}{2-\bar{\tau}_0}\right)(1+2\beta) + (1-\tau_1)\beta\right]^2(2-\bar{\tau}_0)^2} > 0$$

Therefore, the same condition that ensures positive prices in equilibrium also implies $\frac{dP_0}{d\tau_1} < 0$ and $\frac{dP_0}{d\bar{\tau}_0} > 0$.

D.1.2 Model with tax uncertainty

Since we focus on the carbon tax, we let $\bar{\tau}_0 = 0$ for simplicity. With the fossil fuel production constraint binding in both states we have

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

$$f_1^E = \frac{1}{2}\Big[\pi_T(1-\tau_1)P_{1,T} + (1-\pi_T)P_{1,NT}\Big]$$

$$\alpha - \beta P_0 = f_0^I$$

$$\alpha - \beta P_{1,T} = \bar{f}_0^I - f_0^I + f_1^E$$

$$\alpha - \beta P_{1,NT} = \bar{f}_0^I - f_0^I + f_1^E$$

Note that this implies $P_{1,T} = P_{1,NT} = P_1$. Solving this system, we obtain

$$P_0 = \frac{(2\alpha - \bar{f}_0^I)[2\beta + 3(1 - \pi_T\tau_1)]}{(1 + 4\beta)(1 - \pi_T\tau_1) + 2\beta(1 + 2\beta)}$$

Note that, as before, it must be $\alpha > \frac{1}{2}\bar{f}_0^I$ to have a positive price in equilibrium. The effects of changes in tax rate and tax probability are now given by

$$\frac{dP_0}{d\tau_1} = -\frac{4(2\alpha - \bar{f}_0^I)(1 + \beta)\pi_T\beta}{[(1 + 4\beta)(1 - \pi_T\tau_1) + 2\beta(1 + 2\beta)]^2} < 0$$

$$\frac{dP_0}{d\pi_T} = -\frac{4(2\alpha - \bar{f}_0^I)(1 + \beta)\tau_1\beta}{[(1 + 4\beta)(1 - \pi_T\tau_1) + 2\beta(1 + 2\beta)]^2} < 0$$

Therefore, with no stranded assets in period 1, changes in the tax probability or in the tax rate have the same directional effect on the date-0 energy price.

With the incumbent's production constraint binding in the NT state only, equilibrium conditions become

$$\begin{aligned}
f_0^I &= \frac{1 - \pi_T}{2 - \pi_T}\bar{f}_0^I + \frac{1}{2 - \pi_T}\Big[P_0 - (1 - \pi_T)P_{1,NT}\Big] \\
f_{1,T}^I &= (1 - \tau_1)P_{1,T} \\
f_1^E &= \frac{1}{2}\Big[\pi_T(1 - \tau_1)P_{1,T} + (1 - \pi_T)P_{1,NT}\Big] \\
\alpha - \beta P_0 &= f_0^I \\
\alpha - \beta P_{1,T} &= f_{1,T}^I + f_1^E \\
\alpha - \beta P_{1,NT} &= \bar{f}_0^I - f_0^I + f_1^E
\end{aligned}$$

After solving the system, we obtain

$$\begin{aligned}
P_0 = {} & \frac{2\beta^2(\pi_T - 2) + \beta\big((7\pi_T - 10) + (4 - \pi_T^2)\tau_1\big) - 6(1 - \pi_T)(1 - \tau_1)}{2\beta^3(\pi_T - 2) + \beta^2\big((5\pi_T - 10) + (4 - \pi_T^2)\tau_1\big) + \beta\big((4\pi_T - 7) + 3(2 - \pi_T)\tau_1\big) - (1 - \pi_T)(1 - \tau_1)}\alpha \\
& + \frac{(1 - \pi_T)\Big[2\beta^2 + \beta\big(5 - (\pi_T + 2)\tau_1\big) + 3(1 - \tau_1)\Big]}{2\beta^3(\pi_T - 2) + \beta^2\big((5\pi_T - 10) + (4 - \pi_T^2)\tau_1\big) + \beta\big((4\pi_T - 7) + 3(2 - \pi_T)\tau_1\big) - (1 - \pi_T)(1 - \tau_1)}\bar{f}_0^I
\end{aligned}$$

Let us now rewrite

$$P_0(\tau_1) = \frac{A(\tau_1)\,\alpha + B(\tau_1)\,\bar{f}_0^I}{D(\tau_1)}$$

where

$$\begin{aligned}
A(\tau_1) &= 2\beta^2(\pi_T - 2) + \beta\big((7\pi_T - 10) + (4 - \pi_T^2)\tau_1\big) - 6(1 - \pi_T)(1 - \tau_1) \\
B(\tau_1) &= (1 - \pi_T)\Big[2\beta^2 + \beta\big(5 - (\pi_T + 2)\tau_1\big) + 3(1 - \tau_1)\Big] \\
D(\tau_1) &= 2\beta^3(\pi_T - 2) + \beta^2\big(5(\pi_T - 2) + (4 - \pi_T^2)\tau_1\big) \\
&\quad + \beta\big((4\pi_T - 7) + 3(2 - \pi_T)\tau_1\big) - (1 - \pi_T)(1 - \tau_1)
\end{aligned}$$

To show that $dP_0/d\tau_1 > 0$, we first solve the linear system for $P_{1,T}$ to obtain

$$P_{1,T} = \frac{F}{D(\tau_1)}$$

where

$$F = \alpha\Big(2\beta(\beta + 1)(\pi_T - 2) + (1 - \pi_T)\Big) - (\beta + 1)\bar{f}_0^I\,(1 - \pi_T)$$

The derivative of P_0 is then given by

$$\frac{dP_0}{d\tau_1} = \frac{\big(A'(\tau_1)\alpha + B'(\tau_1)\bar{f}_0^I\big)D(\tau_1) - \big(A(\tau_1)\alpha + B(\tau_1)\bar{f}_0^I\big)D'(\tau_1)}{D(\tau_1)^2}$$

A direct simplification shows the numerator factors as

$$\big(A'(\tau_1)\alpha + B'(\tau_1)\bar{f}_0^I\big)D(\tau_1) - \big(A(\tau_1)\alpha + B(\tau_1)\bar{f}_0^I\big)D'(\tau_1) = \beta\,\pi_T\,(\pi_T - 1)\,F$$

hence, using $F = D(\tau_1)P_{1,T}$,

$$\frac{dP_0}{d\tau_1} = \frac{\beta\,\pi_T\,(\pi_T-1)\,F}{D(\tau_1)^2} = \frac{\beta\,\pi_T\,(\pi_T-1)}{D(\tau_1)}\,P_{1,T}$$

We now show that $D(\tau_1) < 0$ for all admissible values. Recall that $\beta > 0$, $0 < \pi_T < 1$, and $0 < \tau_1 < 1$. Consider each term in $D(\tau_1)$:

- $2\beta^3(\pi_T - 2) < 0$ since $\pi_T - 2 < 0$.
- For the β^2-coefficient, define

  $$g(\pi_T, \tau_1) := (5\pi_T - 10) + (4 - \pi_T^2)\tau_1.$$

  Since $4 - \pi_T^2 > 0$ for $\pi_T \in (0,1)$, g is strictly increasing in τ_1, so for $\tau_1 < 1$,

  $$g(\pi_T, \tau_1) < g(\pi_T, 1) = 5\pi_T - 6 - \pi_T^2.$$

  The function $h(\pi_T) := 5\pi_T - 6 - \pi_T^2$ has derivative $h'(\pi_T) = 5 - 2\pi_T > 0$ on $(0,1)$, so $h(\pi_T) < h(1) = -2 < 0$. Hence the β^2 term is < 0.
- For the β-coefficient, define

  $$C(\pi_T, \tau_1) := (4\pi_T - 7) + 3(2 - \pi_T)\tau_1 = (4\pi_T - 7) + (6 - 3\pi_T)\tau_1.$$

  Since $6 - 3\pi_T > 3 > 0$ for $\pi_T \in (0,1)$, C is strictly increasing in τ_1, so for $\tau_1 < 1$,

  $$C(\pi_T, \tau_1) < C(\pi_T, 1) = (4\pi_T - 7) + (6 - 3\pi_T) = \pi_T - 1 < 0,$$

  since $\pi_T < 1$. Hence the β term is < 0.
- Finally, $-(1 - \pi_T)(1 - \tau_1) < 0$ since $\pi_T < 1$ and $\tau_1 < 1$.

Therefore every summand in $D(\tau_1)$ is strictly negative, so $D(\tau_1) < 0$. Since $\beta > 0$, $\pi_T > 0$, $\pi_T - 1 < 0$, and $P_{1,T} > 0$, it follows that

$$\frac{dP_0}{d\tau_1} = \frac{\beta\,\pi_T\,(\pi_T-1)}{D(\tau_1)}\,P_{1,T} > 0.$$

Note that a similar proof does not apply to $\frac{dP_0}{d\pi_T}$, whose sign is in general ambiguous and depends on the parameter values. Hence, with linear demand, all the results of our base model continue to hold.

Finally, the equilibrium expression for $P_{1,NT}$ is given by

$$P_{1,NT} = \frac{G}{D(\tau_1)}$$

where

$$G = \alpha\Big[2\beta(\beta+1)(\pi_T - 2) - (\pi_T + 4) + \tau_1\big(4\beta + 1 - (2\beta - 1)\pi_T\big)\Big] + (\beta+1)\bar{f}_0^I\Big[2(\beta+1) + \pi_T - \tau_1(\pi_T + 2)\Big]$$

To check that the equilibrium production constraint is satisfied, it must be $f_{1,NT} > f_{1,T}$. Inserting the equilibrium prices, we obtain the following condition on the carbon tax rate

$$\tau_1 > \tau_{strand} = \frac{\alpha(4\beta+5) - (\beta+1)(2\beta+3)\,\bar{f}_0^I}{\alpha\big(4(\beta+1) - (2\beta-1)\pi_T\big) - (\beta+1)(\pi_T+2)\,\bar{f}_0^I}$$

Therefore, if the carbon tax rate in the T state is above the threshold τ_{strand}, it becomes optimal for the incumbent to leave some of its assets stranded in the T state. Note that the threshold is decreasing in the amount of initial reserves, $\bar{f}_0^I$, which increases the marginal cost of fully exhausting the production capacity. It then follows that for higher $\bar{f}_0^I$, the carbon tax threshold after which the green paradox is reversed becomes lower.

D.2 Model with stochastic demand

We now still focus on the model without a renewable firm and consider the case where energy demand can be different in the two states in period 1. In particular, we assume that the demand for energy in the Tax state is given by

$$D_{1,T} = \alpha + \varepsilon - \beta P_{1,T}$$

Therefore, a positive ε gives an energy demand that is positively correlated with the carbon tax.

In the case of no stranded assets in period 1, equilibrium conditions thus become

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

$$f_1^E = \frac{1}{2}\Big[\pi_T(1-\tau_1)P_{1,T} + (1-\pi_T)P_{1,NT}\Big]$$

$$\alpha - \beta P_0 = f_0^I$$

$$\alpha + \varepsilon - \beta P_{1,T} = \bar{f}_0^I - f_0^I + f_1^E$$

$$\alpha - \beta P_{1,NT} = \bar{f}_0^I - f_0^I + f_1^E$$

Combining the last two conditions we therefore get,

$$P_{1,T} = P_{1,NT} + \frac{\varepsilon}{\beta}$$

and solving the system, we obtain

$$P_0 = \frac{(2\alpha - \bar{f}_0^I)[2\beta + 3(1-\pi_T\tau_1)]}{(1+4\beta)(1-\pi_T\tau_1) + 2\beta(1+2\beta)} + \frac{2\pi_T(1-\tau_1)}{(1+4\beta)(1-\pi_T\tau_1) + 2\beta(1+2\beta)}\varepsilon$$

$$\varepsilon < \frac{\alpha[(1+4\beta)(1-\pi_T\tau_1) + 2\beta(1+2\beta)] - \beta(2\alpha - \bar{f}_0^I)[2\beta + 3(1-\pi_T\tau_1)]}{2\pi_T\beta(1-\tau_1)}$$

The derivative of the price with respect to the tax rate is now given by

$$\frac{dP_0}{d\tau_1} = -\frac{4(2\alpha - \bar{f}_0^I)(1+\beta)\pi_T\beta}{[(1+4\beta)(1-\pi_T\tau_1) + 2\beta(1+2\beta)]^2} - \frac{(1+4\beta)(1-\pi_T) + 2\beta(1+2\beta)}{[(1-\pi_T\tau_1)(1+4\beta) + 2\beta(1+2\beta)]^2}2\pi_T\varepsilon$$

so the total effect remains negative if

$$-\frac{2\beta(2\alpha - \bar{f}_0^I)(1+\beta)}{(1+4\beta)(1-\pi_T) + 2\beta(1+2\beta)} < \varepsilon$$

Solving the system for $P_{1,T}$, we get

$$P_{1,T} = \frac{2(1+\beta)(2\alpha - \bar{f}_0^I)}{(1-\pi_T\tau_1)(1+4\beta) + 2\beta(1+2\beta)} + \frac{(1+4\beta)(1-\pi_T) + 2\beta(1+2\beta)}{\beta[(1-\pi_T\tau_1)(1+4\beta) + 2\beta(1+2\beta)]}\varepsilon$$

and in order for the equilibrium price to be positive, we thus need

$$-\frac{2\beta(1+\beta)(2\alpha - \bar{f}_0^I)}{(1+4\beta)(1-\pi_T) + 2\beta(1+2\beta)} < \varepsilon$$

which is the same condition for the negativity of the derivative. Therefore, in all feasible equilibria with positive prices, we have $\frac{dP_0}{d\tau_1} < 0$, as in the case without stochastic demand. Turning now to the derivative with respect to the tax probability, we have

$$\frac{dP_0}{d\pi_T} = -\frac{4(2\alpha - \bar{f}_0^I)(1+\beta)\tau_1\beta}{[(1+4\beta)(1-\pi_T\tau_1) + 2\beta(1+2\beta)]^2} + \frac{(1-\tau_1)(1+6\beta+4\beta^2)}{[(1+4\beta)(1-\pi_T\tau_1) + 2\beta(1+2\beta)]^2}2\varepsilon$$

so the total effect remains negative if

$$\varepsilon < \frac{2(2\alpha - \bar{f}_0^I)(1+\beta)\tau_1\beta}{(1-\tau_1)(1+6\beta+4\beta^2)}$$

Therefore, the baseline result $\frac{dP_0}{d\pi_T} < 0$ continues to hold provided that the demand in the T state is not too high compared to the NT state. Intuitively, holding the tax rate fixed, increasing the T-state demand increases the energy price in that state. If the demand in that state is high enough, it can therefore be the case that $(1-\tau_1)P_{1,T} > P_{1,NT}$, so that increasing the probability of the T state induces the incumbent to increase its inventory, thus increasing current energy prices.

