Climate Transition Risk and the Energy Sector*

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Abstract

We build a general equilibrium model to study how climate transition risks affect energy prices and the valuations of different firms in the energy sector. Fossil fuel firms have existing capacity, but their technology to produce energy entails carbon emissions. Renewable energy firms produce energy without generating carbon emission but cannot currently supply to non-electrifiable sectors of the economy. We consider two sources of climate transition risk for fossil fuel firms: (i) the possibility of a technological breakthrough that improves renewable energy firms' ability to provide energy to all sectors, and (ii) the introduction of taxes on carbon emissions and new fossil fuel production capacity. While a greater chance of renewable breakthroughs decreases energy prices and valuations of fossil fuel firms, this need not be the case with carbon taxes and drilling restrictions. These latter transition risks make it less attractive or rule out for fossil fuel firms to create new capacity, so that if breakthrough technologies do not arrive, this reduced capacity will lead to higher energy prices, in particular for non-electrifiable sectors. This, in turn, can create incentives for incumbent fossil fuel firms to carry existing inventories to the future, reducing supply and raising prices today, and possibly boosting their valuations. We provide empirical support for testable implications based on these counter-intuitive and heterogeneous effects of different transition risks on energy prices and different energy sub-sectors.

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

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

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Through the burning of fossil fuels, energy production accounts for around three-quarters of global greenhouse gas emissions (Ritchie and Roser, 2020). The energy sector is thus a key focus of policy makers in the fight against climate change, with the hope that low-emissions renewable energy can replace fossil-fuel-based energy sources. Yet, as we will show, recent news about increasing physical and transition climate risks have not been associated with a broad-based fall of valuations of fossil fuel firms, and Alekseev et al. (2022) document that investors who become more concerned about climate risks have increased their holdings in large fossil-fuel-based energy producers. Motivated by these observations, this paper aims to understand the effects of different climate transition risks on the dynamics of prices, inventories, investment, production, and valuations in the energy sector.

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

We consider two sources of climate transition risk for fossil fuel firms: (i) the possibility of a technological breakthrough that improves renewable energy firms' ability to provide energy to all sectors, i.e., increases the chance of green transition; and, (ii) the introduction of taxes on carbon emissions and new fossil fuel production capacity. In this environment, we show that these two types of transition risks can have heterogeneous effects on energy prices and sub-sectors. raise energy prices and valuations of fossil-fuel firms. While technological breakthrough depresses energy prices and valuations of fossil fuel firms, this need not be the case with carbon taxes and drilling restrictions.

The mechanism behind this counter-intuitive result is that any reduction in investments in additional fossil fuel capacity today—for example, because a potential future carbon tax reduces the profitability of producing energy using fossil fuels—could lead to substantially higher energy prices in the future, in particular absent technological breakthroughs that raise the ability of renewable energy source to power a larger share of the overall economy. The anticipation of higher future energy prices also might incentivize fossil fuel producers today to transfer production capacity into the future, even at the risk that some of that capacity may eventually be stranded. This inter-temporal inventory management can lower supply and raise energy prices today, leading to what the

European Central Bank's Isabel Schnabel (2022) called "fossilflation". This energy price rise, in turn, raises the value of production capacity that fossil fuel firms already have in place, counteracting some of the direct negative effect of transition risks on the valuation of fossil fuel firms with substantial proven reserves.

Let us elaborate. Our model features two periods, which can be interpreted as being one or two decades apart. In the current period, the economy has to rely entirely on the fossil fuel sector to satisfy its demand of energy. Renewable energy firms present today invest in capacity to provide energy in the future, and with some probability (p) a technological breakthrough occurs in the future, that allows these firms to provide energy to all sectors of the economy. The possibility of a technological breakthrough constitutes the first source of transition risk in our model, which can affect the current price of energy through the response of the fossil fuel sector. We denote this scenario as Breakthrough Technology (BT) state.

We also consider the possibility that a social planner might impose taxes, either on carbon emissions in the BT state ($\tau_{1,BT}$) or on the creation of new fossil fuel production capacity ($\hat{\tau}_0$). These two instruments are meant to capture sources of risk coming from the policy response to the transition.

A key result is that the transition path to a green economy can in some cases cause an increase in the *current* price of energy. On the one hand, the expectation of lower future profits, either due to policy or competition from the renewable sector, can induce fossil fuel producers to increase their current energy supply, using up their fossil fuel reserves while there is still demand for them. This can have the effect of reducing the price of energy today. This economic force is the standard intuition for how transition risk may affect energy prices.

On the other hand, lower future profits also have the effect of discouraging investment in *new* production capacity. The fossil fuel sector might thus decide to reduce current production, which is being sold at a low marginal profit, in order to carry as inventory its existing production capacity in the future.[1] This inventory policy has the effect of raising the price of energy today. The rationale for this non-standard result is that, if the transition does not occur, then the fossil fuel sector would remain the main provider of energy to the economy, a scenario in which profits would be very high. Given these higher future profits if the transition does not occur, the inventory policy can be optimal even though it exposes the fossil fuel sector to the risk of its assets becoming *stranded* if the transition indeed occurs, a scenario in which it would not be profitable to fully exhaust the production capacity. Relatedly, the incentive to undertake this inventory policy implies that fossil fuel firms with large existing reserves are less exposed to transition

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[1] Models wherein energy firms use their inventory as a hedging as well as an arbitraging tool between spot and expected future prices are common in the literature on commodity prices. See, for instance, Acharya et al. (2013) and references therein.

Table 1: Summary of model predictions.

Increase in:	Transition probability (p)	Carbon tax in BT state ($\tau_{1,BT}$)	Drilling restrictions ($\hat{\tau}_0$)
Current energy price (P_0)	Decreases	Uncertain	Increases
Future energy price ($E[P_1]$)	Decreases	Increases	Increases
Incumbent fossil fuel producer			
Inventory	Decreases	Uncertain	Increases
Stock price	Decreases (less)	Decreases/Uncertain	Increases
Entrant fossil fuel producer			
Production capacity	Decreases	Decreases	Decreases
Stock price	Decreases (more)	Decreases	Decreases
Renewable energy producer			
Production capacity	Increases	Increases	Increases
Stock price	Increases	Increases	Increases

risk, compared to entrant firms or firms with lower production capacity already in place. In our model, this latter result emerges starkly: Incumbent firms in fossil fuel sector with substantially developed reserves are protected against, and can even benefit from, transition risk; in contrast, entrants to the sector are always hurt.

Besides relating transition risks to energy prices, the model provides testable empirical implications with respect to the stock price of energy sector firms. Unsurprisingly, announcements of subsidies to the renewable energy sector should have a negative effect on the stock price of fossil fuel companies. The less obvious implication is that announcements of carbon taxes and taxes on new fossil fuel production capacity should have a more negative effect on the stock price of fossil fuel companies with little capacity already in place, compared to companies with large existing reserves. Given the counter-intuitive effect of transition risk on energy prices via the inventory channel, companies with large existing reserves can experience virtually no effect (or even an increase) in their stock valuations. These implications for different types of transition risk on energy prices and valuations of energy sub-sectors are summarized in Table 1.

We empirically test these implications by studying the reactions of prices of energy futures and of stocks in different types of energy firm sub-sectors to news about climate transition risks. To achieve this, we construct high-frequency transition news indexes by analyzing news reported in the New York Times (NYT) using GPT-4, one of the most advanced large language models (LLM) developed by OpenAI. Our analysis covers a total of 15,415 articles published over a 10-year period from 2012 to 2022. We create two weekly indexes: 1) the NYT-Emission Cost News Index, which captures news about carbon pricing policies and the regulatory or financial costs of carbon emissions, including the introduction of taxes or other policies on carbon emissions, and 2) the NYT-Renewable Breakthrough News Index, which covers news related to the probability of breakthroughs in renewable energy or battery storage technology, actual technological advancements in these fields, and policies subsidizing or supporting renewable energy production. This latter index reflects the potential for technological breakthroughs that enhance renewable energy firms' ability to supply energy across all sectors.

Figure 1 plots the time series of the two news indexes, with labels indicating related events. Positive scores indicate more restrictions on the fossil fuel industry or greater support for renewable energy; negative scores indicate relaxation of these restrictions or lower support for renewable energy. The NYT-Emission Cost News Index shows spikes around significant climate-related events, such as the announcement of the Clean Power Plan in 2015, its repeal proposal in 2017, and the Inflation Reduction Act (IRA) in 2022. The NYT-Renewable Breakthrough News Index spikes around events favoring renewable energy or announcing technological breakthroughs, such as the drafting of the Paris Agreement at the 2015 United Nations Climate Change Conference and major advancements in fusion energy in 2022.

We then study the response of energy prices and stock returns of energy firms to these two news indexes. First, consistently with our model, we document that oil futures prices decrease with news about possible renewable energy breakthroughs, but they increase with news related to increasing cost of carbon emissions.

Next, in line with our model, we identify three groups of firms: entrants, incumbents, and renewable firms.[2] We find that, consistent with the theory, on average renewable energy companies earn positive returns in weeks with news reporting increases of cost emissions or probability of a renewable breakthrough, whereas fossil fuel companies on average have negative returns on those days. We also observe differential price movements for entrants and incumbents. When news of higher emission costs arrives, entrants' stock prices tend to drop, whereas incumbents' prices remain stable or slightly positive, suggesting that entrants are adversely affected by the potential increased restrictions, while incumbents can leverage their existing inventories to benefit if the transition does not occur. In response to positive news about breakthroughs in renewable energy technology, stock prices for both entrants and incumbents drop significantly, though the decline is less pronounced for incumbents.[3]

Overall, these results line up closely with the main predictions of the theoretical model. In ongoing work, we are building an index that should capture news about drilling restrictions, in order to investigate the implications related to the third source of transition risk in our model.

Finally, we show in the context of our model how the policy response can be tailored in order to minimize the risk of high energy prices over the transition path. Our results

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[2] Incumbents are firms with well-established reserves, such as Exxon, Chevron, Conoco Phillips, Occidental Petroleum, and Devon Energy. Entrants are those that have developed only a small proportion of their total reserves, such as BPZ Energy, ZaZa Energy, and Lonestar Resources. We identify renewable firms using the holding firms of the Invesco WilderHill Clean Energy ETF, which includes publicly traded companies in the United States engaged in the advancement of cleaner energy and conservation. Examples of these firms include Sunrun, Altus Power, Gevo, and Sunnova.

[3] The results are generally robust across different specifications of index construction and to various thresholds for the developed reserves ratio used to distinguish between entrants and incumbents.

suggest that optimal future carbon taxes to be set in the scenario where the technological transition occurs should be decreasing in the transition probability, while optimal taxes on new fossil fuel capacity should be increasing. The rationale is that, in order to meet the energy needs of the economy, it is socially optimal to minimize the amount of existing fossil fuel production capacity that remains unused, while discouraging the installment of new capacity.

In summary, our model highlights how different types of transition risk – technological breakthrough, carbon tax, and drilling restrictions – differently affect energy prices and sub-sectors – renewable firms, and incumbent fossil fuel firms with large and small developed reserves. In terms of positive economics, theory and its tests help understand the relevant heterogeneity in transition risks and energy sub-sectors as well as the energy supply and price mechanisms via which this heterogeneity matters. On the normative front, theory guides how optimal policy should adjust one set of transition risks, namely carbon tax and drilling restrictions, contingent on the other transition risk, namely technological breakthrough in renewable energy and its storage.

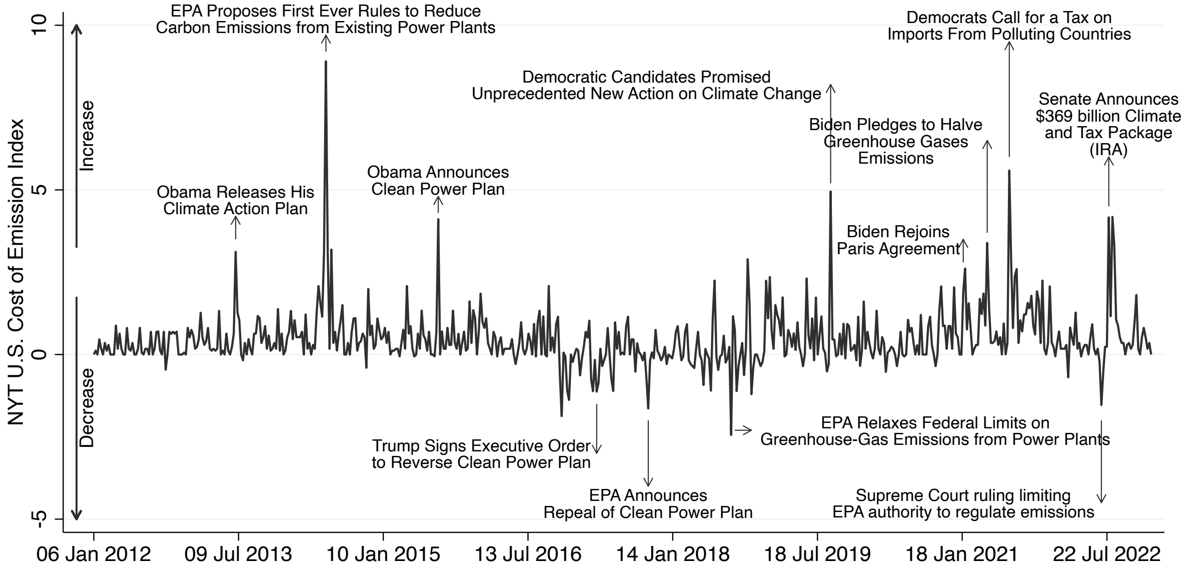
The rest of the paper is organized as follows. Section 1 discusses related literature. Section 2 describes the model in detail. Section 3 presents the main results on the effects of transition risk on energy prices. Section 4 presents the empirical results verifying model implications. Section 5 then derives optimal carbon policies and Section 6 concludes.

1 Related Literature

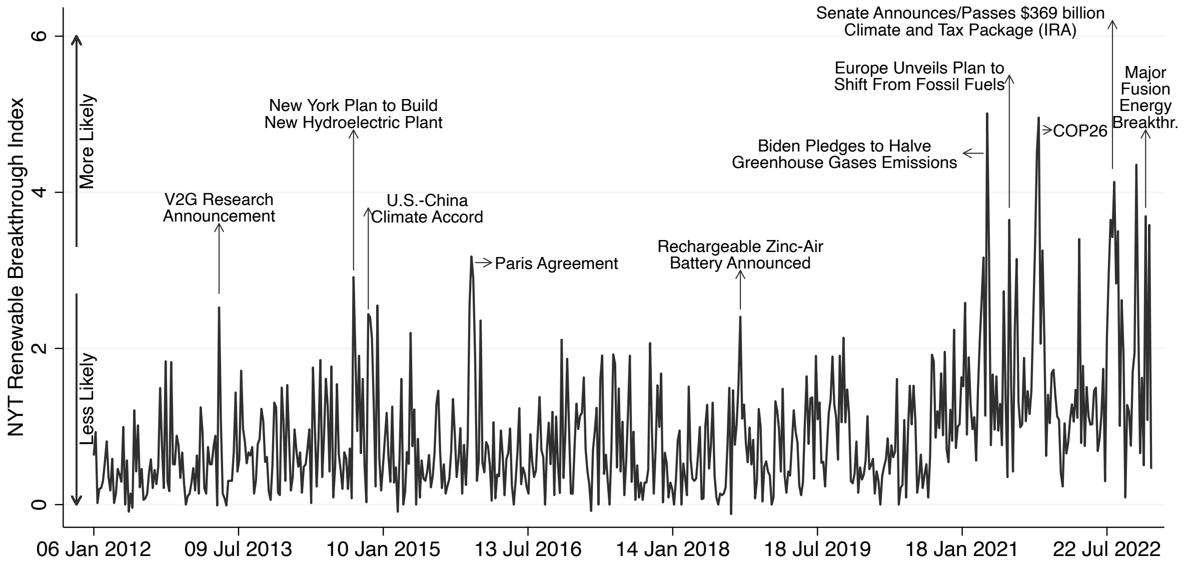
Our paper belongs to the growing literature on climate finance, extensively reviewed by Giglio et al. (2021) and Benthem et al. (2022). Our focus is on studying theoretically the effects of the climate transition on energy prices, but this focus is motivated by existing empirical evidence. Empirically, 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, even though they find that the price of other goods and services are unaffected. Adolfsen et al. (2024) show empirically that firms in the fossil fuel industry with greater exposure to climate change significantly increased their investment in response to the Paris Agreement, arguing that in anticipation of future climate policy, fossil fuel firms might have a short-term incentive to raise production. Relatedly, a large empirical literature finds that oil supply shocks have important effects on energy prices and on the economy (see, for instance, Kilian, 2009; Caldara et al., 2019; Känzig, 2021). Several papers have also shown that climate transition risk is currently reflected in the stock market (Hong et al., 2019; Bolton and Kacperczyk, 2021; Engle et al., 2021). Connecting these inquiries, our model highlights how the fossil fuel sector might respond

Figure 1: Time-Series of NYT News Index

(a) NYT-Emission Cost News



(b) NYT-Renewable Breakthrough News



Note: Panel (a) shows the weekly NYT-Emission Cost News Index and panel (b) shows the weekly NYT-Renewable Breakthrough News Index from 2012 to 2022, annotated with climate-relevant events that have potential effects on cost of emissions and renewable energy supports. IRA: Inflation Reduction Act; V2G: Vehicle-to-Grid; COP26: The 2021 United Nations Climate Change Conference.

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.

On the theoretical front, Pisani-Ferry (2021) makes the case that policymakers should adopt a macroeconomic perspective when analyzing the effects of climate policies, and that their general equilibrium effects on the economy should be taken into account. Along these lines, Engle (2023) develops a "Termination risk model" which captures the idea that fossil fuel assets might become stranded at some point in the future, and this might have the effect of reducing energy supply today. We make a related point in our model, and also argue that technological development in the renewable energy sector can instead push down the current price of energy. Barnett (2023) reaches the conclusion that expectations of future restrictions on fossil fuel use might induce oil producers to increase current supply, thus increasing emissions and pushing down energy prices[4]. Our model naturally delivers this result with respect to expectations of breakthroughs in renewable energy technologies, but also highlights how different types of transition risk, such as carbon taxes or restrictions on new drilling, can have different effects on energy prices, firms in the energy sector, and carbon emissions.

A growing theoretical literature also studies the effects of transition risk on the aggregate inflation level, mostly relying on models based on the New Keynesian framework. Ferrari and Nispi-Landi (2022) argue that expectations of future carbon taxes can have deflationary effects on the economy, while Del Negro et al. (2023) find that the price level response to the green transition depends on the degree of price stickiness in the various sectors of the economy, and in particular of green and non-green sectors.

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

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[4] This possibility has been labeled as the "Green Paradox" (Sinn, 2008).

2 Two-Period Climate Transition Risk Model

2.1 Setup

Time is discrete and there are two periods, denoted by $t = 0, 1$, with a gross discount rate $R = 1$. The economy consists of a sector that consumes energy as well as three different types of competitive energy-producing sub-sectors: an incumbent fossil fuel-based energy producer, an entrant producing fossil fuel-based energy, and a renewable producer ("green firm"). Throughout, we will focus on the representative firm in each sub-sector.

In period 0, the incumbent fossil fuel firm arrives with some level of oil reserves for which exploration and drilling costs have already been paid. It then chooses how much oil to extract at some cost today and how much to leave in the ground to be potentially extracted next period. The entrant has no initial reserves, and chooses via exploration and drilling how much new production capacity to install to be potentially extracted in period 1.[5] The renewable producer can generate clean energy at zero marginal cost. It starts period 0 with no production capacity, and decides how much to invest in new capacity to be used in period 1.

The current technology does not allow the renewable producer to satisfy all energy demand in the economy. This captures the fact that energy use in several key sectors—for example, steel production or maritime and air transportation—cannot be effectively electrified. Similarly, the lack of large-scale energy storage combined with the intermittency of solar and wind energy production means that, with current technologies, some amount of electricity will need to be produced via fossil fuels. As a result, we assume that with current technology, only a fraction q of total demand for energy in period 1 can be satisfied by the renewable sector.

We also assume that with some probability p a breakthrough technology is developed in period 1, which allows renewable energy producers to supply to all sectors of the economy.[6] In this scenario, renewable firms would be able to compete with fossil fuel producers in markets from which they are currently excluded. We denote the scenario that includes these possible developments as the "Breakthrough Technology" (BT) scenario, and this eventuality represents a key source of transition risk for the fossil fuel sector.

If the technological breakthrough does not occur, the renewable firm in period 1 will be able to supply energy only to a subset of sectors in the economy. This is the "Current

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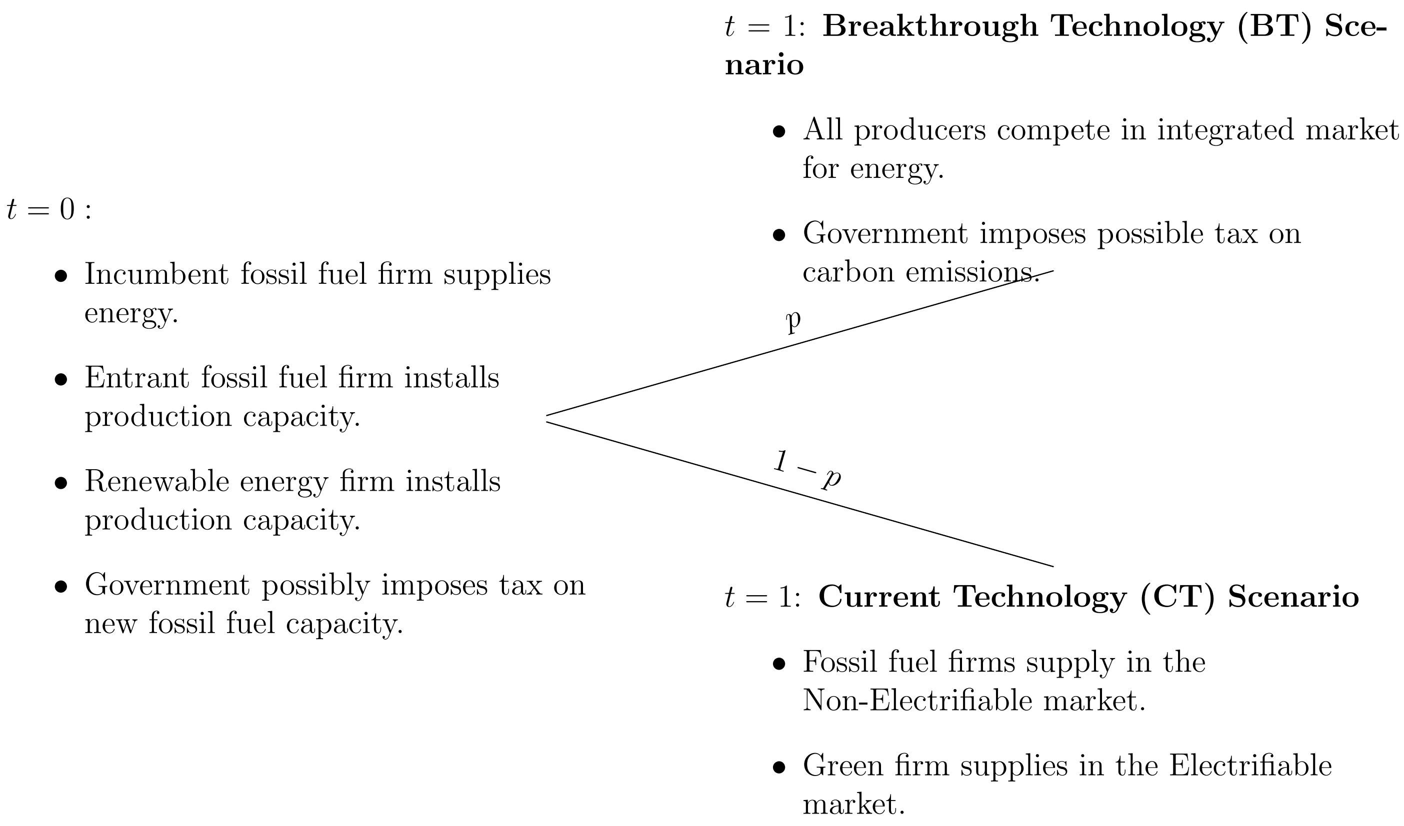
[5] In practice, some of new production and exploration can also be done by incumbent. By separating the problem of how much to extract from current reserves from the problem of how many new reserves to add, we are able to develop insights into how various transition risks might differentially influence incumbents and entrants.