In the case with stranded assets in the T state, we now have

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

$$f_{1,T}^I = (1-\tau_1)P_{1,T}$$

$$f_1^E = \frac{1}{2}\Big[\pi_T(1-\tau_1)P_{1,T} + (1-\pi_T)P_{1,NT}\Big]$$

$$\alpha - \beta P_0 = f_0^I$$

$$\alpha + \varepsilon - \beta P_{1,T} = f_{1,T}^I + f_1^E$$

$$\alpha - \beta P_{1,NT} = \bar{f}_0^I - f_0^I + f_1^E$$

After solving the system with $\varepsilon \neq 0$, we obtain

$$P_0 = \frac{2\beta^2(\pi_T-2) + \beta\big((7\pi_T-10) + (4-\pi_T^2)\tau_1\big) - 6(1-\pi_T)(1-\tau_1)}{2\beta^3(\pi_T-2) + \beta^2\big((5\pi_T-10)+(4-\pi_T^2)\tau_1\big) + \beta\big((4\pi_T-7)+3(2-\pi_T)\tau_1\big) - (1-\pi_T)(1-\tau_1)}\alpha$$

$$+\frac{(1-\pi_T)\Big[2\beta^2 + \beta\big(5-(\pi_T+2)\tau_1\big) + 3(1-\tau_1)\Big]}{2\beta^3(\pi_T-2) + \beta^2\big((5\pi_T-10)+(4-\pi_T^2)\tau_1\big) + \beta\big((4\pi_T-7)+3(2-\pi_T)\tau_1\big) - (1-\pi_T)(1-\tau_1)}\bar{f}_0^I$$

$$+\frac{\pi_T(1-\pi_T)(1-\tau_1)}{2\beta^3(\pi_T-2) + \beta^2\big((5\pi_T-10)+(4-\pi_T^2)\tau_1\big) + \beta\big((4\pi_T-7)+3(2-\pi_T)\tau_1\big) - (1-\pi_T)(1-\tau_1)}\varepsilon$$

We now show that the result $\frac{dP_0}{d\tau_1} > 0$ continues to hold when $\varepsilon \neq 0$. Recall from the solution of the system that

$$P_0(\tau_1) = \frac{A(\tau_1)\,\alpha + B(\tau_1)\,\bar{f}_0^I + C(\tau_1)\,\varepsilon}{D(\tau_1)}$$

$$C(\tau_1) = \pi_T(1-\pi_T)(1-\tau_1)$$

where $A(\tau_1)$, $B(\tau_1)$, and $D(\tau_1)$ are defined as in the $\varepsilon = 0$ case. Differentiating with respect to τ_1 yields

$$\frac{dP_0}{d\tau_1} = \frac{\big(A'(\tau_1)\alpha + B'(\tau_1)\bar{f}_0^I + C'(\tau_1)\varepsilon\big)D(\tau_1) - \big(A(\tau_1)\alpha + B(\tau_1)\bar{f}_0^I + C(\tau_1)\varepsilon\big)D'(\tau_1)}{D(\tau_1)^2}.$$

A direct simplification shows that the numerator again factors as

$$\big(A'(\tau_1)\alpha + B'(\tau_1)\bar{f}_0^I + C'(\tau_1)\varepsilon\big)D(\tau_1) - \big(A(\tau_1)\alpha + B(\tau_1)\bar{f}_0^I + C(\tau_1)\varepsilon\big)D'(\tau_1) = \beta\,\pi_T\,(\pi_T-1)\,F_\varepsilon$$

where F_ε is the numerator of $P_{1,T}$ in the general case $\varepsilon \neq 0$, i.e.

$$P_{1,T} = \frac{F_\varepsilon}{D(\tau_1)}$$

Therefore,

$$\frac{dP_0}{d\tau_1} = \frac{\beta\,\pi_T\,(\pi_T-1)}{D(\tau_1)}P_{1,T}.$$

The sign of $D(\tau_1)$ is unchanged relative to the $\varepsilon = 0$ case. Indeed, under the maintained assumptions $\beta > 0$, $0 < \pi_T < 1$, and $0 < \tau_1 < 1$, each term in $D(\tau_1)$ is strictly negative, hence $D(\tau_1) < 0$. Since $\beta > 0$, $\pi_T(\pi_T - 1) < 0$, and in equilibrium $P_{1,T} > 0$, it follows immediately that $\frac{dP_0}{d\tau_1} > 0$. It follows then that a stochastic demand does not affect the response of P_0 to the tax rate, provided that an equilibrium with positive prices still exists and that the incumbent's assets are still stranded in the T state. The price response to changes in π_T, on the other hand, is still in general ambiguous, as in the main model with $\varepsilon = 0$.

D.3 Model with endogenous renewable technologies

In this section, we use our full model and allow the development of renewable technology to respond to changes in tax policies, and investigate how this affects the response of the energy prices. In particular, we assume that the transition probability and the renewable efficiency are exogenous functions of tax rates of the following modified logistic form

$$\pi_{BT} = \frac{1}{1/\bar{p}_{BT} - 1 + \exp\{-a\tau\}}$$

$$\delta = \frac{1}{1/\bar{\delta} - 1 + \exp\{-a\tau\}}$$

where $\bar{p}_{BT}$ and $\bar{\delta}$ are baseline values in our numerical examples and $a > 0$. These functional forms imply that the renewable technology parameters are equal to their baseline values when the tax value is equal to 0, and then increase as $\tau \to 1$. This formulation captures the intuition that as taxes on the fossil fuel sector are increased, financial investment might endogenously shift into the renewable sector, thus accelerating the transition in the form of either a higher breakthrough probability or a lower cost of green energy production.

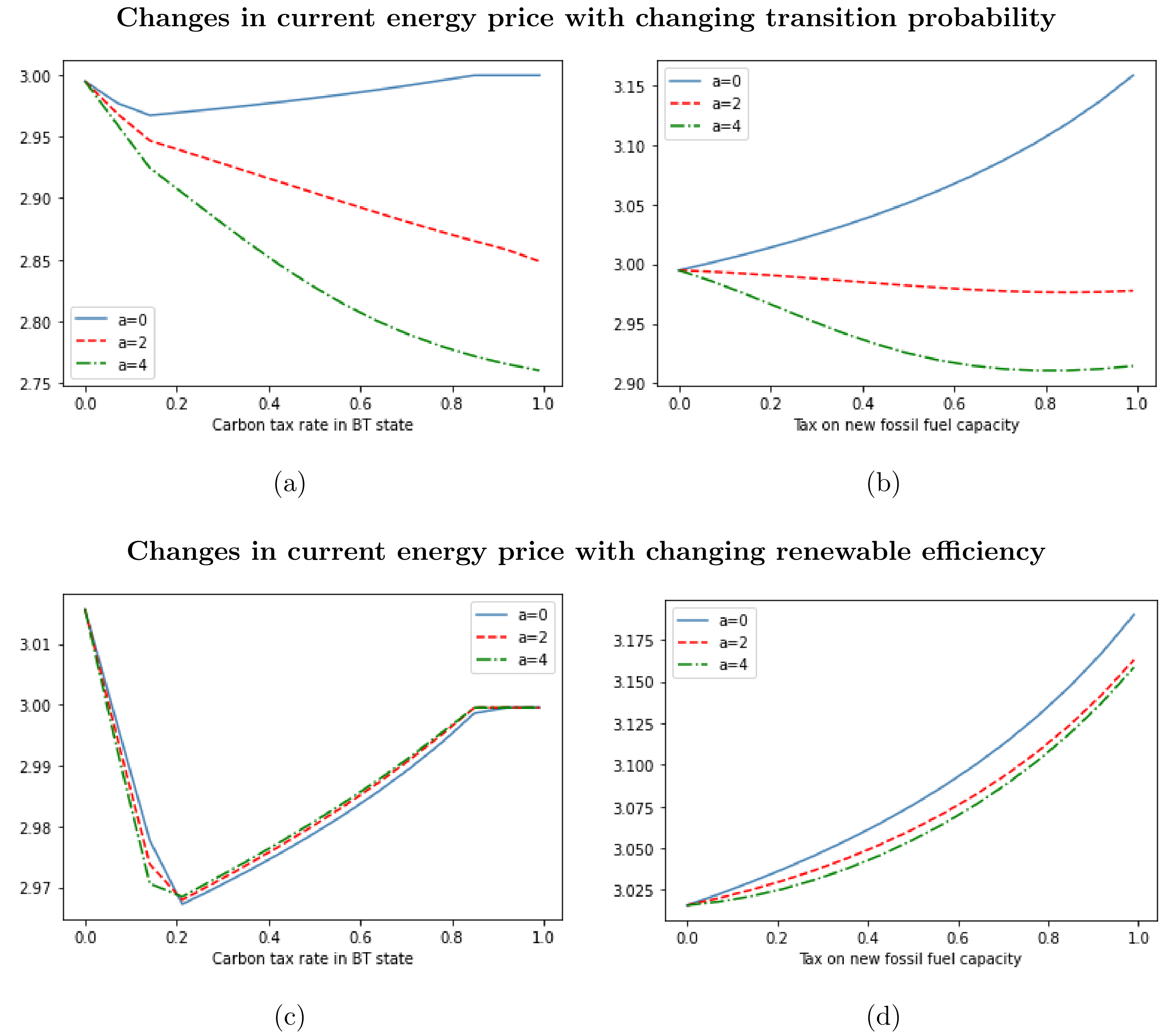


Figure 8: Response of the date-0 energy prices to changes in the tax rates with changes in the renewable sector parameters.

Figure 8 below shows how the response of the date-0 energy price to the various tax rates changes when the renewable sector responds exogenously. In general, we can see that the response of the energy price is attenuated, and for high enough values of a can change sign. The intuition for this result is that increases in the tax rate and in future renewable supply have opposite effects on the inventory decisions of the incumbent. A higher tax rate discourages investment in new fossil fuel capacity, thus reducing future competition from new fossil fuel firms, and in turn incentivizes the incumbent to reduce current supply and carry more inventory into the future. Conversely, higher future competition from the renewable sector lowers future expected profits, thus inducing the incumbent to sell more of its inventory at date 0. If the second effect dominates because of a strong flow of investment into the renewable sector in response to increases in the tax rates, then the current energy price can decrease in response to increases in the tax rates.

A notable exception is presented in panel (c), which shows the price response when renewable efficiency increases in response to increases in the carbon tax. We can see that in this case the price response is instead amplified rather than attenuated. The intuition is that the higher renewable efficiency will generate higher renewable supply only in the BT state, which is the same state where the carbon tax is implemented. The two forces are therefore complementary in this case, as they lower the expected energy price only in the future state of the world where the incumbent will have its assets stranded. Therefore, higher renewable efficiency in that state only affects directly the investment in new capacity by the entrant, and thus induces the incumbent to increase its future inventory, which in turn raises current energy prices.

Appendix E Additional Data Details

E.1 Measuring Climate Transition Risks

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) model designed to understand, generate, and interact with human-like text. LLMs are leading in performance across a range of natural language processing (NLP) tasks, largely due to their extensive scale and architectural innovations. We employ GPT-4o Mini, one of the most advanced LLMs pre-trained by OpenAI.[22]

E.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 6, 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.[23]

E.1.2 Article-level Analysis by GPT

Beyond the initial filtering and cleaning, we made queries to OpenAI's GPT-4o Mini model instance with each query for one NYT news article. We report the 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) guidance on 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.[24] For each topic, we pose four questions. The first question assesses the relevance of the article to the targeted topic, guiding the model toward the specific transition risk we are measuring. The second question determines the direction indicated by the news article concerning the topic, such as whether it suggests a tightening or loosening of 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.

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

[23]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).

[24]In our theoretical analysis, we focus on breakthrough probability π_{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 fuel companies.

Here is a news article:

“%s”

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

{’Question1’: ’(choice id)’};
{’Question2’: ’(choice id)’};
{’Question3’: ’(choice id)’};
{’Question4’: ’(choice id)’};
{’Question5’: ’(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[25]
(b) Highly Significant Impact[26]
(c) Moderate Impact[27]
(d) Minimal Impact[28]
(e) No Impact[29]

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[22]
(b) Highly Significant Impact[23]
(c) Moderate Impact[24]
(d) Minimal Impact[25]
(e) No Impact[26]

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[22]

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

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[22]
(b) Highly Significant Impact[23]
(c) Moderate Impact[24]
(d) Minimal Impact[25]
(e) No Impact[26]

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[22]
(b) Highly Significant Impact[23]
(c) Moderate Impact[24]
(d) Minimal Impact[25]
(e) No Impact[26]

Here is a news article:

“%s”

[25]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.