[6] This technology could either solve the problem of storability of clean energy, thus allowing renewable producers to store and transfer their production over time in order to provide a constant supply of energy. Alternatively, it could allow renewable firms to provide energy to those sectors currently dependent on fossil fuel sources.



$t = 0$:

- Incumbent fossil fuel firm supplies energy.
- Entrant fossil fuel firm installs production capacity.
- Renewable energy firm installs production capacity.
- Government possibly imposes tax on new fossil fuel capacity.

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

- All producers compete in integrated market for energy.
- Government imposes possible tax on carbon emissions.

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

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

Figure 2: Timeline of the model.

Technology" (CT) scenario, which is 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 fuel firms. Energy price can be different across these two markets.

A key externality in the model is that the production of energy by the fossil fuel sector causes a social loss through its carbon emissions. As a result, the government might want to intervene in order to limit carbon emissions and maximize social welfare. In particular, the planner might wish to impose a set of taxes on the fossil fuel producers' carbon emissions in the Breakthrough Technology scenario in period 1, or a tax on the amount of new production capacity that is installed by potential fossil fuel entrants. These taxes reflect transition risks affecting the fossil fuel producers in addition to the evolution of renewable technology. To start with, we take these taxes as exogenously given, and solve for optimal taxes in Section 5.

We now move to the formal description of our model in more detail. We start with the problem of the consumers. We then state the problem of the green firm. Then, we explain the production and investment decision problems of the two fossil fuel firms. Finally, we clear markets to derive the competitive equilibrium. Timeline of the model is summarized in Figure 2.

2.2 Model

2.2.1 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

$$\max_{e_t^i} \ \log e_t^i$$

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

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 be different according to whether the BT or the CT scenario materializes, and, in the latter case, depending on whether the consumer's energy demand is electrifiable or not. Hence, for each scenario $j \in \{BT, CT\}$, we have:

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

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

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

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

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

2.2.2 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 $\frac{1}{2\delta}C^2$, and that this capacity can then be used to produce energy in period 1 at zero marginal cost. Hence, in period 1, the green firm will always choose to activate its full production capacity. The renewable firm maximizes expected profits, taking as given the price of energy $(P_{1,BT}, P_{1,E})$ in the respective markets at date 1 where it is able to sell. The firm's problem is therefore:

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

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

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

2.2.3 Fossil Fuel Firm: Incumbent

At time 0, we assume that an incumbent fossil fuel producer has an existing capacity of $\bar{f}_0$, which can be activated immediately to produce energy, or saved for the next period as inventory. Producing an amount of energy f_0 has a cost of $\frac{1}{2\kappa_1}f_0^2$. In period 1, if the BT scenario realizes, then the firm will always be facing competition of the renewable producer. If the CT scenario realizes, the fossil fuel producer will be the only supplier of energy for a fraction $(1-q)$ of total demand, where it might thus earn high profits. The firm maximizes expected profits by choosing its time- and state-contingent supplies $(f_0, f_{1,BT}, f_{1,E}, f_{1,NE})$, taking as given the price of energy at time 0, P_0, and in all the possible states in period 1, $(P_{1,BT}, P_{1,E}, P_{1,NE})$. Furthermore, we assume that in case the transition occurs in period 1, a social planner imposes a carbon tax on fossil fuel firms at a rate $\tau_{1,BT} > 0$ on their sales $P_{1,BT}f_{1,BT}$. We assume, and show in Section 5 that it is socially optimal, that the no-transition carbon tax rate $\tau_{1,CT}$ is lower than $\tau_{1,BT}$. For simplicity, we assume for now that $\tau_{1,CT} = 0$.

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

$$\max_{f_0} \; f_0P_0 - \frac{1}{2\kappa_1}f_0^2 + E[V_f^I] \tag{2}$$

subject to $0 \leq f_0 \leq \bar{f}_0$. The date-1 continuation value V_f^I is equal to $V_f^{I,BT}$ with probability p, which is given by

$$V_f^{I,BT} = \max_{f_{1,BT}^I} (1-\tau_{1,BT})P_{1,BT}f_{1,BT}^I - \frac{1}{2\kappa_1}(f_{1,BT}^I)^2, \tag{3}$$

subject to $0 \leq f_{1,BT}^I \leq \bar{f}_0 - f_0$, and V_f^I is equal to $V_f^{I,CT}$ otherwise, which is given by

$$V_f^{I,CT} = \max_{f_{1,E}^I, f_{1,NE}^I} P_{1,E}f_{1,E}^I + P_{1,NE}f_{1,NE}^I - \frac{1}{2\kappa_1}(f_{1,E}^I + f_{1,NE}^I)^2, \tag{4}$$

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

2.2.4 Fossil Fuel Firm: Entrant

In order to cleanly model fossil fuel firms with low existing reserves, we also assume that there is a representative entrant firm that has to choose how much new production capacity to install to be potentially produced in period 1. Installing an amount of capacity $\hat{f}_1$ has a cost $\frac{1}{2(1-\hat{\tau}_0)\kappa_2}\hat{f}_1^2$, where $\hat{\tau}_0$ represents a tax imposed by the social planner on the construction of new fossil fuel production capacity.[7] The fossil fuel entrant firm (superscript E) therefore chooses its supplies to solve in period 0:

$$\max_{\hat{f}_1} -\frac{1}{2(1-\hat{\tau}_0)\kappa_2}\hat{f}_1^2 + E[V_f^E] \tag{5}$$

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

$$V_f^{E,BT} = \max_{f_{1,BT}^E} (1-\tau_{1,BT})P_{1,BT}f_{1,BT}^E - \frac{1}{2\kappa_1}(f_{1,BT}^E)^2, \tag{6}$$

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

$$V_f^{E,CT} = \max_{f_{1,E}^E, f_{1,NE}^E} P_{1,E}f_{1,E}^E + P_{1,NE}f_{1,NE}^E - \frac{1}{2\kappa_1}(f_{1,E}^E + f_{1,NE}^E)^2, \tag{7}$$

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

We describe the solutions to the fossil fuel producers' problems in Appendix A.

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[7] This could correspond to a range of actual policies, including increasing the cost of new drilling (or making fewer new oil field leases available). But it could also capture an increase in the cost of capital for new energy production, for example due to raising banks' cost of lending for such projects.

2.2.5 Market Clearing and Equilibrium

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

$$S_0 = f_0,$$

$$S_{1,BT} = C + f^I_{1,BT} + f^E_{1,BT},$$

$$S_{1,E} = C + f^I_{1,E} + f^E_{1,E}, \text{ and}$$

$$S_{1,NE} = f^I_{1,NE} + f^E_{1,NE}.$$

By imposing market clearing, we obtain the following equilibrium conditions

$$\frac{W}{P_0} = f_0, \tag{8}$$

$$\frac{W}{P_{1,BT}} = C + f^I_{1,BT} + f^E_{1,BT}, \tag{9}$$

$$q\frac{W}{P_{1,E}} = C + f^I_{1,E} + f^E_{1,E}, \text{ and} \tag{10}$$

$$(1-q)\frac{W}{P_{1,NE}} = f^I_{1,NE} + f^E_{1,NE}. \tag{11}$$

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,* $(f_0, f^I_{1,BT}, f^I_{1,E}, f^I_{1,NE})$*, fossil fuel entrant producer quantities,* $(\hat{f}_1, f^E_{1,BT}, f^E_{1,E}, f^E_{1,NE})$*, and prices,* $(P_0, P_{1,BT}, P_{1,E}, P_{1,NE})$*, such that*

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

To focus on the more interesting implications of our analysis, we assume that the initial fossil fuel reserves $\bar{f}_0$ are not so high that the producer is always unconstrained in all periods.

3 Model Analysis

We can now use our model to understand how the endogenous quantities of interest, especially energy prices and profits of energy firms, change with the model parameters that represent various types of transition risk. In particular, we will focus on:

1. Changes in the probability of the Breakthrough Technology scenario, p.
2. Changes in the tax on fossil fuel emissions, $\tau_{1,BT}$.
3. Changes in the tax on new fossil fuel production capacity, $\hat{\tau}_0$.

3.1 Changes in the Probability of a Technological Breakthrough

We first focus on the effects of changes in the probability of transitioning to a scenario where the renewable sector can reliably supply energy to the entire economy, represented by the parameter p. We can interpret these changes as deriving either from technological breakthroughs in the private sector, or from a policy perspective, we can view these changes as reflecting the size of government subsidies to R&D in the green energy sector. We assume throughout this analysis that carbon and production capacity taxes are zero. Our conjecture, based on results to follow in Section 5, is that the analysis generalizes to positive taxes.

Figure 3 shows how the model outcomes change as p increases.[8] The various panels show 1) the price of energy in period 0 (top left plot), 2) the price of energy in period 1 in various markets and technology scenarios (top right), 3) the supply of fossil fuel in period 0 (middle left), 4) the production capacity of various energy producers in period 1 (middle right), 5) total expected profits for various energy producers (bottom left), and 6) fossil fuel emissions (bottom right). Note that profits for each producer are normalized by their profits for $p = 0$, whereas emissions are normalized for each period and total by the corresponding value for $p = 1$.

We can see that as the probability of the Breakthrough Technology scenario increases the renewable firm increases its installed capacity. This is due to the fact that the firm is expecting to be able to supply energy to a larger share of the economy in the future, and hence wants to increase its capacity to be able to capture this additional demand.

As a consequence, the incumbent fossil fuel producer anticipates that, as p increases, it will have to face higher competition from the renewable sector with a higher probability, and hence wants to produce more in period 0 rather than carrying inventory into period 1. Similarly, the expectation of increasing competition from the renewable producer in

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[8] All the numerical examples are based on the following calibration: $\bar{f}_0 = 1.7$, $\kappa_1 = 0.4$, $\kappa_2 = 0.15$, $\delta = 0.3$, $W = 3$, $q = 0.2$, $\tau_{1,BT} = \hat{\tau}_0 = 0$. We choose parameters such that the incumbent fossil fuel firm is not always unconstrained in all states.