[26]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.

[27]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.

[28]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.

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

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 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[30]
(b) Highly Significant Impact[31]
(c) Moderate Impact[32]
(d) Minimal Impact[33]
(e) No Impact[34]

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 policies or regulations that expand or restrict fossil fuel infrastructure license and permit 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 license and permit availability.

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 license and permit 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[28]
(b) Highly Significant Impact[29]
(c) Moderate Impact[30]
(d) Minimal Impact[31]
(e) No Impact[32]

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[28]
(b) Highly Significant Impact[29]
(c) Moderate Impact[30]
(d) Minimal Impact[31]
(e) No Impact[32]

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[28]
(b) Highly Significant Impact[29]
(c) Moderate Impact[30]
(d) Minimal Impact[31]
(e) No Impact[32]

We analyzed a total of 33,965 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 breakthrough probability
- Actual technology breakthroughs on renewable energy or battery storage
- Regulations that affect the production capacity of fossil fuels

Tables 6 to 10 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.

[30]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.

[31]This news will have a large impact on the 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.

[32]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.

[33]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.

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

Table 6: 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 7: 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 8: 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 9: 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 10: 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	Most 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.

E.1.3 Aggregation

To measure the overall views of climate transition news in a given week, we construct news indices by aggregating article-level scores to a weekly level. Compared with daily scores, weekly scores are more likely to capture discussions around the event date. They also better capture 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". Accordingly, positive values of the resulting index should be interpreted as tightening shocks (higher expected carbon costs, more restrictions, or higher π_{BT}), and negative values as loosening shocks. This signing convention is applied consistently across all three indices and ensures that the empirical results can be directly compared to the model's predictions. For the question measuring the strength of direction, responses range from neutral to extremely likely. We code "Extremely Likely" and "Very Likely" as 1; and "Somewhat Likely," "Slightly Likely," and "Neutral" as 0. This coding scheme accounts for the GPT's noisy yet broadly accurate characterizations, allowing for the detection of overarching patterns while acknowledging the unreliability of fine-grained distinctions in magnitude. For the question measuring the potential impact of the news on market prices and operational strategies of fossil fuel companies, responses range from no impact to highly significant impact. Similarly to the question measuring strength, we code "Most Significant Impact" and "Highly Significant Impact" as 1; and "Moderate Impact," "Minimal Impact," and "No Impact" as 0.

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

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

where $D_{k,j,t}$ is the direction score for index k of article j at week t, $S_{k,j,t}$ is the strength score for index k of article j at week t, and $I_{k,j,t}$ is the importance score for index k of article j at week t. N is the total number of articles within each week. We build an index for each of the topics mentioned in section E.1.2.[35]

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 its standard deviation. Figure 6 plots the standardized AR(1) innovations of these two news indices, together with those of the oil capacity news index, with labels indicating related events.

E.1.4 Index Validation

To validate that each index captures its intended type of climate transition risk, we examine the news articles that drive the major spikes of each index and verify that they correspond to events specific to that category. Tables 11–13 present representative articles from the labeled spike weeks of each index in Figure 6, along with the sign assigned by GPT-4o Mini. We discuss the key patterns below.

Emission Cost Index. Table 11 shows that the positive spikes of the *NYT-Emission Cost News Index* are driven by landmark carbon-regulation events. The index peaks during the week of June 6, 2014, when the Obama administration proposed the Clean Power Plan, which is the first-ever federal regulation of carbon emissions from existing power plants. Other prominent positive spikes coincide with the finalization of the Clean Power Plan in August 2015, the 2019 Democratic primary climate town hall where several candidates endorsed a carbon tax, Biden's inauguration-week executive orders rejoining the Paris Agreement and revoking the Keystone XL permit (January 2021), and the signing

[35]The construction differs slightly for the index of actual renewable-energy technology breakthroughs. As the renewable-breakthrough prompt in section E.1.2 shows, for this topic we ask GPT only whether the article reports an actual breakthrough and, if so, how significant its impact is; unlike the other topics, it is not assigned a separate direction or strength question. The reason is that a realized breakthrough is, by construction, an unambiguous and already-resolved improvement in renewable technology, so its direction is fixed at +1 and there is no likelihood to score.

of the Inflation Reduction Act in August 2022. On the negative side, the index declines sharply when the Trump administration moved to dismantle the Clean Power Plan (March 2017), withdrew from the Paris Agreement (June 2017), and when the Democrats' climate spending plan was stalled in the Senate (July 2022).

Renewable Breakthrough Index. Table 12 demonstrates that the *NYT-Renewable Breakthrough News Index* responds to a qualitatively different set of events: advances in clean energy technology and investment in renewable infrastructure. The articles driving the largest spikes cover geothermal energy development in France (September 2014), a zinc-based battery breakthrough for grid-scale storage (September 2018), the IPCC Working Group III report documenting dramatic declines in renewable energy costs over the preceding decade (April 2022), Biden's $7.5 billion EV charging infrastructure plan (September 2022), and China's emerging dominance in sodium-ion battery technology (April 2023). Notably, every spike in the table carries a positive sign. This is expected, since the index is designed to capture technological progress in renewable energy, and such progress is inherently cumulative and genuine reversals in technological capability are rare.

Oil Capacity Index. Table 13 confirms that the *NYT-Oil Capacity News Index* is driven by events directly affecting fossil fuel production capacity. The index's largest spike occurs during the week of March 4, 2022, when Russia's invasion of Ukraine disrupted global oil supply and sent prices above $110 per barrel. Other positive spikes are associated with Obama's climate plan imposing restrictions on power plants (June 2014), Exxon Mobil shareholders demanding climate-risk disclosures (June 2017), and Biden's cancellation of the Keystone XL pipeline (January 2021). Negative spikes correspond to policies expanding fossil fuel production capacity: Trump's revival of the Keystone XL and Dakota Access pipelines (January 2017), the rollback of post-Deepwater Horizon offshore drilling safety rules (April 2017), and McCarthy's debt ceiling proposal that included provisions to expand fossil fuel leasing (April 2023). These articles center on oil supply, drilling regulations, and pipeline infrastructure rather than on carbon pricing mechanisms or renewable technology.

Table 11: Spike Validation, NYT-Emission Cost Index

Date	Headline	Sign	Article Body
2013-06-28	Obama Unveils New Plans To Address Climate Change	+	WASHINGTON – President Obama, declaring that ”Americans across the country are already paying the price of inaction,” announced sweeping measures on Tuesday to reduce greenhouse gas pollution and prepare the nation for a future of rising temperatures.Embracing wholeheartedly an issue that could define his legacy but is sure to ignite new political battles with Republicans, Mr. Obama said he would use his executive powers to require reductions in the amount of carbon dioxide emitted by the nat...
2014-06-06	Obama to Take Action to Slash Coal Pollution	+	WASHINGTON – The Obama administration on Monday will announce one of the strongest actions ever taken by the United States government to fight climate change, a proposed Environmental Protection Agency regulation to cut carbon pollution from the nation's power plants 30 percent from 2005 levels by 2030, according to people briefed on the plan who spoke anonymously because they had been asked not to reveal details.The regulation takes aim at the largest source of carbon pollution in the United S...
2015-08-07	Obama to Unveil Tougher Climate Plan With His Legacy in Mind	+	WASHINGTON – In the strongest action ever taken in the United States to combat climate change, President Obama will unveil on Monday a set of environmental regulations devised to sharply cut planet-warming greenhouse gas emissions from the nation's power plants and ultimately transform America's electricity industry.The rules are the final, tougher versions of proposed regulations that the Environmental Protection Agency announced in 2012 and 2014. If they withstand the expected legal challenge...

Table 11: Spike Validation, NYT-Emission Cost Index (continued)

Date	Headline	Sign	Article Body
2017-03-31	What to Know About Trump's Order to Dismantle the Clean Power Plan	–	President Trump is set to undo key aspects of Obama's climate legacy, targeting regulations for coal-fired power plants. President Trump signed an executive order Tuesday that calls on Scott Pruitt, the administrator of the Environmental Protection Agency, to take steps to dismantle the Clean Power Plan, a set of rules regulating energy plants powered by fossil fuels.What was happening with the Clean Power Plan until now?The plan, which would have regulated carbon dioxide emissions from existing...
2017-06-02	What to Expect as U.S. Leaves Paris Climate Accord	–	Other nations will most likely continue to pursue clean energy policies while the United States is sidelined in international talks. President Trumpsaid on Thursday that the United States was officially withdrawing from the Paris climate agreement, following through on a campaign promise and defying fellow world leaders who had pleaded with him to remain a party to the pact.The move was sure to provoke a sharp backlash from the rest of the world, and it could prove to be a major setback for inte...
2017-10-13	E.P.A. Announces Repeal of Major Obama-Era Carbon Emissions Rule	–	The rollback of the Clean Power Plan, which limits greenhouse gas emissions from power plants, sets up a bitter fight over United States climate policy. Correction AppendedWASHINGTON — The Environmental Protection Agency announced on Tuesday that Scott Pruitt, the chief of the agency, had signed a measure to repeal President Barack Obama's signature policy to curb greenhouse gas emissions from power plants, setting up a bitter fight over the future of America's efforts to tackle global warming.M...

Table 11: Spike Validation, NYT-Emission Cost Index (continued)

Date	Headline	Sign	Article Body
2019-09-06	Climate Town Hall: Several Democratic Candidates Embrace a Carbon Tax	+	At a CNN forum on climate change, the first such prime-time event in a presidential campaign, candidates vowed to take aggressive action to combat global warming. At a CNN forum on climate change, the first such prime-time event in a presidential campaign, candidates vowed to take aggressive action to combat global warming.WASHINGTON — Democratic candidates promised unprecedented new action on climate change on Wednesday night in the first prime-time televised forum devoted to the issue in a pre...
2021-01-22	Biden Cancels Keystone XL Pipeline and Rejoins Paris Climate Agreement	+	In a burst of climate orders, the president also ordered federal agencies to begin the process of reinstating environmental regulations reversed under the Trump administration. In a burst of climate orders, the president also ordered federal agencies to begin the process of reinstating environmental regulations reversed under the Trump administration.WASHINGTON — President Joseph R. Biden Jr. on Wednesday recommitted the United States to the Paris climate agreement, the international accord desi...
2021-10-29	Climate Change Became the Largest Part of Biden Spending Bill	+	As paid family leave and other priorities were taken out of the president's plan, the largest piece became a $555 billion plan to fight climate change. As paid family leave and other priorities were taken out of the president's plan, the largest piece became a $555 billion plan to fight climate change.WASHINGTON — Climate has emerged as the single largest category in President Biden's new framework for a huge spending bill, placing global warming at the center of his party's domestic agenda in a...

Table 11: Spike Validation, NYT-Emission Cost Index (continued)

Date	Headline	Sign	Article Body
2022-07-15	Biden Concedes Defeat on Climate Bill as Manchin and Inflation Upend Agenda	−	Rising prices, party infighting and the aftershocks from Russia's invasion of Ukraine have undercut the president's plans to speed an energy transition. Rising prices, party infighting and the aftershocks from Russia's invasion of Ukraine have undercut the president's plans to speed an energy transition.WASHINGTON — President Biden bowed to political reality on Friday, conceding that he had been unable to persuade a holdout coal-state Democrat, or any Republicans in the Senate, to back legislati...
2022-08-19	Biden Signs Climate, Health Bill Into Law as Other Economic Goals Remain News Analysis	+	The bill is the latest victory for the president on overhauling the physical economy, but he has found less support for plans to help workers. The bill is the latest victory for the president on overhauling the physical economy, but he has found less support for plans to help workers.WASHINGTON — President Biden signed into law a landmark tax, health and energy bill on Tuesday that takes significant steps toward fulfilling his goal to modernize the American economy and reduce its dependence on f...

Note: Articles selected from labelled spikes of *Emission Cost Index* in panel (a) of Figure 6.

Table 12: Spike Validation, NYT-Renewable Breakthrough Index

Date	Headline	Sign	Article Body
2014-04-18	Dual Turning Point for Biofuels	+	HUGOTON, Kan. – There is an old joke in the energy business that advanced biofuels are the fuel of the future, and always will be.A Spanish company, Abengoa Bioenergy, has bet $500 million on robbing that joke of its punch line. In the middle of a cornfield here it is building a 38-acre Erector set of electrical cable and pipe that will soon begin producing cellulosic ethanol, which it calls a low-polluting alternative to petroleum products. This is just as the George W. Bush administration and...
2014-09-19	France Bets on Geothermal Energy	+	France is making a new push to develop geothermal energy. The goal is to reduce the carbon emissions that contribute to global warming while ensuring the nation's energy independence. Hydraulic fracturing for oil and natural gas was banned in France in 2011, and the government of President François Hollande has pledged to reduce the country's dependence on nuclear power from 75 percent of electricity produced to 50 percent by 2025. It thus makes sense to develop geothermal energy.Metropolitan Pa...
2014-11-21	A Road Test of Alternative Fuel Visions	+	LOS ANGELES – Remember the hydrogen car?A decade ago, President George W. Bush espoused the environmental promise of cars running on hydrogen, the universe's most abundant element. "The first car driven by a child born today," he said in his 2003 State of the Union speech, "could be powered by hydrogen, and pollution-free."That changed under Steven Chu, the Nobel Prize-winning physicist who was President Obama's first Secretary of Energy. "We asked ourselves, 'Is it likely in the next 10 o...

Table 12: Spike Validation, NYT-Renewable Breakthrough Index (continued)

Date	Headline	Sign	Article Body
2015-12-11	In Paris: 'The Scale of the Climate Challenge'	+	To the Editor:"What the Climate Meeting Must Do" (editorial, Nov. 29) rightly emphasizes the need for greater urgency in the international community's efforts to tackle climate change. But the reference to efforts to "enlist" businesses and investors risks understating the central role of the private sector in meeting this challenge. The scale of the climate challenge is too great for governments to tackle alone. To take just one angle: The International Energy Agency estimates that $53 tril...
2017-02-10	Offshore Wind Moves Into Energy's Mainstream	+	Offshore wind projects are luring big-name investors who are attracted to strong returns and declining costs. LIVERPOOL, England — When engineers faced resistance from residents in Denmark over plans to build wind turbines on the Nordic country's flat farmland, they found a better locale: the sea. The offshore wind farm, the world's first, had just 11 turbines and could power about 3,000 homes.That project now looks like a minnow compared with the whales that sprawl for miles across the seas of...
2017-06-09	China Looks to Capitalize on Clean Energy as U.S. Retreats	+	China, which has a considerable hold on solar and wind businesses, wants to use its technological expertise to help other countries meet their climate goals. LIULONG, China — China's devastating pollution problems began here, in coal country, where legions of workers toiled and often died to exhume the rich deposits that fueled the country's sooty rise to economic power.Today, these muddy plains are home to a potent symbol of China's new ambition: to bypass the United States and cement its dom...

Table 12: Spike Validation, NYT-Renewable Breakthrough Index (continued)

Date	Headline	Sign	Article Body
2018-09-28	Cheaper Battery Is Unveiled as a Step to a Carbon-Free Grid	+	The entrepreneur Patrick Soon-Shiong says his company's tests of zinc-based storage for solar and wind energy show the potential for large-scale use. Lithium-ion batteries have become essential for powering electric cars and storing energy generated by solar panels and wind turbines. But their drawbacks are also by now familiar: They use scarce minerals, are vulnerable to fires and explosions, and are pricey.A plentiful, safe and more affordable alternative would be worth a lot.On Wednesday, an...
2022-04-08	Stopping Climate Change Is Doable, but Time Is Short, U.N. Panel Warns	+	A major new scientific report offers a road map for how countries can limit global warming, but warns that the margin for error is vanishingly small. A major new scientific report offers a road map for how countries can limit global warming, but warns that the margin for error is vanishingly small.Nations need to move away much faster from fossil fuels to retain any hope of preventing a perilous future on an overheated planet, according to a major new report on climate change released on Monday,...
2022-09-16	At Detroit Auto Show, Biden Announces Money for Charging Stations	+	The president announced the first phase of a plan to invest $7.5 billion toward building a national network for recharging electric vehicles. The president announced the first phase of a plan to invest $7.5 billion toward building a national network for recharging electric vehicles.DETROIT — President Biden, a self-described “car guy” and Corvette owner, toured the North American International Auto Show in Detroit on Wednesday and announced the approval of an initial $900 million investment to b...

Table 12: Spike Validation, NYT-Renewable Breakthrough Index (continued)

Date	Headline	Sign	Article Body
2023-04-14	Why China Could Dominate the Next Big Advance in Batteries	+	China is far ahead of the rest of the world in the development of batteries that use sodium, which are starting to compete with ubiquitous lithium power cells. China is far ahead of the rest of the world in the development of batteries that use sodium, which are starting to compete with ubiquitous lithium power cells.In Changsha, deep in China's interior, thousands of chemists, engineers and manufacturing workers are shaping the future of batteries.The city's Central South University churns out...

Note: Articles selected from labelled spikes of *Renewable Breakthrough Index* in panel (b) of Figure 6.

Table 13: Spike Validation, NYT-Oil Capacity Index

Date	Headline	Sign	Article Body
2014-06-06	Obama to Take Action to Slash Coal Pollution	+	WASHINGTON – The Obama administration on Monday will announce one of the strongest actions ever taken by the United States government to fight climate change, a proposed Environmental Protection Agency regulation to cut carbon pollution from the nation's power plants 30 percent from 2005 levels by 2030, according to people briefed on the plan who spoke anonymously because they had been asked not to reveal details.The regulation takes aim at the largest source of carbon pollution in the United S...

Table 13: Spike Validation, NYT-Oil Capacity Index (continued)

Date	Headline	Sign	Article Body
2017-01-27	Trump Revives Keystone Pipeline Rejected by Obama	−	The new president continued dismantling his predecessor's policies by clearing the way for a project at the heart of the battle over climate change. WASHINGTON - President Trump sharply changed the federal government's approach to the environment on Tuesday as he cleared the way for two major oil pipelines that had been blocked, and set in motion a plan to curb regulations that slow other building projects.In his latest moves to dismantle the legacy of his predecessor, Mr. Trump resurrected th...
2017-04-28	Trump Orders Easing Safety Rules Implemented After Gulf Oil Spill	−	President Trump aims to roll back the Obama administration's attempts to ban oil drilling off the southeastern Atlantic and Alaskan coasts. WASHINGTON — Just past the seventh anniversary of the Deepwater Horizon oil spill, President Trump on Friday directed the Interior Department to "reconsider" several safety regulations on offshore drilling implemented after one of the worst environmental disasters in the nation's history.Friday's executive order was aimed at rolling back the Obama administ...
2017-06-02	Exxon Mobil Shareholders Demand Accounting of Climate Change Policy Risks	+	The nonbinding vote backed an assessment of the impact of greenhouse-gas limits on the business. The company opposed the motion but said it would consider the result. A majority of Exxon Mobil's shareholders, in a reversal, have voted in favor of more open and detailed analyses of the risks posed to its business by policies aimed at stemming climate change.Those policies include the goal of the Paris climate agreement to restrict global temperatures to no more than 2 degrees Celsius above prei...

Table 13: Spike Validation, NYT-Oil Capacity Index (continued)

Date	Headline	Sign	Article Body
2018-06-08	An Oil Auction Provides Brazil a Needed Boost	−	Global oil companies see a promising future in Brazil's offshore fields, setting the country apart from the rest of the world. RIO DE JANEIRO — Oil companies bid for offshore drilling rights in an auction here on Thursday that provided some welcome good news for Brazil's economy after weeks of political uncertainty and unrest.The auction, the fourth one since September, came days after a strike by truck drivers over rising diesel prices paralyzed the country for nearly two weeks and prompted the...
2019-09-06	Climate Town Hall: Several Democratic Candidates Embrace a Carbon Tax	+	At a CNN forum on climate change, the first such prime-time event in a presidential campaign, candidates vowed to take aggressive action to combat global warming. At a CNN forum on climate change, the first such prime-time event in a presidential campaign, candidates vowed to take aggressive action to combat global warming.WASHINGTON — Democratic candidates promised unprecedented new action on climate change on Wednesday night in the first prime-time televised forum devoted to the issue in a pre...
2021-01-22	Biden Cancels Keystone XL Pipeline and Rejoins Paris Climate Agreement	+	In a burst of climate orders, the president also ordered federal agencies to begin the process of reinstating environmental regulations reversed under the Trump administration. In a burst of climate orders, the president also ordered federal agencies to begin the process of reinstating environmental regulations reversed under the Trump administration.WASHINGTON — President Joseph R. Biden Jr. on Wednesday recommitted the United States to the Paris climate agreement, the international accord desi...

Table 13: Spike Validation, NYT-Oil Capacity Index (continued)

Date	Headline	Sign	Article Body
2021-11-05	Biden Administration Moves to Limit Methane, a Potent Greenhouse Gas	+	The new rule was announced at a U.N. summit where the United States is facing skepticism about its commitment to climate change. The new rule was announced at a U.N. summit where the United States is facing skepticism about its commitment to climate change.GLASGOW — The Biden administration said Tuesday that it would heavily regulate methane, a potent greenhouse gas that spews from oil and natural gas operations and can warm the atmosphere 80 times as fast as carbon dioxide in the short term.For...
2022-03-04	Markets are roiled as sanctions on Russia take hold.	+	Energy prices jumped and stocks in Europe tumbled, while futures on Wall Street pointed to a decline when U.S. trading starts. Energy prices jumped and stocks in Europe tumbled, while futures on Wall Street pointed to a decline when U.S. trading starts.Stocks sank on Monday and commodity markets rose as the war in Ukraine entered its fifth day and a widening array of sanctions aimed at punishing Russia for its invasion began to bite.On Wall Street, futures pointed to a drop of more than 1 percen...
2023-04-21	McCarthy Proposes One-Year Debt Ceiling Increase Tied to Spending Cuts	−	Clashing with President Biden, who has called for raising the debt limit with no conditions, the Republican speaker went to Wall Street to pitch what he called a "responsible, sensible" solution. Clashing with President Biden, who has called for raising the debt limit with no conditions, the Republican speaker went to Wall Street to pitch what he called a "responsible, sensible" solution.WASHINGTON — Speaker Kevin McCarthy on Monday proposed a one-year debt ceiling increase paired with a set of...

Note: Articles selected from labelled spikes of *Oil Capacity Index* in panel (c) of Figure 6.

E.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 barrels of oil equivalents (BOE) by the combined amount of *total* proved reserves for these resources in BOE.[36] 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 built the infrastructure to develop a large fraction of the reserves that they own, and are more similar to entrants in our model.

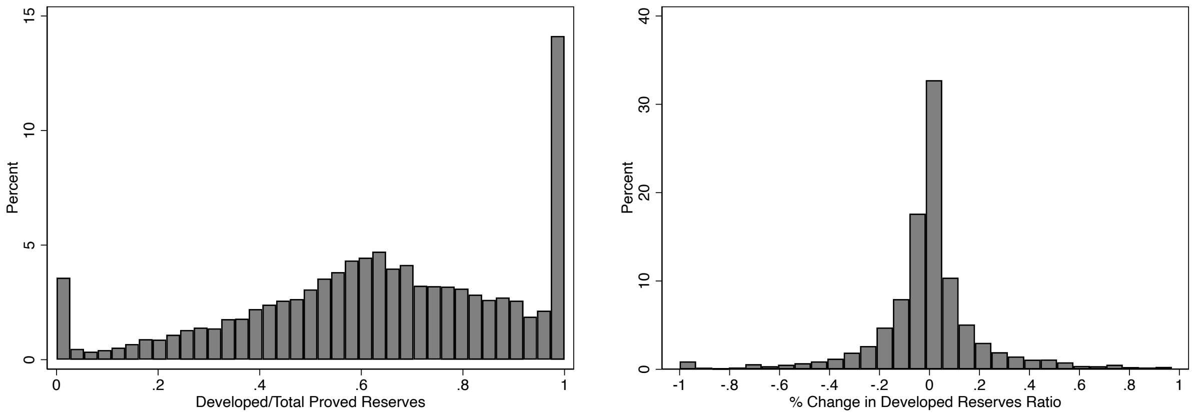
We obtain the proved developed reserves and total proved reserves from the Industry Specific Annual section of Compustat where available. Otherwise, we manually looked up reserves values in the SEC's EDGAR database to input 116 instances of companies missing yearly reserves data in the Compustat database. 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 9 shows the histogram of the developed reserves ratio.

[36]Barrels of oil equivalents (BOE) allow us to aggregate oil, natural gas, and natural gas liquids reserves by the amount of energy they produce.

Figure 9: 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 include companies in the solar and wind energy industry respectively. We use these ETFs to categorize 19 companies listed on U.S. stock exchanges as renewable companies.

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

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

where $\text{Idx}_{k,t}$ is index k in week t and $\nu_{k,t}$ represents the AR(1) innovations of index k in week t. We scale the residuals by their standard deviation.

E.3 Oil Futures Price

Table 14 reports the data description and sources of the variables utilized in our study of oil futures prices.

E.4 Well-Level Permits Data

We obtain well-level permitting data from Enverus covering the period 2012–2023. Each record contains the permit submission date, operator name, and well location. For consistency with our analysis of

Table 14: 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 4.4). The last column details the processing methods applied to convert raw data into the variables used in our analysis.

financial markets, we restrict attention to wells operated by U.S. oil and gas exploration and production companies that can be matched to our Compustat sample. The raw dataset includes a small number of Canadian wells, but all of these fall outside the 2012–2023 sample window used in our analysis. After applying this restriction, the dataset covers 142,708 wells with permits, associated with 49 operators over the sample period.