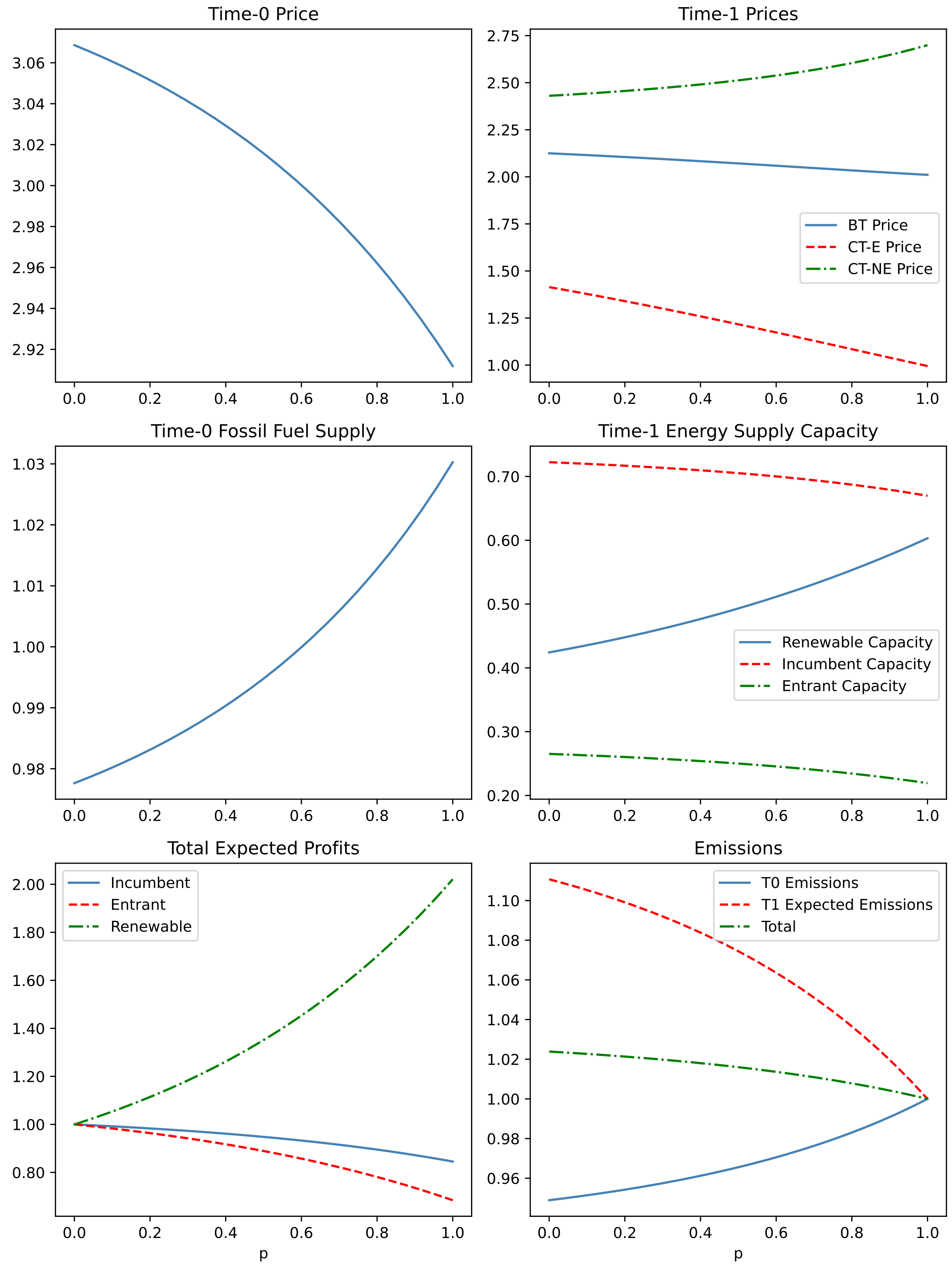

Figure 3: Equilibrium effects of changes in the transition probability. Note that profits for each producer are normalized by their profits for $p = 0$, whereas emissions are normalized for each period and total by the corresponding value for $p = 1$.

period 1 induces the entrant in the fossil fuel market to install less production capacity. As a result, as p increases, total emissions in period 0 rise—driven by an increase in the relative attractiveness for incumbents of producing oil today versus in the future—while expected time-1 emissions fall.

The production and investment choices of the three firms as p increases have the following effect on the prices. First, the increasing supply of green energy pushes the prices down in period 1 in the Breakthrough Technology scenario and in the electrifiable market of the Current Technology scenario. Second, the transfer of fossil fuel production by the incumbent firm from time 1 to time 0 pushes down the price of energy at time 0. Finally, the lower installed capacity from the fossil fuel entrant firm, and the lower level of inventory carried by the incumbent firm into period 1, push up the price in period 1 in the non-electrifiable market of the CT scenario. These different dynamics of energy price between the electrifiable and non-electrifiable markets is due to the fact that, if the technological breakthrough does not realize, the renewable sector will not be able to supply energy to the non-electrifiable sectors of the economy, and supply of energy from the fossil fuel sector is also lower because of the lower investment in production capacity. These results can be formally derived as the following Proposition.

Proposition 1. *As the probability of a technological breakthrough, p, increases:*

- *The current price of energy decreases.*
- *The future price of energy decreases in the Breakthrough Technology scenario and in the electrifiable market of the Current Technology scenario, and increases in the non-electrifiable market of the Current Technology scenario.*

In this context, therefore, government subsidies that increase the probability of technological breakthroughs in period 1 should not translate into a higher price of energy in period zero, but can instead have deflationary effects on the price of energy. Since future expected profits are lower as p increases for both fossil fuel firms in our model, we also have the following result:

Corollary 2. *Announcements of subsidies to the renewable sector, which make the Breakthrough Technology scenario more likely, have a negative effect on the stock price of fossil fuel firms. Moreover, the new fossil fuel entrant firm is affected more negatively than the incumbent fossil fuel producer.*

3.2 Changes in the Tax on Fossil Fuel Emissions

We now turn to the analysis of the effects of the introduction of a tax on carbon emissions in case the Breakthrough Technology scenario realizes. Carbon taxes are extensively analyzed both in the literature and in policy discussions (see Section 1), hence understanding their effect on energy prices in our framework is particularly important.

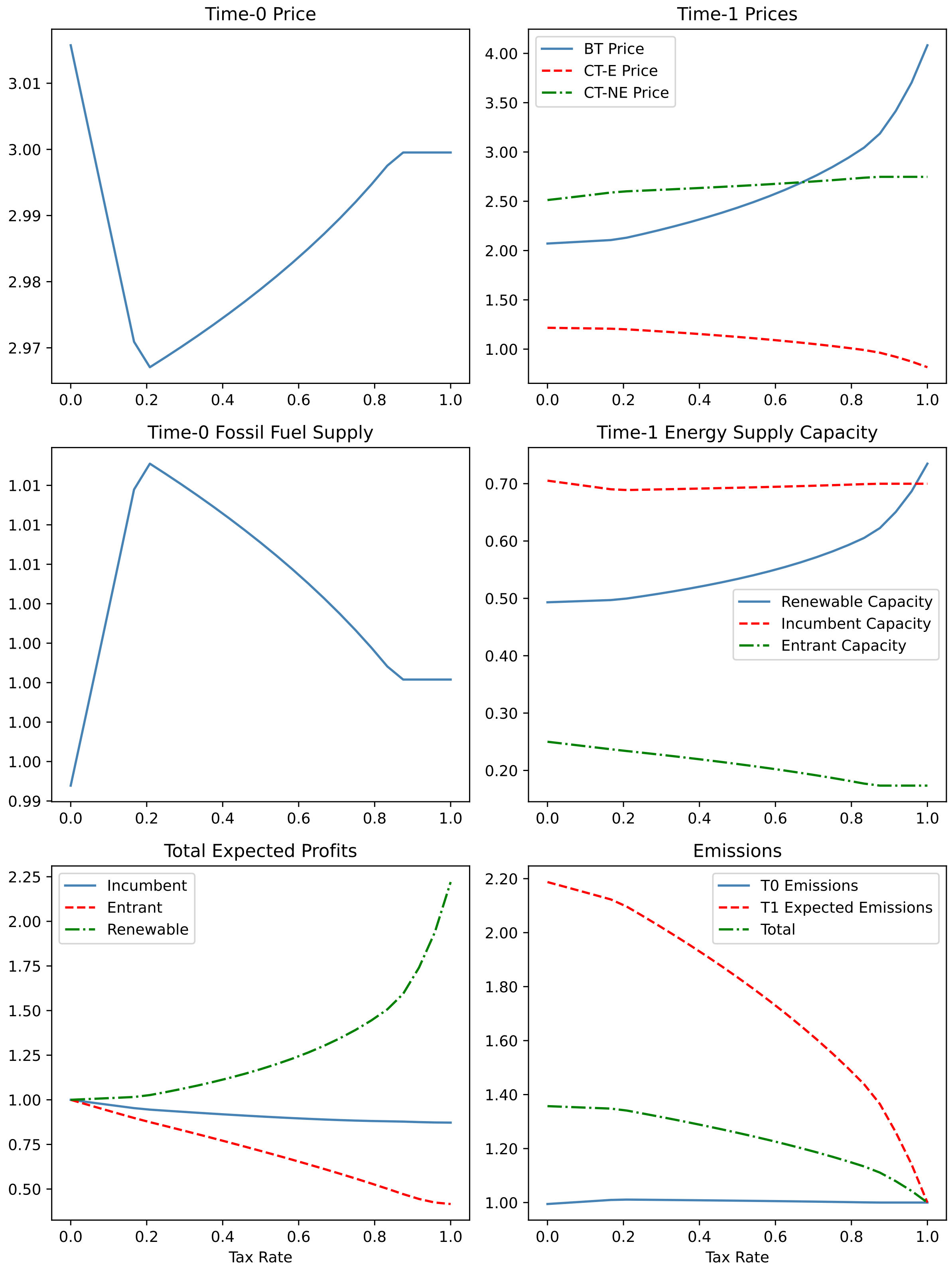

Figure 4: Equilibrium effects of changes in BT tax rate. Note that profits for each producer are normalized by their profits for $p = 0$, whereas emissions are normalized for each period and total by the corresponding value for $p = 1$. BT scenario probability is fixed at $p = 0.5$.

Figure 4 shows how the endogenous quantities in the model change as the tax rate on carbon emissions in the BT scenario increases. We fix a value for the transition probability ($p = 0.5$) and abstract from the fact that carbon taxes might endogenously induce firms to invest more in clean technologies, thus accelerating the transition (Acemoglu et al., 2012; Aghion et al., 2018). We can immediately note an interesting difference compared to the previous case of changes in the transition probability, namely that the effect of the tax rate on the current price of energy is nonmonotone. For low levels of the tax rate, tax increases push down the current price of energy; if the tax rate is high enough, however, then further increases will push up the current price of energy.

In order to understand this result, it is important to note that a tax on carbon emissions affects both the incumbent and the entrant fossil fuel producer. We have therefore two opposite forces affecting the incumbent firm's incentive to supply energy in period 0, which is what drives the potentially counter-intuitive behavior of current price.