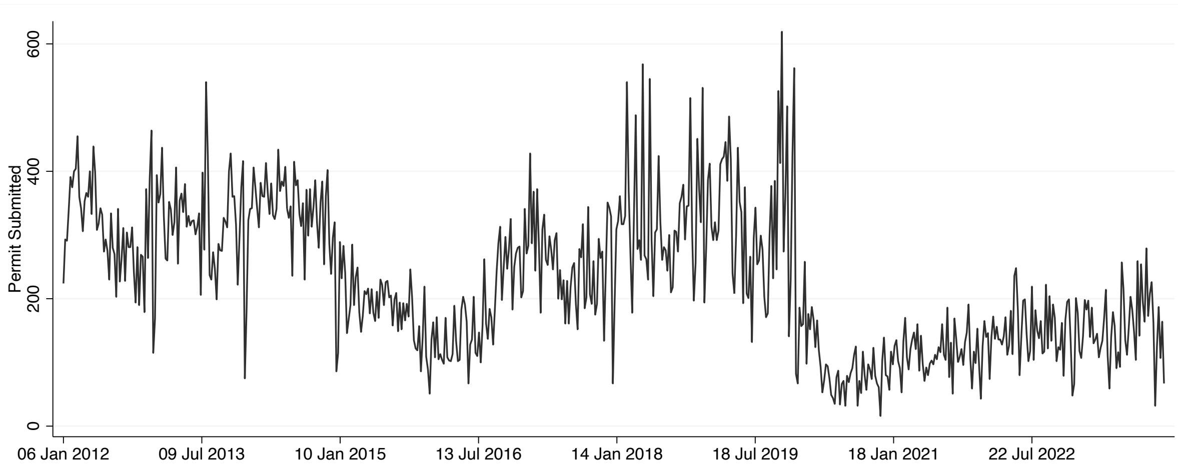
Figure 10 plots the time series of weekly permit submissions. The data show substantial variation over time, with activity declining after the 2014 oil price collapse and again during the COVID-19 pandemic, before partially recovering in subsequent years. The median number of permits submitted per week is 210, with a 10–90 percentile range of 94 to 375. Overall, the permitting data provide a detailed and high-frequency measure of real investment activity in the upstream oil and gas sector that can be directly linked to the firms in our financial market analysis.

E.4.1 Regulatory Framework: Federal, State, and Private Mineral Estates

Regulatory authority over oil and gas well permitting in the United States is determined by who owns the *subsurface* mineral rights, not the surface. Three categories of mineral ownership govern which permit regime applies.

The *federal mineral estate* covers approximately 700 million subsurface acres managed by the Bureau of Land Management (BLM). Figure 11 maps county-level well counts against lands administered by BLM, showing that many of the post-2000 drilling activity is concentrated in areas with significant federal land presence. When federal minerals are involved—regardless of surface ownership—the operator must

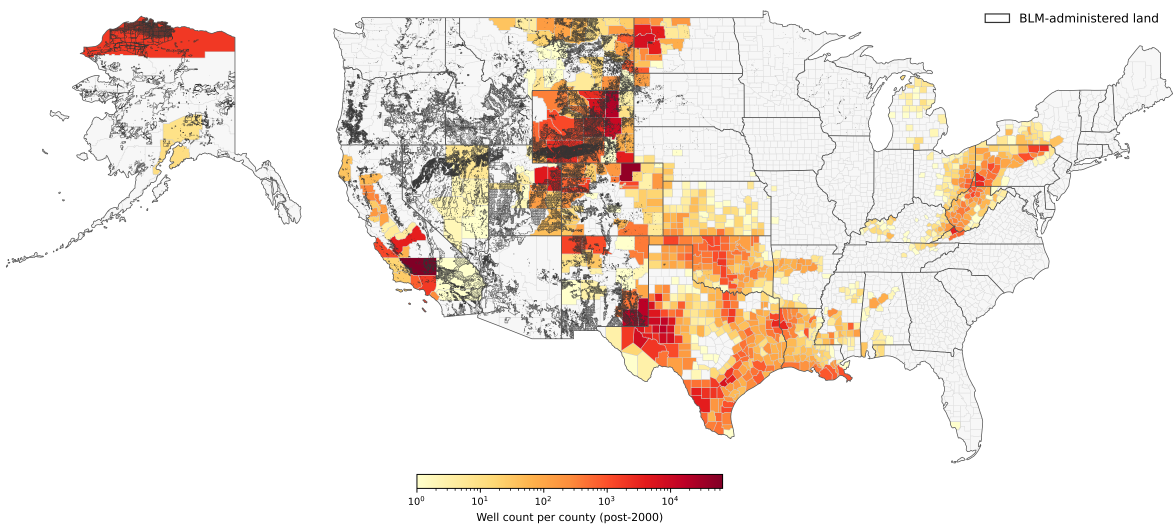
Figure 10: Time-Series of Permit Submissions



Note: The figure shows the weekly permit submissions for wells from 2012 to 2023.

obtain a federal Application for Permit to Drill (APD) from the BLM before any well may be spudded, under the Mineral Leasing Act of 1920 (30 U.S.C. §181 et seq.) and 43 CFR Part 3160. On *state-owned* lands, the relevant state oil and gas conservation agency issues the permit and collects royalties. On *private* mineral estates—the predominant case in Texas, Oklahoma, and West Virginia—only a state permit is required. In practice, a single horizontal well may traverse private mineral tracts and federal mineral tracts simultaneously, requiring both a federal APD and a state permit.

Figure 11: County-level Well Counts and BLM-administered Land



Note: County-level well counts and BLM-administered land in the contiguous United States and Alaska. County shading reflects the total number of wells drilled since 2000 (log scale), ranging from light yellow (few wells) to dark red (over 60,000 wells). Black outlines delineate Bureau of Land Management (BLM) surface land. Well data are sourced from Enverus; BLM boundaries are from the BLM National Surface Management Agency (SMA) MapServer.

E.4.2 The Permit Application Process

Regardless of jurisdiction, obtaining a well permit requires meaningful preparation before an application can be submitted. A complete permit package typically includes a certified survey plat locating the proposed surface and bottom-hole positions, an engineering plan specifying the casing and cementing program, a surface use and reclamation plan, and evidence of financial assurance (bonding). On federal lands, the BLM additionally requires documentation satisfying the National Environmental Policy Act (NEPA) and the National Historic Preservation Act, and operators must file at least 30 days before the desired spud date (43 CFR § 3162.3-1). Federal approval processes are generally more involved than state processes, as they entail an onsite inspection, a NEPA review, and a mandatory 30-day public notice period before a permit can be issued. State-level review is considerably faster—Texas, the largest producing state, processes standard applications in approximately two business days, while most other states take days to a few weeks.[37] Once approved, permits are valid for one to two years in most states (four years for federal APDs as of 2025), giving operators a window in which to commence drilling without re-applying.

E.4.3 Permits as Investment Signals: Immediate and Lagged Responses

A key feature of the permit process is that permit *preparation* and permit *submission* are separable decisions. An operator can invest the weeks or months of engineering, landwork, and regulatory coordination needed to assemble a complete permit package, and then hold the application without submitting it. Submission is the final, discrete step that commits the application to the regulatory record and is captured in the Enverus database. This separation means that at any point in time a firm maintains a *pipeline* of permit applications at varying stages of readiness: some fully prepared and awaiting submission, others mid-preparation, and others still in early planning. This separation is reinforced by the substantial preparation burden. Each APD requires a certified surveyor's well plat, a detailed drilling plan, a Surface Use Plan of Operations, evidence of bond coverage, and multi-party coordination with the BLM, surface managing agencies, and landowners (43 CFR §3171.6). There is also a non-refundable

[37] State permitting agencies include the Railroad Commission of Texas (Form W-1), the North Dakota Industrial Commission (NorthStar system), the Oklahoma Corporation Commission (Form 1000), the Colorado Energy and Carbon Management Commission (Form 2), the Wyoming Oil and Gas Conservation Commission (Form 1), the Pennsylvania Department of Environmental Protection (Chapter 78a), and the New Mexico Oil Conservation Division (Form C-101), among others.

$10,230 filing fee triggered only upon submission, which gives operators a direct financial incentive to complete their packages well in advance but delay filing until market or regulatory conditions are favorable. A climate transition risk shock that prompts a firm to revise its drilling program downward can therefore affect permit submissions at multiple points in this pipeline simultaneously, generating both an immediate and a distributed lagged response in the data—precisely the pattern we found in Table 4.

Immediate response. Firms routinely maintain a stock of fully assembled permit applications that are ready to submit on a rolling basis as part of their ongoing drilling program. When an adverse transition risk shock arrives, management can immediately suspend the submission of applications that were ready to go. Because the preparation cost has already been incurred, stopping submission is effectively costless at the margin, so this channel can produce an instantaneous reduction in observed permit filings with no further delay.

Lagged response. Several mechanisms generate a distributed effect over subsequent weeks. First, applications mid-preparation at the time of the shock may continue through the internal pipeline and be filed before the organizational response fully propagates—representing inertia in the permit queue rather than an unchanged investment view. Second, drilling programs at large firms are typically set on a quarterly or semi-annual planning cycle; a shock arriving mid-cycle may not fully translate into cancelled permit submissions until the next internal budget review. Third, some permit-related commitments (e.g., survey plats, bonding and surface use agreements) involve third-party contractors whose work may already be underway, delaying the visible reduction in filings by several weeks. Fourth, on federal lands, operators who have initiated the voluntary pre-application Notice of Staking (NOS) process, which triggers a BLM onsite inspection and creates a 60-day window in which the APD is expected to follow, may take additional time to reassess the project economics in light of the shock before deciding to forgo the application. Fifth, state-level permitting turnaround times vary considerably (from as little as two business days in Texas to several weeks in other jurisdictions), so the same shock can suppress permit filings at different lags depending on where the affected wells are located, further spreading the observed response across subsequent weeks.

Together, these channels imply that the full investment response to a transition risk shock is spread over several weeks rather than concentrated entirely at the point of the shock—consistent with the pattern in our baseline regression, where the lag coefficients are uniformly negative across lags: individual significance varies, but the sum of the coefficients is statistically significant.

E.5 Robustness

In this section, we present a set of robustness checks to ensure that our results are not driven by specific modeling or data choices.

E.5.1 Look-ahead Bias and Article Neutering

A potential concern in constructing our indices is information leakage from sources outside the contemporaneous news flow. This can arise in two distinct ways. First, if multiple articles were processed together, information from one could spill into the classification of another, or material from later weeks could contaminate earlier indices. To mitigate this risk, we process each article through a separate GPT request. The model sees only the text of that single article, and there is no memory or shared context across requests. Once classified, scores are stored and later aggregated into the index corresponding to the article's LexisNexis publication week, with Saturday and Sunday articles rolled into the following trading week. This construction ensures that the index for week t is built only from articles timestamped within that week, without contamination from articles in other periods.

Second, large language models are trained on broad corpora that may include information published after the articles in our sample. In that case, the model might implicitly draw on parametric knowledge of future outcomes when assigning scores. For example, when evaluating an article published in 2014 about a proposed emissions regulation, a model trained on later reporting could implicitly "know" that the regulation was repealed in 2017 and let that knowledge affect its classification. To evaluate this risk, we follow Engelberg et al. (2025) to create an entity-neutered version of our news articles. Each article is first preprocessed using a GPT prompt (reproduced below this section) that systematically replaces all identifying information with placeholders. This neutering covers company names, tickers, individual names, locations, industries, sectors, product names, services, slogans, years, dates, numbers, percentages, and web links. For example:

> <u>Original:</u> "The biggest environmental decision for New York State in 2012 will be how to regulate drilling for natural gas on the Marcellus Shale ..."
>
> <u>Neutered:</u> "The biggest environmental decision for location_x in year_a will be how to

regulate drilling for resource_x on location_y ..."

We then construct weekly indices from these anonymized classifications. The anonymized indices are highly correlated with the baseline series, as shown in Table 15, and yield materially similar coefficients in our empirical regressions, as shown in Tables 16–18. This exercise suggests that our indices capture contemporaneous news content rather than forward-looking information embedded in model training.

> Your role is to ANONYMIZE all text that is provided by the user. After you have anonymized a text, NOBODY, not even an expert financial analyst should be able to read the text and know the identity of the company nor the industry the company operates in. For example, if the text is: The country's largest phone producer Apple had great phone related earnings but Google did not in 2024 likely because of Apple's slogan Think Different, then you should ANONYMIZE it to: The country's largest product_type_1 producer Company_1 had great product_type_1 related earnings but Company_2 did not in time_1 likely because of Company_1's slogan slogan_1. You should also ANONYMIZE any other information which one could use to identify the company or make an educated guess at its identity. Stock tickers are identifiers and are usually four capitalized letters or less (consider TIK as a stand-in for an arbitrary ticker) and are sometimes referenced in the text in the following formats; SYMBOL:TIK, $TIK, >TIK, $ TIK, SYMBOL TIK, SYMBOL: TIK, > TIK. Make sure you censor TIK to ticker_x, and any other identifiers related to companies. This includes the names of individuals, locations, industries, sectors, product names and types and generic product lines, services, times, years, dates and all numbers and percentages in the text including units. These should be replaced with name_x, location_x, industry_x, sector_x, product_x, product_type_x, product_line_x, service_x, time_x, year_x, date_x and number a, b, c, respectively. Also replace any website or internet links with link_x. You should never just delete an identifier; instead, always replace it with an anonymous analog. After you read and ANONYMIZE the text, you should output the anonymized text and nothing else.

Table 15: Correlation between Original and Neutered NYT Indices

	(1)	(2)	(3)	(4)	(5)	(6)
(1) NYT-EmissionCostNews	1.00					
(2) NYT Neutered-EmissionCostNews	0.82	1.00				
(3) NYT-RenewableBTNews	0.16	0.14	1.00			
(4) NYT Neutered-RenewableBTNews	0.20	0.17	0.86	1.00		
(5) NYT-OilCapacityNews	0.43	0.39	0.20	0.23	1.00	
(6) NYT Neutered-OilCapacityNews	0.40	0.38	0.20	0.23	0.83	1.00

Table 16: Stock Returns and Neutered NYT Index

	Emission Cost (1)	Renewable Breakthrough (2)	Oil Capacity (3)
Fossil Fuel Company × Index AR(1) Innovation	-0.0050*	-0.0077***	-0.0086***
	(0.0027)	(0.0022)	(0.0027)
Fossil Fuel Company × Index AR(1) Innovation × Developed Ratio	0.0090**	0.0091***	0.0108**
	(0.0039)	(0.0033)	(0.0043)
Renewable × Index AR(1) Innovation	0.0016**	0.0033***	0.0011
	(0.0008)	(0.0008)	(0.0007)
Company FE	Yes	Yes	Yes
Remove Market from Stock Returns	Yes	Yes	Yes
R^2	0.006	0.006	0.006
Observations	51003	51003	51003

Note: This table reports robustness checks for Table 3, re-estimated using *neutered* NYT news indices. Regression (1) shows coefficients of regressing stock returns on AR(1) innovations of *NYT Neutered-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 (2) and (3) instead show coefficients of regressing stock returns on AR(1) innovations of the *NYT Neutered-Renewable Breakthrough News Index* and AR(1) innovations of the *NYT Neutered-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).

Table 17: Well Permits and Neutered NYT Index

	Emission Cost (1)	Renewable Breakthrough (2)	Oil Capacity (3)
0 Week Lagged Index AR(1) Innovation	-0.1050	-0.1131	-0.0889
	(0.0764)	(0.0772)	(0.0746)
1 Week Lagged Index AR(1) Innovation	-0.0342	-0.1232*	-0.1533*
	(0.0649)	(0.0700)	(0.0791)
2 Week Lagged Index AR(1) Innovation	-0.1756	-0.1138	-0.1697
	(0.1145)	(0.0701)	(0.1109)
3 Week Lagged Index AR(1) Innovation	-0.1582	-0.1615	-0.1969*
	(0.1071)	(0.1009)	(0.1053)
4 Week Lagged Index AR(1) Innovation	-0.1651*	-0.2738***	-0.1757**
	(0.0858)	(0.0938)	(0.0700)
5 Week Lagged Index AR(1) Innovation	-0.0145	-0.0600	-0.1720
	(0.0792)	(0.0925)	(0.1229)
6 Week Lagged Index AR(1) Innovation	-0.1346*	-0.1591*	-0.0834
	(0.0760)	(0.0848)	(0.0747)
1 Week Lagged Permits Submitted	0.3225***	0.3217***	0.3213***
	(0.0579)	(0.0573)	(0.0580)
Firm FE	Yes	Yes	Yes
Cumulative effect p-value	0.036	0.0010	0.023
Observations	27,996	27,996	27,996

Note: This table reports robustness checks for Table 4, re-estimated using *neutered* NYT news indices. Regression (1) shows coefficients from a firm-level weekly panel regression of permits submitted on contemporaneous and lagged (0–6 weeks) standardized AR(1) innovations of the *NYT Neutered-Emission Cost News Index*, together with one lag of the dependent variable to capture persistence in permitting activity. Regressions (2) and (3) instead use standardized innovations from the *NYT Neutered-Renewable Breakthrough News Index* and the *NYT Neutered-Oil Capacity News Index*, respectively. All regressions include firm fixed effects. The cumulative effect p-value tests whether the sum of all lag coefficients is zero. Standard errors are in parentheses and are clustered at the firm and week level. Significance levels: * (p<0.10), ** (p<0.05), *** (p<0.01).

Table 18: Oil Futures Price and Neutered NYT Index

	Monthly Level		
	Avg 1-12m (1)	Avg 13-60m (2)	Avg 1-60m (3)
Index AR(1) Innovation - Emission Cost	0.0178**	0.0127***	0.0150***
	(0.0069)	(0.0047)	(0.0054)
Index AR(1) Innovation - Renewable Breakthrough	-0.0147***	-0.0111***	-0.0127***
	(0.0056)	(0.0039)	(0.0046)
Index AR(1) Innovation - Oil Capacity	-0.0155***	-0.0086**	-0.0101**
	(0.0059)	(0.0042)	(0.0049)
Controls	Yes	Yes	Yes
p-value Emission Cost = Renewable Breakthrough	0.0019	0.00057	0.00054
p-value Emission Cost = Oil Capacity	0.0026	0.0076	0.0055
p-value Renewable Breakthrough = Oil Capacity	0.93	0.67	0.71
R^2	0.509	0.488	0.536
Observations	143	143	143

Note: This table reports robustness checks for Table 5, re-estimated using *neutered* NYT news indices. 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, 36 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, 36 and 60-month treasury yields. The p-values for testing the difference between the coefficients of each pair of *neutered* 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).

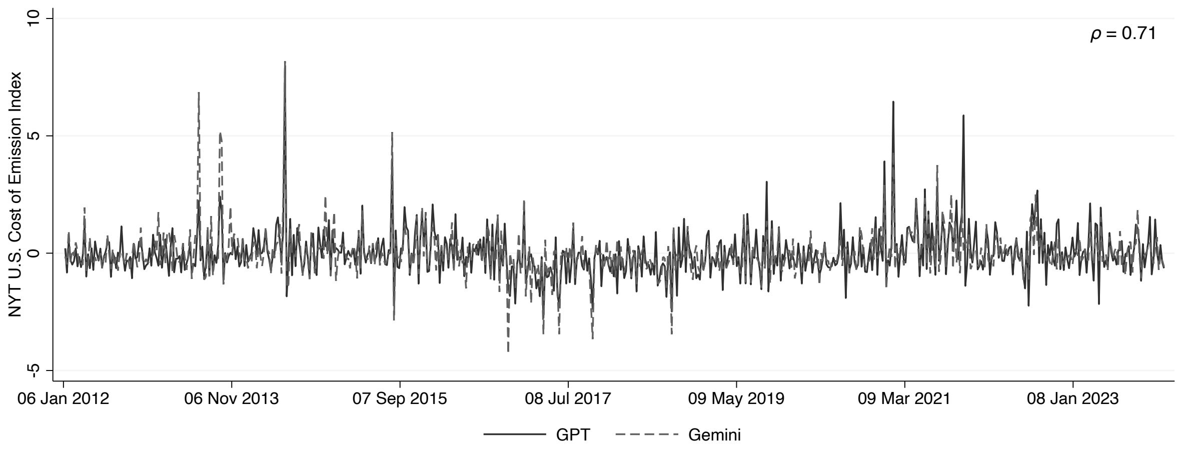
E.5.2 Alternative LLMs

Our baseline indices rely on a single language model, raising the question of whether the results are sensitive to this choice. To address this, we replicate the full classification pipeline using Google's Gemini 2.5 Flash Lite, a model from a different provider with a distinct architecture and training corpus. We use the same prompts as in our baseline GPT-4o Mini classification, changing only the model endpoint. Figure 12 compares the weekly AR(1) innovations of the Gemini-based indices with the innovations of the GPT-based indices. The two series track each other closely across all three index types, with correlations of 0.71, 0.68, and 0.58 for the emission cost, renewable breakthrough, and oil capacity indices, respectively. Since the high-frequency weekly innovations make it difficult to visually discern this correlation, we also report four-week moving averages in Figure 13. The smoothed Gemini- and GPT-based series align closely, confirming the high correlations. These results suggest that the news content driving our indices is robust to the choice of classifier rather than an artifact of idiosyncratic model behavior.

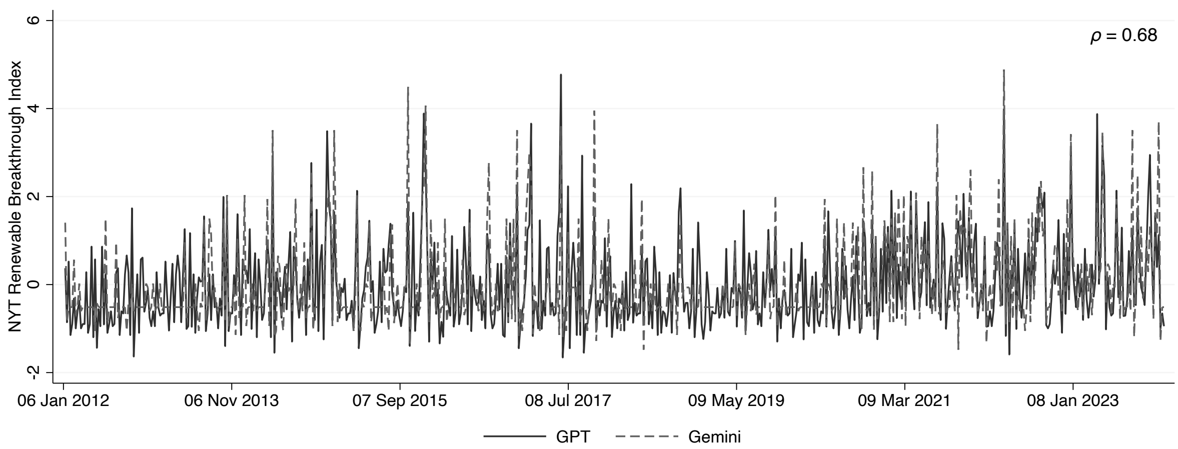
We then re-estimate our three main empirical specifications—stock returns (Table 19), well permits (Table 20), and oil futures returns (Table 21)—using both the Gemini indices and an equal-weighted average of the GPT and Gemini indices. Across all three specifications, the coefficient signs remain consistent with the baseline, and the estimated magnitudes are generally similar. In few cases, the Gemini-only specification yields somewhat less precise estimates (e.g., the renewable breakthrough coefficient in the oil futures regression loses statistical significance) but the overall pattern of results remains intact. The combined index, which averages across two independent classifiers, produces estimates that are close to the baseline. Taken together, the consistency in signs and the stability of the mixed-index results reinforce the view that our indices capture meaningful variation in climate transition news rather than model-specific classification noise.

Figure 12: Time-Series of NYT News Index (GPT vs Gemini)

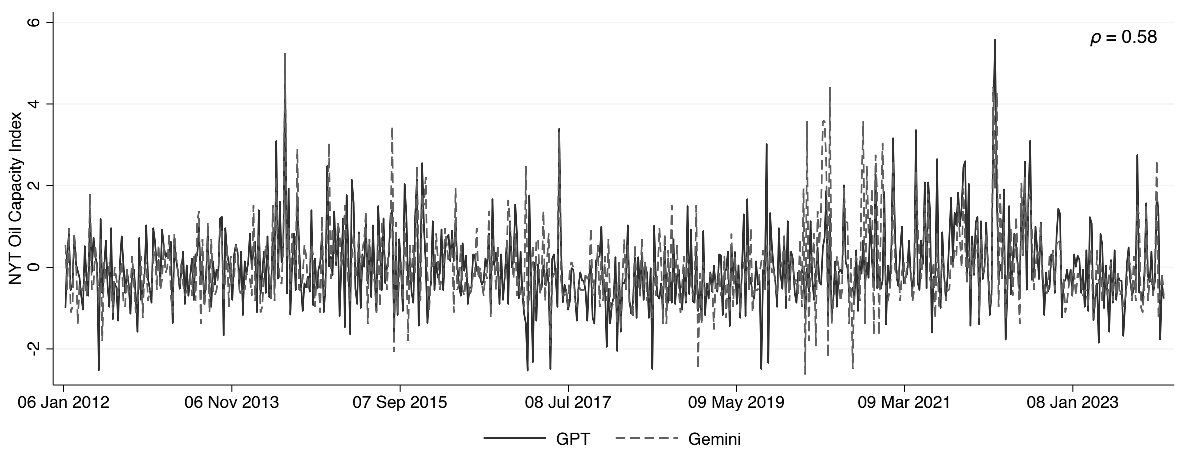
(a) NYT-Emission Cost News



(b) NYT-Renewable Breakthrough News



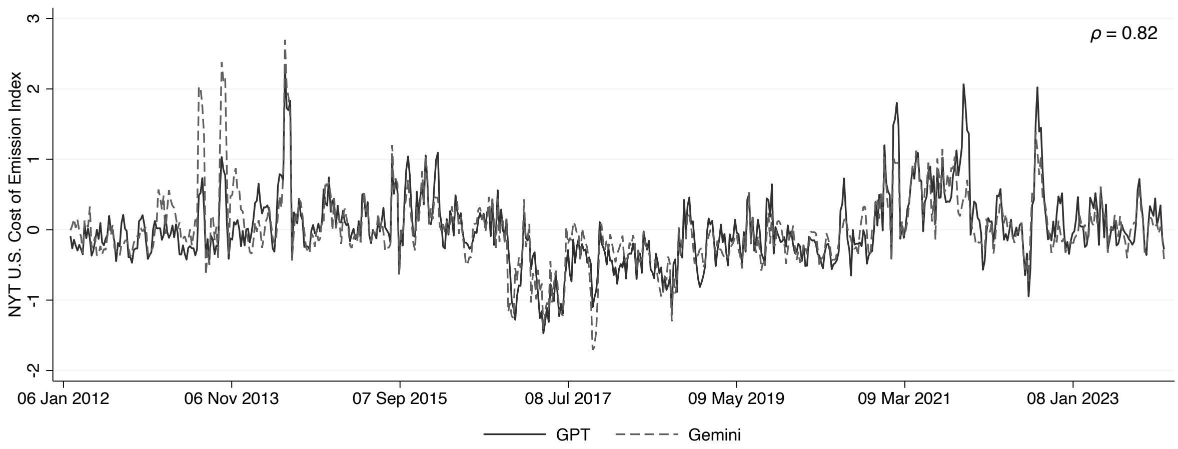
(c) NYT-Oil Capacity News



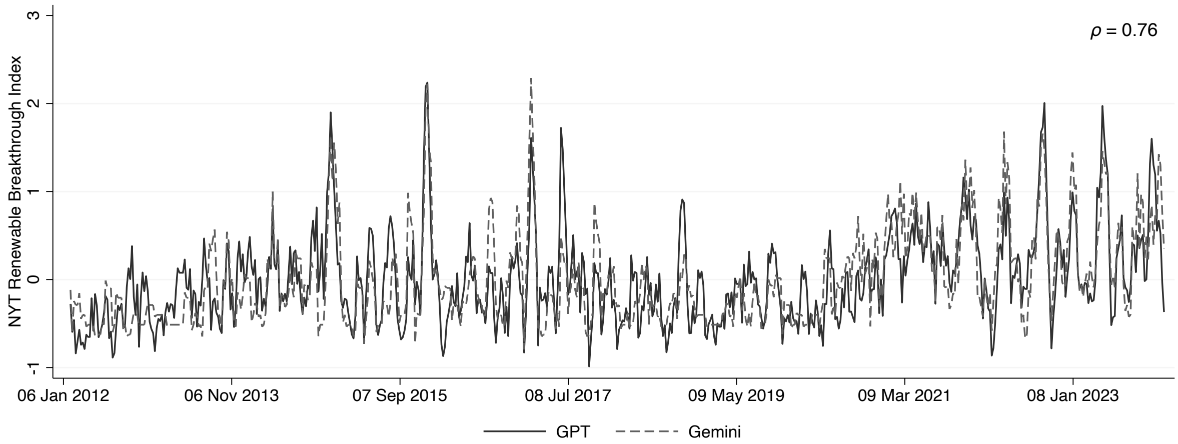
Note: Each panel plots the weekly AR(1) innovations of the GPT-4o Mini baseline index (solid) and the Gemini 2.5 Flash Lite index (dashed) for the same index type, from 2012–2023. Panel (a) shows the NYT-Emission Cost News Index, panel (b) the NYT-Renewable Breakthrough News Index, and panel (c) the NYT-Oil Capacity News Index. The correlation between the two series is reported in the top-right corner of each panel.