On the one hand, expectations of a higher carbon tax in the future should induce the incumbent firm to produce more in period 0, as expected future profits decrease. This has the effect of incentivizing the incumbent firm to increase current supply of energy, thus reducing the current price. This is the standard effect of carbon tax on energy prices.

On the other hand, a future carbon tax reduces investment in new fossil fuel production capacity by entrants. This implies that, if the transition does not occur, the incumbent firm will be able to gain large profits in the non-electrifiable market for energy, where it will be the main energy supplier. This has the effect of inducing the incumbent firm to carry inventory into period 1, thereby decreasing current supply of energy and thus increasing current price.

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

Note that since the incumbent firm has production capacity already in place, it does not have to bear the additional costs of setting up new capacity, and therefore it can exploit the potential high price of energy in the Current Technology scenario. The rightmost region where the response of period 0 price to carbon tax becomes flat corresponds to the case where the tax rate in the BT scenario is so high, and fossil fuel production is so low, that the entrant firm only takes into account the expected price in the CT scenario

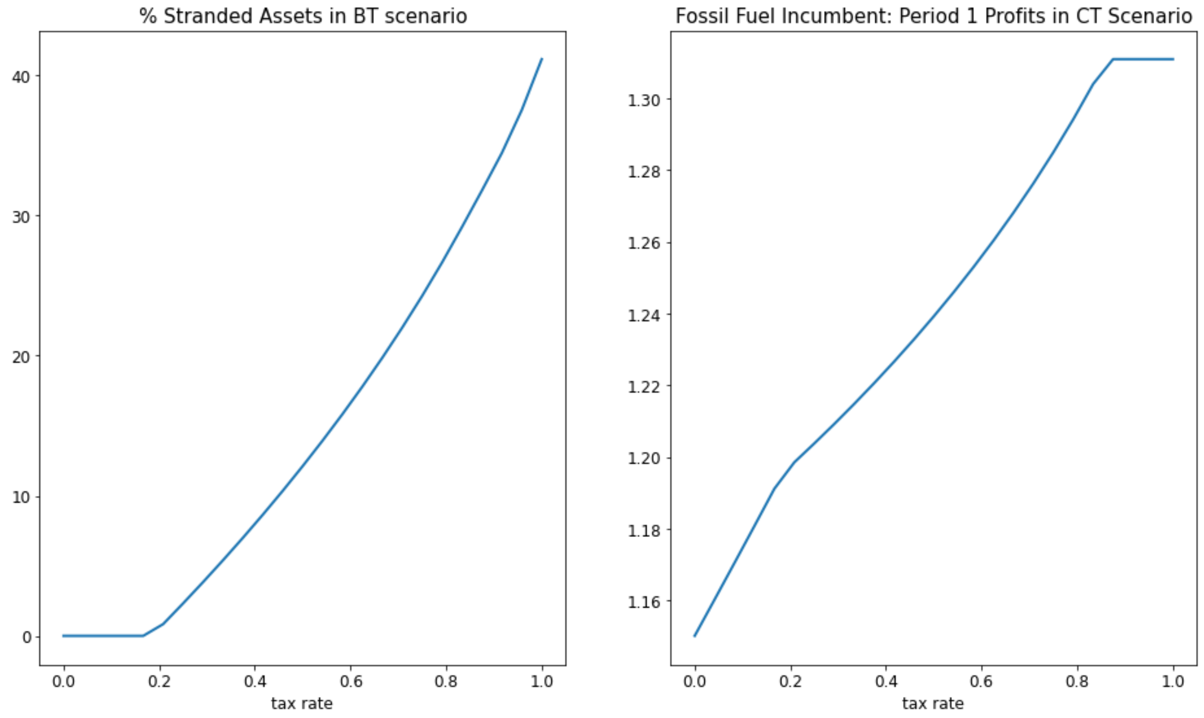

Figure 5: Fossil fuel stranded assets in the BT scenario, and profits in CT scenario, as a function of the tax rate. BT scenario probability is fixed at $p = 0.5$.

when deciding how much capacity to install. 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.

Also note that this strategy exposes the incumbent fossil fuel firm to the possibility of ending up with *stranded assets* in the Breakthrough Technology scenario. Indeed, if the transition does realize, then the carbon firm will be exposed to a very high tax rate. In that case, it might not be profitable to fully use the production capacity that has been left from period 0, and it might actually be optimal to leave fossil fuel reserves unused in the ground. Figure 5 illustrates this result, showing how the proportion of initial reserves of the fossil fuel sector that remains unused in the Breakthrough Technology scenario is increasing in the carbon tax rate. However, and again counter-intuitively, profits for the incumbent fossil fuel firm in the Current Technology scenario are increasing in the tax rate, and so it finds it optimal to let its assets become stranded in the Breakthrough Technology scenario.

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

Proposition 3. *An increase in the tax rate on carbon emissions in the Breakthrough Technology scenario has a nonmonotone effect on the price of energy in period 0:*

- *For* $\tau_{1,BT} \to 0$*, we have* $\frac{dP_0}{d\tau_{1,BT}} \leq 0$*.*
- *For* $\tau_{1,BT} \to 1$*, we have* $\frac{dP_0}{d\tau_{1,BT}} \geq 0$*.*

We also have the following implication related to the profitability and in turn the stock prices of the fossil fuel sector, where we can relate the entrant fossil fuel sector in the model with fossil fuel firms that in practice have low existing production capacity.

Corollary 4. *Announcements of future carbon emission taxes have a more negative effect on the stock price of fossil fuel producers with low existing capacity, compared to producers with large unused reserves that are already in place. This latter set of firms can potentially experience an increase in their stock valuations for intermediate tax increases, if the increase in price in the Current Technology scenario is large enough*[9]*.*

In Appendix C we show that these results are robust to assuming that carbon taxes are on production quantities of fossil fuel firms rather than on their sales.

3.3 Changes in the Tax on new Fossil Fuel Production Capacity

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

Figure 6 shows the implications of changes in this policy instrument on energy prices and the other equilibrium quantities in the model. We can now see that the current price of energy in period 0 always increases as the tax rate on new carbon installed capacity increases. The intuition for this result is that this form of tax only affects the entrant firm, but not the incumbent producer whose reserves of fossil fuels are already in place. Therefore, as the tax rate increases, investment in new production capacity decreases. This implies that the incumbent producer is expecting lower competition from other fossil fuel producers in the future, hence it has the incentive to reduce current supply of energy in expectation of higher future profits, driven by the fact that, in case the transition does not realize, the incumbent will be the main supplier of energy in the non-electrifiable market of the Current Technology scenario. We thus have the following Proposition.

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[9] In our numerical examples, total profits are always slightly decreasing for the incumbent producer

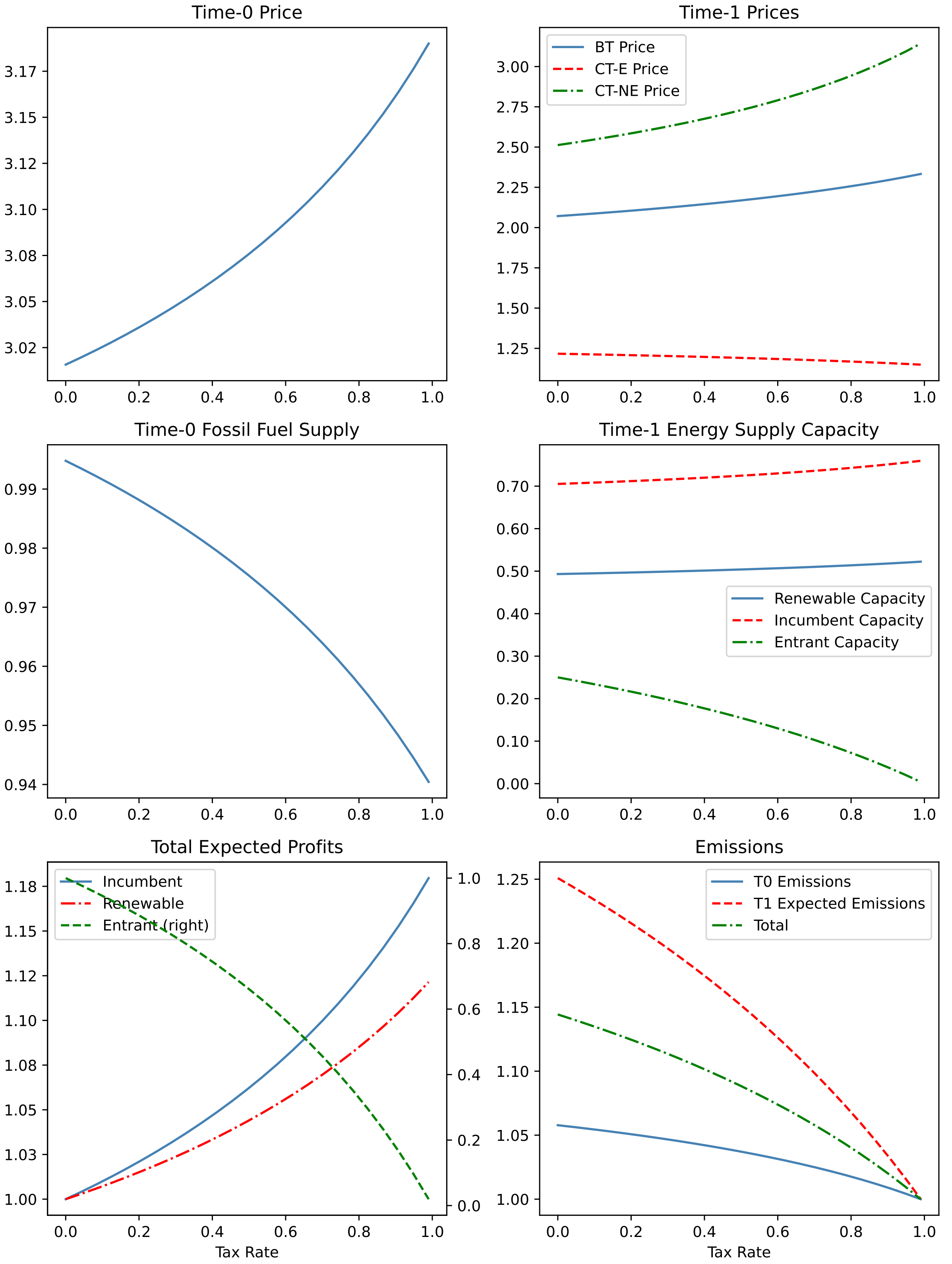

Figure 6: Equilibrium effects of changes in new production capacity tax rate. Note that profits for each producer are normalized by their profits for $p = 0$, whereas emissions are normalized for each period and total by the corresponding value for $p = 1$. BT scenario probability is fixed at $p = 0.5$.

Proposition 5. *An increase in taxes on new fossil fuel production capacity induces the incumbent fossil fuel firm to decrease its current production, thus increasing the price of energy in period 0.*

The following Corollary can also be derived relating to the fossil fuel producers' stock prices, based on the fact that future profits in period 1 are increasing for the incumbent firm in the tax rate, but decreasing for the entrant firm.

Corollary 6. *Announcements of taxes on new fossil fuel production capacity have a more negative effect on the stock price of fossil fuel producers with low existing capacity, compared to producers with large unused reserves that are already in place. The latter set of firms should experience an increase in their stock valuations.*

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

4 Empirical Analysis

We now test the main empirical implications of the model, summarized in Table 1.[10]

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

We then study how transition risk affects the valuation of energy companies. A first prediction of the model is that renewable energy companies should gain from an increase in transition risk, no matter its type. A second prediction is that transition risk also affects fossil fuel companies, but the effects on them are more nuanced—they depend on the type of transition risk (whether the transition risk relates to a potential increase of the cost of emissions, or to an increased probability of a renewables breakthrough) and on whether the company has installed capacity or is an entrant.

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

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

4.1 Climate Transition News Indexes

We build our high-frequency climate transition measures by analyzing news reported in the New York Times (NYT) using GPT-4. We next summarize how we construct these climate news indices, and provide additional details in Appendix E. We first obtain all news articles from the NYT via LexisNexis, covering a 10-year period between 2012 and 2022. We then filtered the universe of NYT news articles, isolating those containing at least one of the terms "carbon" and "renewable," in order to identify articles related to the cost of emissions and the probability of breakthroughs in renewable energy technology. This is a very broad set of articles, that included many items that do not relate to transition risk. We refined our selection and extracted our transition risk measures using a more sophisticated approach, based on GPT-4.

Specifically, we uploaded each of the articles in that subset to OpenAI's GPT-4 model, together with a specific prompt aimed to identify whether the article was relevant for transition risk, and to qualify what type of transition risk it referred to, and to quantify the strength of the content of the news for transition risk probabilities. We analyzed a total of 15,415 news articles, filtered by the above keywords over our 10-year sample period. The prompt to GPT included questions on five topics: 1) U.S. carbon pricing policy; 2) U.S. regulatory or financial costs of carbon emissions; 3) the probability of breakthroughs in renewable energy or battery storage technology; 4) actual technological breakthroughs in renewable energy or battery storage; 5) policies subsidizing or supporting the production of renewable energy. The first two topics capture the introduction of taxes or other policies on carbon emissions, while the latter three topics capture the possibility of technological breakthroughs that improve renewable energy firms' ability to supply energy across all sectors. The outcome of the GPT processing step yields, for each article, a set of scores on each topic. Positive scores indicate more restrictions on the fossil fuel industry or greater support for renewable energy; negative scores indicate relaxation of these restrictions or lower support for renewable energy. Irrelevant articles get a score of 0. Appendix E provides further details on article filtering, the prompt structure for GPT requests, and example GPT outputs for each topic.

To reduce noise, yet maintain power, we conduct our empirical analysis at the weekly level. We therefore aggregate the article-level scores to a weekly level, by summing up each of the 5 scores across all articles in each week, for each of the topics.[11] We then further combine these 5 scores into two categories:[12] the first two (carbon pricing policy and costs of carbon emissions) into the NYT-Emission Cost News Index, and the

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

[12] We combine these indices by taking the arithmetic mean of each index divided by their standard deviation. Appendix E shows more details on aggregating article-level scores to week-level and index combinations.

remaining three (concerning renweable energy and subsidies) into the NYT-Renewable Breakthrough News Index.

Figure 1 plots the time series of the two news indices, with labels indicating related events. The cost of emissions news were on average more positive during the Obama and Biden periods, and more negative the Trump administration. The NYT-Emission Cost News Index spikes around significant climate-related events, such as the Clean Power Plan announcement in 2015, its repeal proposal in 2017, and the Inflation Reduction Act (IRA) in 2022. The intensity of the NYT-Renewable Breakthrough News Index has increased in recent years, with spikes around events favoring renewable energy or announcing technological breakthroughs. Notable examples include the drafting of the Paris Agreement at the 2015 United Nations Climate Change Conference and major breakthroughs in fusion energy in 2022. The correlation between these two indices is 0.39, suggesting that despite some common events affecting both, they capture different aspects of climate transition news.

Armed with these high-frequency indices of transition risk, we now move to the empirical tests of the implications of our model. For now, we focus on the predictions related to changes in transition probability and changes in the likelihood of a carbon tax.

4.2 Oil Futures Price Response to Transition News

We start with the analysis of the model's predictions for energy prices by estimating the following specification:

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

where f_t^h denotes percentage change in the WTI oil futures price from $t-1$ to t for maturity h, ν_t^{EC} represents the AR(1) innovations of the NYT-Emission Cost News Index, and ν_t^{BT} represents the AR(1) innovations of the NYT-Renewable Breakthrough News Index. We scale the residuals by their standard deviation. The regression also includes controls for other major determinants of oil prices, described in more detail below.

We run this regression at both the weekly and monthly frequencies. The weekly frequency provides a tighter link between the oil price movement and the underlying transition news, but is also more noisy. The monthly frequency smooths out some of the noise, and aligns better with some controls that are typically measured on a monthly basis. To perform the analysis at the monthly level, we aggregate the news indexes to a monthly frequency, and then obtain the residuals from an AR(1) model applied to the monthly data.

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

We include in the regression controls that help capture other determinants of oil prices (see a discussion of these variables in Alquist et al. (2013)): the U.S. inflation rate, U.S. real GDP growth, percentage change in M1 money supply, percentage change in M2 money supply, Chicago Fed National Activity Index (CFNAI), Kilian's (2009) global real activity index, and percentage change in zero-coupon treasury yields by Liu and Wu (2019).[14] We also control for the stock market excess returns and an additional demand factor OECD liquid fuel consumption change from EIA. The data spans a 10-year period between 2012 and 2022, aligning with our news index. A detailed overview of the data and its sources is provided in Appendix Table 10. Given that most of these macroeconomic factors are reported monthly, we apply the same values for all weeks within a given month when estimating the model at a weekly frequency.

Table 2 shows the results of the regression. Panel A performs the analysis at the weekly frequency, and Panel B at the monthly frequency. Each column of the table reports a different regression using oil futures prices of different maturities (1 month to 60 months) as well as the two averages described above.

Across all maturities, the results in the table nicely align with the prediction of the model (although the statistical significance varies somewhat across specifications). Oil futures on average decrease in response to news about a possible renewables breakthrough, as oil companies decide to shift production forward in anticipation of higher competition from the renewables sector in the future. On the other hand, the prices increase on news of higher future emission costs; this is consistent with the lowered incentive, predicted in the model, to build new capacity, which can leads to a higher equilibrium price along the transition path. The last line shows that the reactions to the two news terms are significantly different from each other.

Overall, the table shows that, consistent with the predictions of the model, different types of transition risk can have drastically different effects on oil prices. This highlights the importance of distinguishing different sources of transition risk. In the next section, we study the stock price response for different firms in the energy sections, which provides a more nuanced test of the rich implications of the model.

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

[14] The U.S. inflation rate is computed as the percentage change in the U.S. consumer price index (CPI). Both the CFNAI and Kilian's 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 2: Oil Futures Price and NYT Index

	Panel A: Weekly Level							
	CL1 (1)	CL3 (2)	CL6 (3)	CL12 (4)	CL24 (5)	CL60 (6)	Avg 1-12m (7)	Avg 13-60m (8)
Index AR(1) Innovation - Emission Cost	0.0008 (0.0018)	0.0015 (0.0016)	0.0016 (0.0015)	0.0016 (0.0013)	0.0016 (0.0010)	0.0010 (0.0009)	0.0013 (0.0015)	0.0016 (0.0011)
Index AR(1) Innovation - Renewable BT	-0.0035* (0.0020)	-0.0035* (0.0019)	-0.0030* (0.0017)	-0.0025* (0.0015)	-0.0018 (0.0012)	-0.0011 (0.0010)	-0.0032* (0.0017)	-0.0020* (0.0012)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
p-value Emission Cost = Renewable BT	0.19	0.091	0.078	0.067	0.051	0.15	0.086	0.052
R^2	21.4	23.3	24.8	25.0	25.0	19.0	25.5	25.3
Observations	573	573	573	573	573	573	573	573
	Panel B: Monthly Level							
	CL1 (1)	CL3 (2)	CL6 (3)	CL12 (4)	CL24 (5)	CL60 (6)	Avg 1-12m (7)	Avg 13-60m (8)
Index AR(1) Innovation - Emission Cost	0.0127* (0.0068)	0.0113* (0.0061)	0.0111* (0.0057)	0.0096** (0.0048)	0.0078** (0.0035)	0.0033 (0.0033)	0.0109* (0.0057)	0.0081** (0.0038)
Index AR(1) Innovation - Renewable BT	-0.0140** (0.0066)	-0.0125** (0.0060)	-0.0106* (0.0055)	-0.0083* (0.0045)	-0.0055 (0.0036)	-0.0016 (0.0030)	-0.0104* (0.0054)	-0.0056 (0.0039)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
p-value Emission Cost = Renewable BT	0.014	0.018	0.019	0.018	0.018	0.29	0.021	0.021
R^2	61.0	49.9	44.2	43.3	44.9	37.6	49.7	46.8
Observations	131	131	131	131	131	131	131	131

Note: Panel A presents the regression results at weekly frequency, while Panel B shows the results at monthly frequency. Columns (1) to (6) analyze WTI oil futures returns for maturities of 1, 3, 6, 12, 24, and 60 months, respectively. Columns (7) and (8) report on two equally weighted averages of oil futures returns: Column (7) covers returns for futures with maturities ranging from 1 to 12 months, and Column (8) includes futures with maturities from 13 to 24 months, as well as 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 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, 1-month treasury yields are used when analyzing 1-month oil futures, and for the average oil futures returns across 1 to 12 months, we use 1, 3, 6, and 12-month treasury yields. Similarly, for the average returns of oil futures across 13 to 60 months, 24 and 60-month treasury yields are used. The p-values for testing the difference between the coefficients of the NYT-Emission Cost News Index and the NYT-Renewable Breakthrough News Index are also reported. Standard errors are in parentheses and are corrected for heteroscedasticity. Significance levels: * (p<0.10), ** (p<0.05), *** (p<0.01).

4.3 Stock Price Reactions of Energy Firms

In this section, we now study study energy firms' price response to transition risk news. In line with our model, we identify three groups of firms: entrants, incumbents, and renewable firms. We obtain stock prices from CRSP and industry classification (GICS codes) from Compustat; we use the detailed GICS codes to identify fossil fuel firms: we focus on integrated oil companies engaged in the exploration and production of oil and gas, excluding manufacturers of drilling equipment, drilling contractors, oil marketing, and storage and transportation companies that are not directly involved in oil production (see more details in Appendix E).

Having identified fossil fuel companies, we need to subdivide them between entrants and incumbents. We do so by computing the ratio between the dollar amount of developed reserves for oil, natural gas, and natural gas liquids by the dollar amount of total proved reserves for these resources, obtained Compustat. This ratio indicates the extent to which a firm has capitalized on its reserves: firms with a higher ratio have developed more of theirs, suggesting they are incumbents with established operations. Conversely, firms with a lower ratio are classified as entrants: in line with the model, these are firms that have not yet built the infrastructure to develop a large fraction of the reserves that they own.