Figure 13: Time-Series of 4 Week Moving Averages of NYT News Index (GPT vs Gemini)

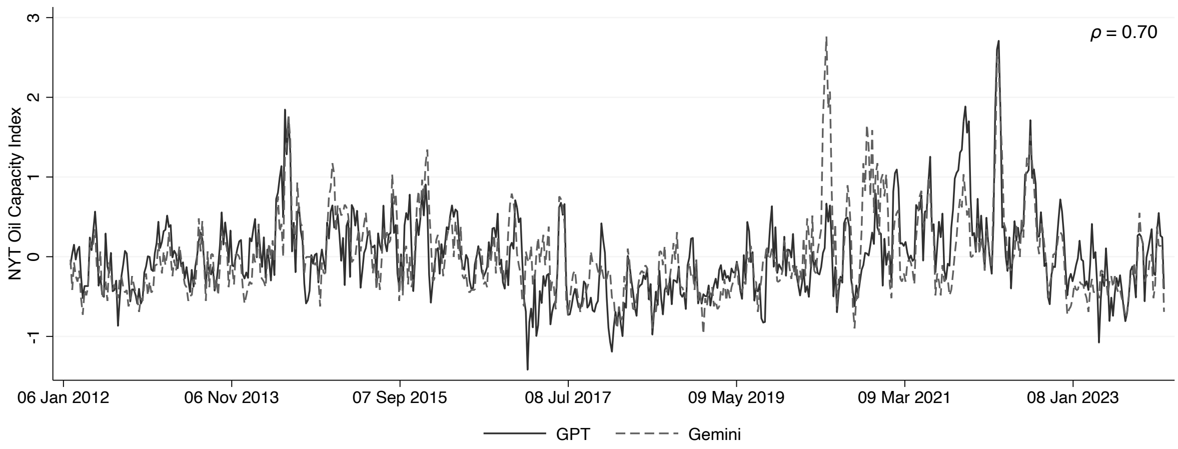
(a) NYT-Emission Cost News



(b) NYT-Renewable Breakthrough News



(c) NYT-Oil Capacity News



Note: Each panel plots four-week moving averages of the weekly AR(1) innovations of the GPT-4o Mini baseline index (solid) and the Gemini 2.5 Flash Lite index (dashed) for the same index type, from 2012–2023. Panel (a) shows the NYT-Emission Cost News Index, panel (b) the NYT-Renewable Breakthrough News Index, and panel (c) the NYT-Oil Capacity News Index. The correlation between the two series is reported in the top-right corner of each panel.

Table 19: Stock Returns and NYT Index (Alternative LLMs)

	Panel A: Gemini		
	Emission Cost (1)	Renewable Breakthrough (2)	Oil Capacity (3)
Fossil Fuel Company × Index AR(1) Innovation	-0.0029	-0.0012	-0.0054*
	(0.0023)	(0.0019)	(0.0028)
Fossil Fuel Company × Index AR(1) Innovation × Developed Ratio	0.0050	0.0051*	0.0080*
	(0.0035)	(0.0028)	(0.0045)
Renewable × Index AR(1) Innovation	0.0014**	0.0024***	0.0020***
	(0.0007)	(0.0008)	(0.0006)
Company FE	Yes	Yes	Yes
Remove Market from Stock Returns	Yes	Yes	Yes
R^2	0.006	0.006	0.006
Observations	51003	51003	51003
	Panel B: GPT & Gemini Mix		
	Emission Cost (1)	Renewable Breakthrough (2)	Oil Capacity (3)
Fossil Fuel Company × Index AR(1) Innovation	-0.0048*	-0.0053**	-0.0058**
	(0.0028)	(0.0021)	(0.0028)
Fossil Fuel Company × Index AR(1) Innovation × Developed Ratio	0.0082**	0.0095***	0.0094**
	(0.0041)	(0.0032)	(0.0046)
Renewable × Index AR(1) Innovation	0.0024**	0.0030***	0.0022**
	(0.0010)	(0.0008)	(0.0009)
Company FE	Yes	Yes	Yes
Remove Market from Stock Returns	Yes	Yes	Yes
R^2	0.006	0.006	0.006
Observations	51003	51003	51003

Note: This table reports robustness checks for Table 3, re-estimated using alternative LLM-based NYT news indices. Panel A uses indices constructed from Gemini 2.5 Flash Lite classifications; Panel B uses an equal-weighted average of the GPT-4o Mini and Gemini indices. 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. Regressions (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).

Table 20: Well Permits and NYT Index (Alternative LLMs)

	Panel A: Gemini		
	Emission Cost (1)	Renewable Breakthrough (2)	Oil Capacity (3)
0 Week Lagged Index AR(1) Innovation	-0.0031	-0.2739***	-0.0828
	(0.0684)	(0.0859)	(0.0765)
1 Week Lagged Index AR(1) Innovation	-0.1406	-0.1840**	-0.2616**
	(0.1004)	(0.0786)	(0.0983)
2 Week Lagged Index AR(1) Innovation	-0.1098	-0.2440**	-0.2397**
	(0.1106)	(0.0992)	(0.1151)
3 Week Lagged Index AR(1) Innovation	-0.0570	-0.2514**	-0.1378
	(0.0750)	(0.1149)	(0.0884)
4 Week Lagged Index AR(1) Innovation	-0.1061	-0.2256**	-0.2249***
	(0.1063)	(0.0960)	(0.0743)
5 Week Lagged Index AR(1) Innovation	0.0096	-0.1835*	-0.2135*
	(0.1073)	(0.0983)	(0.1261)
6 Week Lagged Index AR(1) Innovation	-0.0738	-0.1931**	-0.1044
	(0.0968)	(0.0726)	(0.0872)
1 Week Lagged Permits Submitted	0.3235***	0.3178***	0.3198***
	(0.0578)	(0.0565)	(0.0577)
Firm FE	Yes	Yes	Yes
Cumulative effect p-value	0.22	0.00027	0.0060
Observations	27,996	27,996	27,996
	Panel B: GPT & Gemini Mix		
	Emission Cost (1)	Renewable Breakthrough (2)	Oil Capacity (3)
0 Week Lagged Index AR(1) Innovation	-0.0646	-0.2478**	-0.1009
	(0.0845)	(0.0932)	(0.0890)
1 Week Lagged Index AR(1) Innovation	-0.1425	-0.1857**	-0.2322**
	(0.1070)	(0.0802)	(0.1012)
2 Week Lagged Index AR(1) Innovation	-0.1601	-0.2479**	-0.2630**
	(0.1158)	(0.0998)	(0.1228)
3 Week Lagged Index AR(1) Innovation	-0.1274	-0.2191*	-0.1869
	(0.1035)	(0.1205)	(0.1268)
4 Week Lagged Index AR(1) Innovation	-0.1254	-0.2679***	-0.1988**
	(0.0909)	(0.0966)	(0.0806)
5 Week Lagged Index AR(1) Innovation	-0.0331	-0.1667	-0.2103
	(0.1227)	(0.1095)	(0.1478)
6 Week Lagged Index AR(1) Innovation	-0.0824	-0.2067***	-0.0999
	(0.0872)	(0.0768)	(0.0903)
1 Week Lagged Permits Submitted	0.3226***	0.3188***	0.3203***
	(0.0580)	(0.0568)	(0.0579)
Firm FE	Yes	Yes	Yes
Cumulative effect p-value	0.082	0.00044	0.012
Observations	27,996	27,996	27,996

Note: This table reports robustness checks for Table 4, re-estimated using alternative LLM-based NYT news indices. Panel A uses indices constructed from Gemini 2.5 Flash Lite classifications; Panel B uses an equal-weighted average of the GPT-4o Mini and Gemini indices. Regression (1) shows coefficients from a firm-level weekly panel regression of permits submitted on contemporaneous and lagged (0–6 weeks) standardized AR(1) innovations of the *NYT-Emission Cost News Index*, together with one lag of the dependent variable to capture persistence in permitting activity. Regressions (2) and (3) instead use standardized innovations from the *NYT-Renewable Breakthrough News Index* and the *NYT-Oil Capacity News Index*, respectively. All regressions include firm fixed effects. The cumulative effect p-value tests whether the sum of all lag coefficients is zero. Standard errors are in parentheses and are clustered at the firm and week level. Significance levels: * ($p<0.10$), ** ($p<0.05$), *** ($p<0.01$).

Table 21: Oil Futures Price and NYT Index (Alternative LLMs)

	Panel A: Gemini		
	Avg 1-12m (1)	Avg 13-60m (2)	Avg 1-60m (3)
Index AR(1) Innovation - Emission Cost	0.0105*	0.0073*	0.0082*
	(0.0059)	(0.0037)	(0.0045)
Index AR(1) Innovation - Renewable Breakthrough	-0.0065	-0.0063	-0.0078
	(0.0060)	(0.0042)	(0.0052)
Index AR(1) Innovation - Oil Capacity	-0.0153**	-0.0087**	-0.0084
	(0.0060)	(0.0039)	(0.0051)
Controls	Yes	Yes	Yes
p-value Emission Cost = Renewable Breakthrough	0.057	0.018	0.019
p-value Emission Cost = Oil Capacity	0.0099	0.0098	0.038
p-value Renewable Breakthrough = Oil Capacity	0.35	0.69	0.95
R^2	0.484	0.456	0.506
Observations	143	143	143
	Panel B: GPT & Gemini		
	Avg 1-12m (1)	Avg 13-60m (2)	Avg 1-60m (3)
Index AR(1) Innovation - Emission Cost	0.0137**	0.0100**	0.0113**
	(0.0065)	(0.0043)	(0.0050)
Index AR(1) Innovation - Renewable Breakthrough	-0.0117*	-0.0106**	-0.0116**
	(0.0062)	(0.0045)	(0.0053)
Index AR(1) Innovation - Oil Capacity	-0.0171**	-0.0102**	-0.0098*
	(0.0066)	(0.0043)	(0.0056)
Controls	Yes	Yes	Yes
p-value Emission Cost = Renewable Breakthrough	0.011	0.0022	0.0027
p-value Emission Cost = Oil Capacity	0.0057	0.0069	0.020
p-value Renewable Breakthrough = Oil Capacity	0.58	0.95	0.84
R^2	0.492	0.471	0.517
Observations	143	143	143

Note: This table reports robustness checks for Table 5, re-estimated using alternative LLM-based NYT news indices. Panel A uses indices constructed from Gemini 2.5 Flash Lite classifications; Panel B uses an equal-weighted average of the GPT-4o Mini and Gemini indices. 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, 36 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, 36 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: * ($p<0.10$), ** ($p<0.05$), *** ($p<0.01$).

E.5.3 Reverse Causality

A potential concern is that observed correlations between climate news and stock returns may reflect reverse causality: sharp movements in oil and gas stocks could shape contemporaneous news coverage, rather than the other way around. To address this, we flag and exclude all articles containing explicit references to financial or commodity price movements using the keywords 'oil price', 'stock price', 'price of oil', 'stock returns', 'gas price', 'price of gas', which would be expected to appear if coverage were mechanically triggered by recent price swings. After removing these articles, the re-estimated results in Table 22 remain highly similar to the baseline, reinforcing the conclusion that our findings are not driven by price movement-induced shifts in news coverage.