Finally, to identify renewable firms, we use the holding firms of the Invesco WilderHill Clean Energy ETF, which includes publicly traded companies in the United States engaged in the advancement of cleaner energy and conservation. The number of firms classified as entrants, incumbents, and renewable are 107, 143, and 41, respectively.[15]

Having identified the three groups of firms, we based our empirical analysis on the following regression:

$$R_{i,t} = \alpha_k + \gamma_i + \beta_{1,k}\nu_{k,t} + \beta_{2,k}\text{Inc}_{i,t} + \beta_{3,k}\text{Ren}_{i,t} + \beta_{4,k}\nu_{k,t}\text{Inc}_{i,t} + \beta_{5,k}\nu_{k,t}\text{Ren}_{i,t} + \epsilon_{k,i,t},$$

where $R_{i,t}$ is the market-hedged return of stock i at week t.[16] and γ_i represents firm fixed effects. We include the indexes in this regression after estimating an AR(1) model for each using weekly data; we include in the regression the AR(1) innovations $\nu_{k,t}$, where t is the week and k is the index (either the NYT-Emission Cost News Index or the NYT-Renewable Breakthrough News Index); we focus on AR(1) innovations because returns should reflect the unexpected component of the news, though the results are similar if we include the index directly instead of the innovations. We scale the residuals by their standard deviation. We also include dummies for whether firm i at time t is an incumbent ($\text{Inc}_{i,t}$) or a renewable company ($\text{Ren}_{i,t}$); entrants will have both dummies set to zero and will therefore represent the baseline in the regression. Finally, we include in the regression the interaction of the type of firm (incumbent, entrant, renewable) with the index.

Table 3 reports the results of the regression. The first two columns use the NYT-Emission Cost News Index for the analysis, and the last two columns use the NYT-Renewable Breakthrough News Index. For each index, there are two columns: in the left column, we use all the NYT articles for our analysis, and in the right columns we focus exclusively on the most relevant sections (described in the figure note) of the newspaper.

For readability, the table reports only the coefficients that involve the index term $\nu_{k,t}$. The first coefficient captures the stock price reaction to the two types of news for the baseline group – the entrants. The second and third coefficients capture the additional effect for incumbents and renewables, respectively. We also report the p-value testing the additional effect for renewable firms compared to fossil fuel firms, including both

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[15] Note that a firm could be classified as an entrant or incumbent in different years.

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

Table 3: Stock Returns and NYT Index

	Cost of Emission		Renewable BT	
	(1)	(2)	(3)	(4)
Index AR(1) Innovation	-0.0025***	-0.0022**	-0.0041***	-0.0037***
	(0.0009)	(0.0009)	(0.0010)	(0.0009)
Incumbent × Index AR(1) Innovation	0.0029***	0.0032***	0.0028**	0.0031***
	(0.0010)	(0.0011)	(0.0011)	(0.0012)
Renewable × Index AR(1) Innovation	0.0046***	0.0053***	0.0049***	0.0048***
	(0.0014)	(0.0015)	(0.0013)	(0.0014)
Company FE	Yes	Yes	Yes	Yes
Section Filtering	No	Yes	No	Yes
Remove Market from Stock Returns	Yes	Yes	Yes	Yes
p-value for Renewable - Fossil Fuel	0.025	0.015	0.005	0.017
R^2	0.47	0.48	0.49	0.48
Observations	34,670	34,670	34,670	34,670

Note: Regressions (1) and (2) show coefficients of regressing stock returns on AR(1) innovations of NYT-Emission Cost News Index and the interaction terms with dummies indicating incumbents and renewable firms, controlling for firm fixed effects. Regressions (3) and (4) instead show coefficients of regressing stock returns on AR(1) innovations of NYT-Renewable Breakthrough News 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 focus on energy firms in these regressions. The benchmarks are entrants, and the interactions test the differences between incumbents or renewable firms compared to entrants. The NYT articles we analyzed are categorized by sections. Regression (1) and (3) include all sections, while Regression (2) and (4) only include the top 10 sections by frequency to further reduce noise from analyzing non-related sections like 'travel'. The 10 sections are 'business financial', 'national', 'foreign', 'metropolitan', 'science', 'climate', 'us', 'editorial', 'opinion', 'business'. We also report the p-value for testing the difference between renewable firms and fossil fuel firms, including both incumbents and entrants. Standard errors are in parentheses and are clustered at the company level. Significance levels: * (p<0.10), ** (p<0.05), *** (p<0.01).

incumbents and entrants.

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

More interestingly from the perspective of the model, we also find differential price movements for entrants and incumbents. When news arrives of higher emission costs, we find that entrants' stock price drops, but incumbents' price is zero or slightly positive, exactly in line with the predictions of the model: entrants are hurt by the increased potential restrictions, whereas incumbents can rely on their inventory to benefit if the transition does not occur. Finally, in response to positive news on a breakthrough in renewable energy technology, once again entrants' price drops significantly, and incumbents' price drops as well though less strongly so (and the effect is still statistically significant).

Overall, these results line up closely with the main predictions of the theoretical model. Appendix E.4 reports a number of robustness tests on this analysis. In particular, the results are robust to reconstructing the indices based on alternative methodological choices. We also show that our results are similar when we split fossil fuel firms by different developed reserves ratio percentiles.

5 Optimal Climate Policy

We now return to our model to analyze optimal climate policy. In the model and its analysis (Sections 2 and 3 respectively), we took the two tax instruments $(\tau_{1,BT}, \hat{\tau}_0)$ as exogenously given. We now consider the problem of a social planner which can choose how to optimally set these instruments to maximize consumer welfare, in the presence of a negative externality associated with carbon emissions.

5.1 Optimal Carbon Tax

Let us first focus on the optimal carbon tax rate that the planner might choose to set in case the transition to a green economy is successful. We define social welfare (W) based on its components in each period and technology scenario as

$$W := W_0 + pW_{1,BT} + (1-p)W_{1,CT} \tag{12}$$

where

$$W_0 := \log\left(\frac{W}{P_0}\right) - \frac{\lambda}{2} f_0^2 \tag{13}$$

$$W_{1,BT} := \log\left(\frac{W}{P_{1,BT}}\right) - \frac{\lambda}{2}(f_{1,BT}^I + f_{1,BT}^E)^2 \tag{14}$$

$$W_{1,CT} := q\log\left(\frac{W}{P_{1,E}}\right) + (1-q)\log\left(\frac{W}{P_{1,NE}}\right) - \frac{\lambda}{2}(f_{1,E}^I + f_{1,E}^E + f_{1,NE}^I + f_{1,NE}^E)^2 \tag{15}$$

where λ is a parameter that captures the extent to which emissions are socially costly, and we associate to it a quadratic loss function.

We assume that if the Breakthrough Technology scenario realizes then the social planner chooses the tax rate that solves

$$\max_{\tau_{1,BT}\in[0,1]} W_{1,BT}(\tau_{1,BT})$$

where we have made explicit the fact that equilibrium quantities, and consequently social welfare, depend on the chosen tax rate. Note that we do not allow the planner to choose the tax rate in period 0 in order to maximize total welfare (12). This is because such a policy would not be time-consistent, as in case the BT scenario realizes, then the planner would have an incentive to deviate and choose the tax rate that maximizes welfare in that scenario. In our model, agents are rational and forward-looking, so they anticipate the government's behavior. Therefore, we assume that the optimal tax in the BT scenario is set in order to maximize (14). However, note that even though the tax is only imposed in period 1 of the economy, it also affects time-0 outcomes. In particular, expectation of future taxes have an impact on the decision of the incumbent fossil fuel firm on how much to produce in period 0, and on the decision of the entrant firm on how much production capacity to install.

Figure 7 plots key model outcomes with an endogenous tax in the BT scenario as a function of the transition probability p, fixing a value for the penalty parameter λ. The top panel shows the optimal tax rate chosen by the planner. The middle panel shows the percentage of the incumbent fossil fuel producer's stranded assets in the BT scenario, and the last panel shows total welfare.

We can see that our model predicts a tax rate in the BT scenario which is decreasing in the transition probability. The intuition behind this result is that, as p increases, both the incumbent and the entrant fossil fuel producers have a lower production capacity at the beginning of period 1. Therefore, the planner does not need to set a high tax rate to limit carbon emissions, as fossil fuel production capacity is already lower. It follows that under this optimal tax policy the fraction of stranded assets of the incumbent fossil fuel firm decreases with the transition probability p. Our result can be viewed as broadly consistent with Lemoine and Traeger (2014), who argue that the optimal carbon tax should be increasing in the probability of reaching a "climate tipping point", which in our model can roughly be interpreted as being equal to $(1 - p)$.

Figure 7 also shows how total (expected) social welfare changes over the climate transition when the government is setting the carbon tax in an optimal way. Note that this calculation also takes into account energy consumption and carbon emissions in period 0 and in the CT scenario, despite the fact that the planner is not taking them into account when setting the optimal tax in the BT scenario. However, we can see that the government is able to obtain an increasing social welfare over the transition path to a green economy through the optimal tax policy in the BT scenario.

Finally, Figure 8 shows the evolution of the endogenous quantities in the model as the transition probability p increases, taking into account the endogenous government reaction through the carbon tax rate. We saw in Section 3 that carbon taxes in the Breakthrough Technology scenario can potentially cause an increase in the energy price in period 0. However, by choosing the tax rate optimally as p increases, the planner is able to generate a smooth transition to a green economy, with the energy price in period 0 that does not increase as the transition becomes more likely, and in fact the price is decreasing in p.

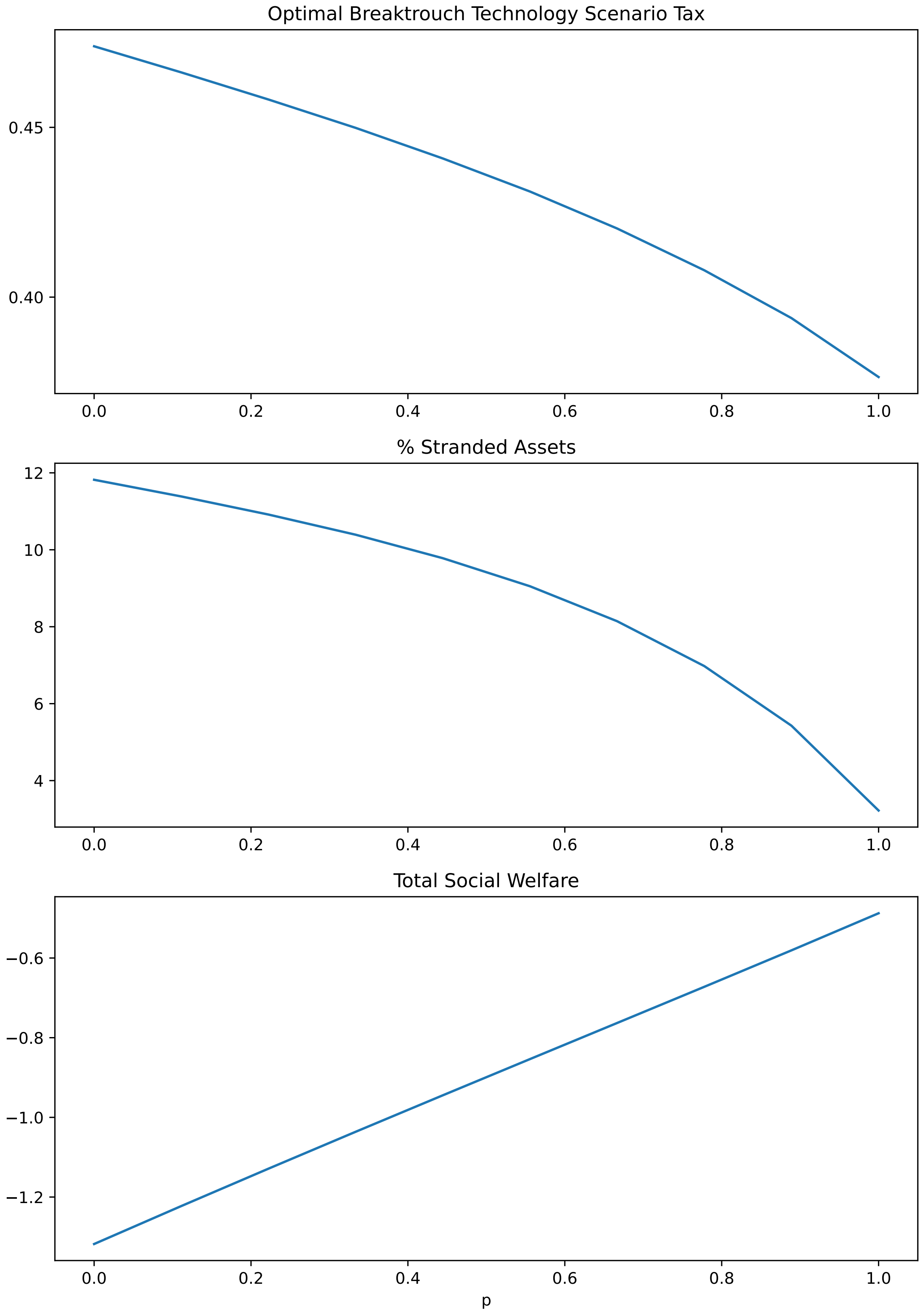

Figure 7: Optimal carbon tax and fossil fuel stranded assets. The value for the carbon emissions penalty parameter is fixed at $\lambda = 1$.