Table 22: Stock Returns and NYT Index (Excluding Price-Related Articles)

	Emission Cost (1)	Renewable Breakthrough (2)	Oil Capacity (3)
Fossil Fuel Company × Index AR(1) Innovation	-0.0051* (0.0027)	-0.0079*** (0.0020)	-0.0033* (0.0018)
Fossil Fuel Company × Index AR(1) Innovation × Developed Ratio	0.0080** (0.0039)	0.0098*** (0.0031)	0.0050* (0.0028)
Renewable × Index AR(1) Innovation	0.0023** (0.0011)	0.0015*** (0.0005)	0.0014 (0.0009)
Company FE	Yes	Yes	Yes
Remove Market from Stock Returns	Yes	Yes	Yes
R^2	0.006	0.006	0.006
Observations	51003	51003	51003

Note: This is a robustness table of Table 3, re-estimated using NYT news indices constructed after excluding articles containing explicit price-related terms. Regression (1) shows coefficients of regressing stock returns on AR(1) innovations of the *NYT Keyword Filtered-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 (2) and (3) instead show coefficients of regressing stock returns on AR(1) innovations of the *NYT Keyword Filtered-Renewable Breakthrough News Index* and AR(1) innovations of the *NYT Keyword Filtered-Oil Capacity News Index*, respectively. Prior to constructing these indices, we excluded all articles containing the keywords 'oil price', 'stock price', 'price of oil', 'stock returns', 'gas price', 'price of gas'. 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).

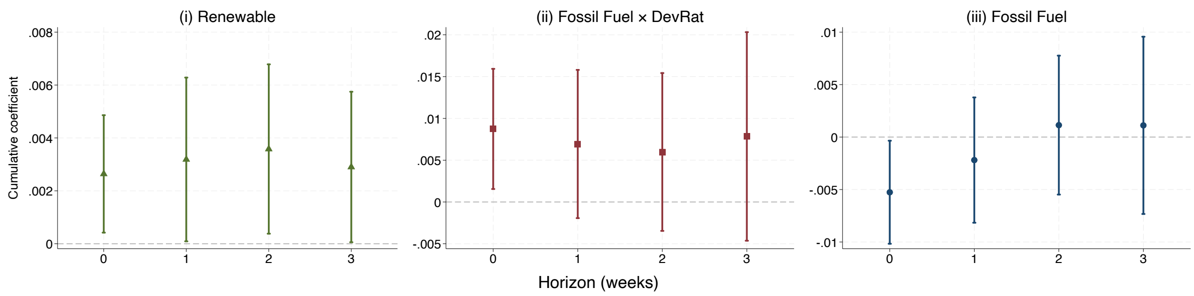
E.5.4 Forward-Looking Horizons

To address whether the impact of climate news shocks on stock returns is transitory or persistent, we re-estimate specification (14) using as the dependent variable the sum of future returns $\sum_{s=0}^{h} R_{i,t+s}$, where h ranges from 0 to 3 weeks. This specification summarizes the total dynamic effect over the horizon.

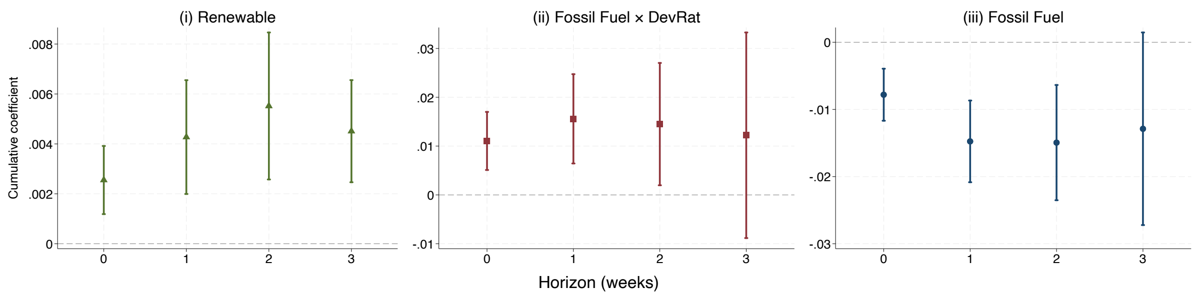
Figure 14 plots the cumulative coefficients across horizons for each index, with 95% confidence intervals. The cumulative coefficients are broadly stable across horizons: fossil fuel firms load negatively (particularly those with low developed reserves), while renewable firms load positively. The fossil fuel coefficient under the emissions cost index is the one exception, attenuating and changing sign at longer horizons. Outside of this case, the point estimates retain their expected signs and remain similar in magnitude, but confidence intervals widen as the horizon lengthens and additional weeks of idiosyncratic return noise are incorporated, eroding statistical significance. This pattern is consistent with a persistent price response, though the loss of precision at longer horizons limits the strength of this conclusion.

Figure 14: Stock Returns and NYT Index, Cumulative Forward Horizons

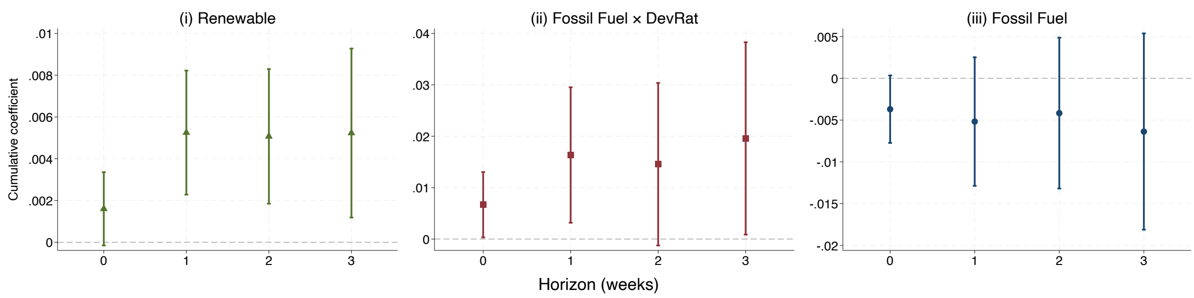
(a) NYT-Emission Cost News



(b) NYT-Renewable Breakthrough News



(c) NYT-Oil Capacity News



Note: Each panel plots cumulative coefficients from re-estimating specification (14) with the sum of future returns $\sum_{s=0}^{h} R_{i,t+s}$ as the dependent variable, for horizons $h = 0, 1, 2, 3$ weeks. This specification summarizes the total dynamic effect over the horizon. Subplots (i)–(iii) within each panel show the coefficients on the renewable indicator, the fossil fuel $\times$ developed reserves ratio interaction, and the fossil fuel indicator, respectively. Shaded regions denote 95% confidence intervals based on standard errors clustered by firm. The sample covers 2012–2023.

E.5.5 Other Robustness Checks

We include several other 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 23 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 24 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.

One notable feature of our baseline oil futures results is that the oil capacity index enters with a statistically significant negative coefficient, which is at odds with the fossilflation mechanism predicted by the model. However, this result appears to be partially driven by the extreme dislocation in oil markets around April 2020, when WTI front-month contracts briefly traded below zero. Table 25 re-estimates the specification after excluding a four-month window around this episode. The negative coefficient on oil capacity remains negative but is no longer statistically significant, suggesting that the anomalous baseline result may reflect the outsized leverage of this period on the regression estimates.

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 3–5. The corresponding results are reported in Tables 26–28. For the stock-price regressions, most coefficients are statistically insignificant. Among the statistically significant estimates, the signs generally align with our baseline results, except for Bua's Transition News measure interacted with a renewable dummy. For the well-permit regressions, Ardia's and Faccini's measures are associated with statistically significant reductions in permits submitted, in line with our baseline findings, whereas Bua's measure does not yield a corresponding decline. For the oil-futures regressions, only Ardia's Media Climate Change Concern (MCCC) Index is statistically significant, with a large positive coefficient, indicating that greater climate-change concern is associated with higher oil futures prices.

Table 23: 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**	-0.0060**	-0.0077***	-0.0075***	-0.0076***	-0.0041*	-0.0038*	-0.0041*
	(0.0025)	(0.0026)	(0.0025)	(0.0018)	(0.0019)	(0.0017)	(0.0022)	(0.0022)	(0.0022)
Fossil Fuel Company × Index AR(1) Innovation × Developed Ratio	0.0099***	0.0090**	0.0098***	0.0110***	0.0106***	0.0107***	0.0071**	0.0068**	0.0071**
	(0.0036)	(0.0038)	(0.0037)	(0.0027)	(0.0029)	(0.0026)	(0.0034)	(0.0034)	(0.0034)
Renewable × Index AR(1) Innovation	0.0022**	0.0026**	0.0023**	0.0026***	0.0026***	0.0024***	0.0015*	0.0015	0.0015*
	(0.0010)	(0.0011)	(0.0011)	(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	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Observations	51003	51003	51003	51003	51003	51003	51003	51003	51003

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 24: 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	-0.0074***	-0.0031	-0.0056***	-0.0069***	-0.0053***	-0.0063***	-0.0038	-0.0026	-0.0030*
	(0.0024)	(0.0023)	(0.0019)	(0.0022)	(0.0018)	(0.0017)	(0.0024)	(0.0017)	(0.0018)
Fossil Fuel Company × Index AR(1) Innovation ×	0.0116***	0.0057*	0.0093***	0.0094***	0.0074***	0.0088***	0.0080**	0.0047*	0.0054*
Developed Ratio	(0.0034)	(0.0034)	(0.0028)	(0.0034)	(0.0027)	(0.0026)	(0.0037)	(0.0028)	(0.0028)
Renewable × Index AR(1) Innovation	0.0027***	0.0028**	0.0025**	0.0022***	0.0021***	0.0026***	0.0019**	0.0015	0.0015
	(0.0010)	(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	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006	0.006
Observations	51003	45911	50709	51003	45911	50709	51003	45911	50709

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 25: Oil Futures Price and NYT Index, Excluding COVID-19

	Monthly Level		
	Avg 1-12m	Avg 13-60m	Avg 1-60m
	(1)	(2)	(3)
Index AR(1) Innovation - Emission Cost	0.0128**	0.0104**	0.0111**
	(0.0060)	(0.0044)	(0.0050)
Index AR(1) Innovation - Renewable Breakthrough	-0.0114**	-0.0107**	-0.0110**
	(0.0054)	(0.0041)	(0.0046)
Index AR(1) Innovation - Oil Capacity	-0.0091	-0.0071	-0.0052
	(0.0066)	(0.0043)	(0.0054)
Controls	Yes	Yes	Yes
p-value Emission Cost = Renewable Breakthrough	0.0073	0.0013	0.0023
p-value Emission Cost = Oil Capacity	0.042	0.025	0.073
p-value Renewable Breakthrough = Oil Capacity	0.79	0.55	0.43
R^2	0.377	0.411	0.434
Observations	139	139	139

Note: This table reports robustness checks for Table 5, re-estimated after excluding observations from March to June 2020 to remove the influence of the extreme negative WTI pricing episode. 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, 36 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, 36 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: * ($p<0.10$), ** ($p<0.05$), *** ($p<0.01$).

Table 26: 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	0.006	0.006	0.029
Observations	51003	49208	29790

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 27: Well Permits and Other Indices

	Bua	Faccini	Ardia
	(1)	(2)	(3)
0 Week Lagged Index AR(1) Innovation	0.2066**	-0.0822	-0.0049
	(0.0955)	(0.0640)	(0.1122)
1 Week Lagged Index AR(1) Innovation	-0.0621	-0.1081	-0.1200
	(0.0822)	(0.0683)	(0.0875)
2 Week Lagged Index AR(1) Innovation	-0.1264	-0.3211***	-0.2081**
	(0.0788)	(0.0879)	(0.0924)
3 Week Lagged Index AR(1) Innovation	-0.0699	-0.2881***	-0.3093***
	(0.0828)	(0.0972)	(0.0970)
4 Week Lagged Index AR(1) Innovation	-0.1497*	-0.3223***	-0.1568
	(0.0795)	(0.0984)	(0.1033)
5 Week Lagged Index AR(1) Innovation	-0.0201	-0.1447**	-0.1281
	(0.0708)	(0.0617)	(0.1049)
6 Week Lagged Index AR(1) Innovation	0.0346	-0.1680**	-0.0552
	(0.0675)	(0.0740)	(0.1286)
1 Week Lagged Permits Submitted	0.3243***	0.3271***	0.2117***
	(0.0572)	(0.0540)	(0.0425)
Firm FE	Yes	Yes	Yes
Cumulative effect p-value	0.44	0.00013	0.015
Observations	27,996	26,982	15,614

Note: This table reports robustness checks for Table 4. Regression (1) shows coefficients from a firm-level weekly panel regression of permits submitted on contemporaneous and lagged (0–6 weeks) standardized AR(1) innovations of the Bua et al. (2024) Transition Risk Index, together with one lag of the dependent variable to capture persistence in permitting activity. Regressions (2) and (3) instead use standardized 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. All regressions include firm fixed effects. The cumulative effect p-value tests whether the sum of all lag coefficients is zero. Standard errors are in parentheses and are clustered at the firm and week level. Significance levels: * (p<0.10), ** (p<0.05), *** (p<0.01).

Table 28: 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	0.0014	-0.0004
	(0.0055)	(0.0035)	(0.0043)
Controls	Yes	Yes	Yes
R^2	0.447	0.420	0.476
Observations	143	143	143
	(1)	(2)	(3)
Index AR(1) Innovation - Faccini Climate Policy	0.0063	0.0020	0.0042
	(0.0071)	(0.0046)	(0.0051)
Controls	Yes	Yes	Yes
R^2	0.469	0.441	0.495
Observations	137	137	137
	(1)	(2)	(3)
Index AR(1) Innovation - Ardia Media Climate Change Concern	0.0197***	0.0135**	0.0179***
	(0.0057)	(0.0058)	(0.0050)
Controls	Yes	Yes	Yes
R^2	0.473	0.349	0.495
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, 36 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, 36 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: * ($p<0.10$), ** ($p<0.05$), *** ($p<0.01$).