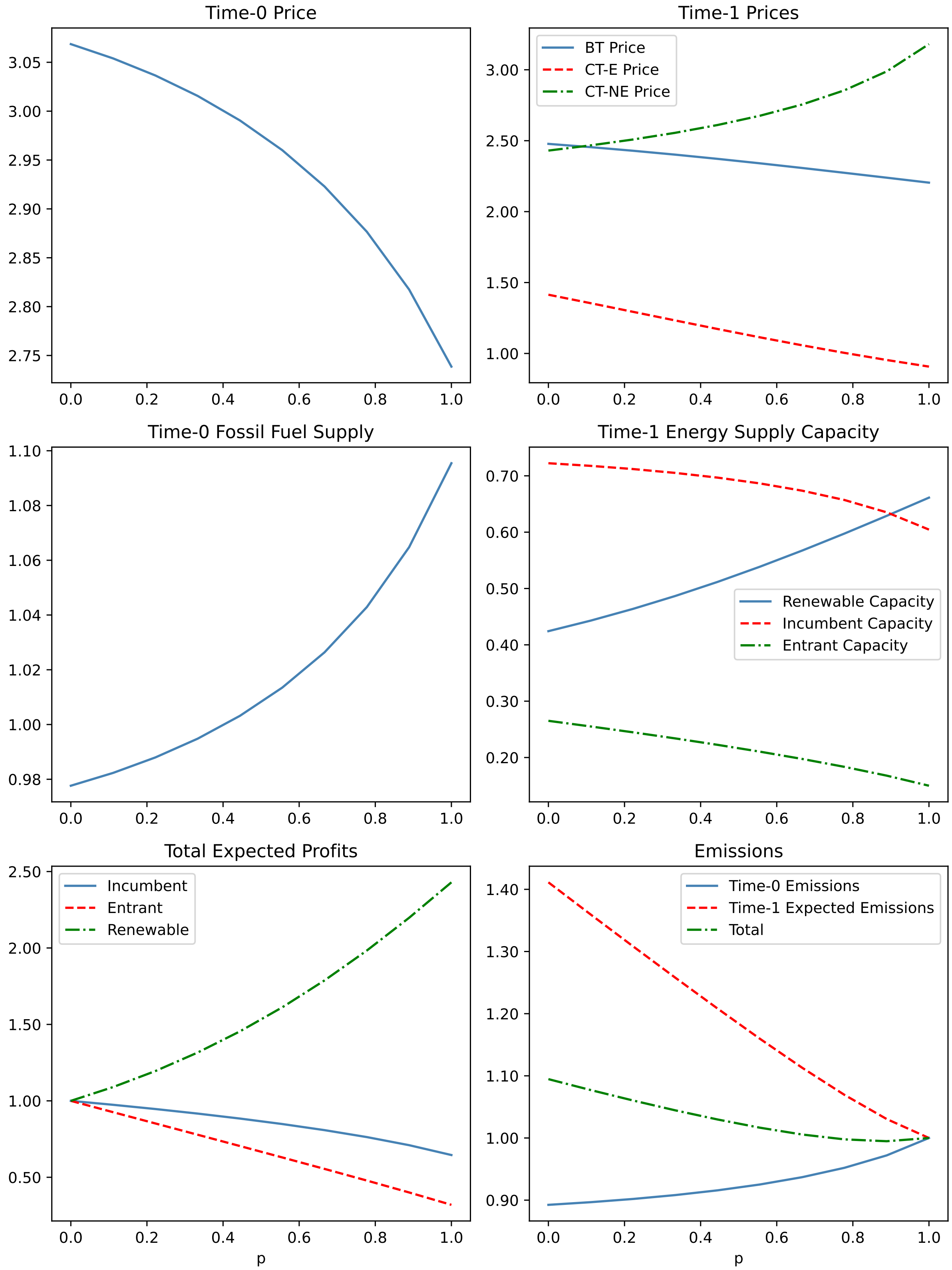

Figure 8: Changes in transition probability with endogenous BT carbon tax. The value for the carbon emissions penalty parameter is fixed at $\lambda = 1$.

5.1.1 Carbon taxes in both technology scenarios

Up to this point, we have assumed that the social planner will only tax the fossil fuel sector in case the Breakthrough Technology scenario realizes. We verify in Appendix B that in case the Current Technology scenario realizes and the size of the electrifiable market is small, then the planner would optimally choose to tax the fossil fuel sector less than in the Breakthrough Technology scenario. The intuition is that if the technological breakthrough does not realize, then the economy is still largely dependent on the fossil fuel sector for supply of energy. Taxes on carbon emissions would therefore have a larger negative welfare effect in this state compared to the state where there is a renewable sector that is able to supply the energy needed by the economy. Hence, the planner would optimally set a lower tax when there is no technological breakthrough. We thus abstract for now from the issue of solving for optimal taxes in both states in period 1, and leave it as a future extension of the model.

5.2 Optimal Tax on New Fossil Fuel Capacity

Suppose now that the planner can choose a tax to be imposed on newly created fossil fuel capacity. Since the tax is imposed in period 0, the planner would choose it by taking into account also the effects in period 1. Therefore, the optimal tax now solves $\max_{\hat{\tau}_0 \in [0,1)} W(\hat{\tau}_0)$.

Figure 9 shows how the optimal tax on newly installed fossil fuel capacity changes as the probability of the BT scenario increases. We can see that unlike for the carbon tax the tax on new fossil fuel capacity is increasing in the transition probability p. The intuition for this result is that as the transition becomes more likely, it is not optimal to have newly installed fossil fuel production capacity. This is because the renewable sector will be able to satisfy future demand for energy with a greater likelihood. In our numerical simulation of the model, it is actually optimal not to have newly installed capacity at all for high enough transition probabilities.

Figure 10 shows the behavior of the equilibrium quantities over the transition under an optimal capacity tax policy. As with the carbon tax, we can see that the optimal policy is able to ensure a smooth transition by avoiding increases in the price of energy in period 0 as the breakthrough scenario becomes more likely. This result, together with the result on the optimal carbon tax, suggests that in order to minimize the damage to the economy from high energy prices due to transition risk, it is optimal to induce the fossil fuel sector to use efficiently its existing reserves, rather than installing new fossil fuel production capacity. Indeed, in Figure 9 where carbon taxes are not imposed, we can see that the fraction of stranded assets is always equal to zero over the transition.

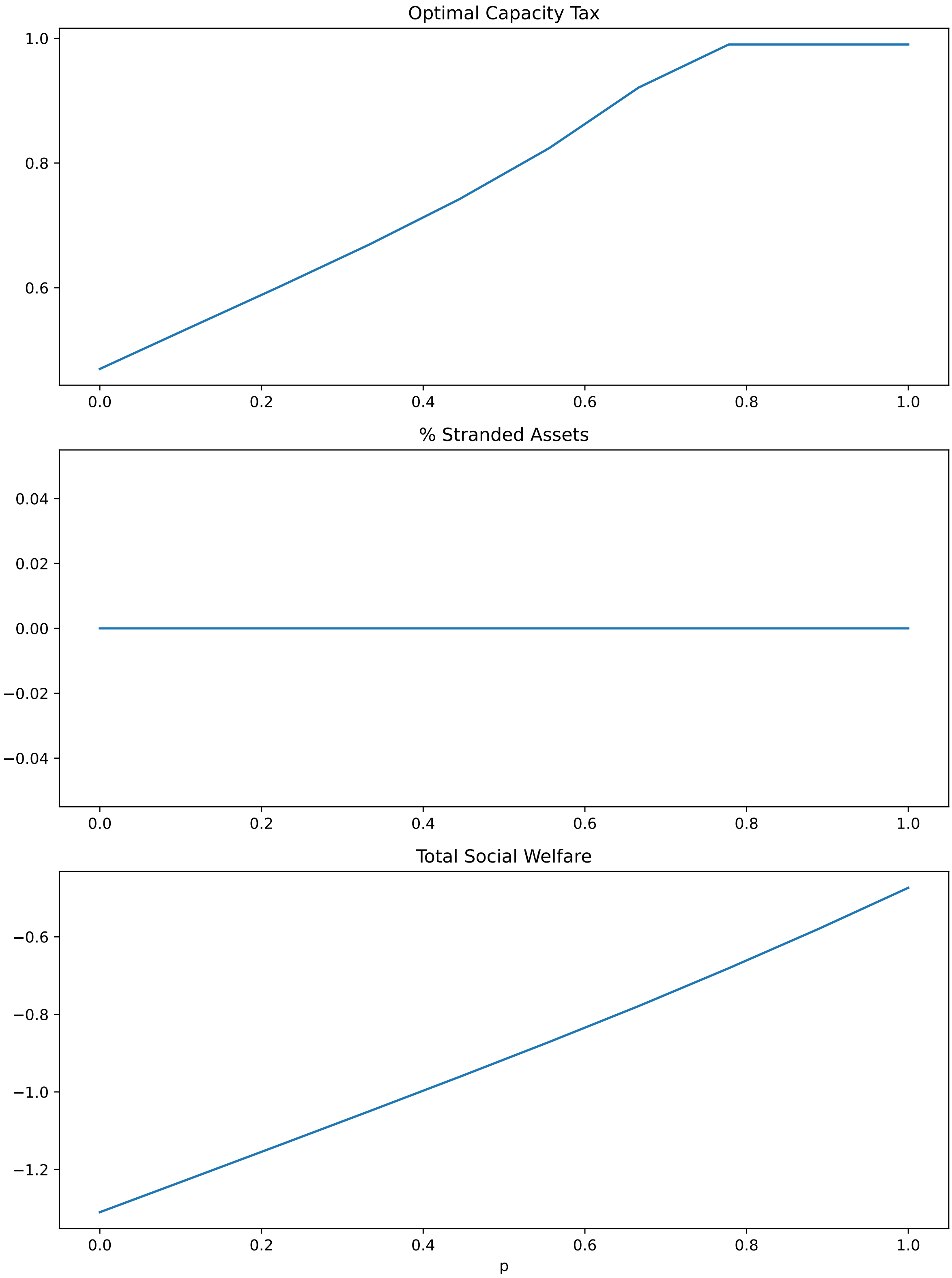

Figure 9: Optimal tax on new capacity and fossil fuel stranded assets. The value for the carbon emissions penalty parameter is fixed at $\lambda = 1$.

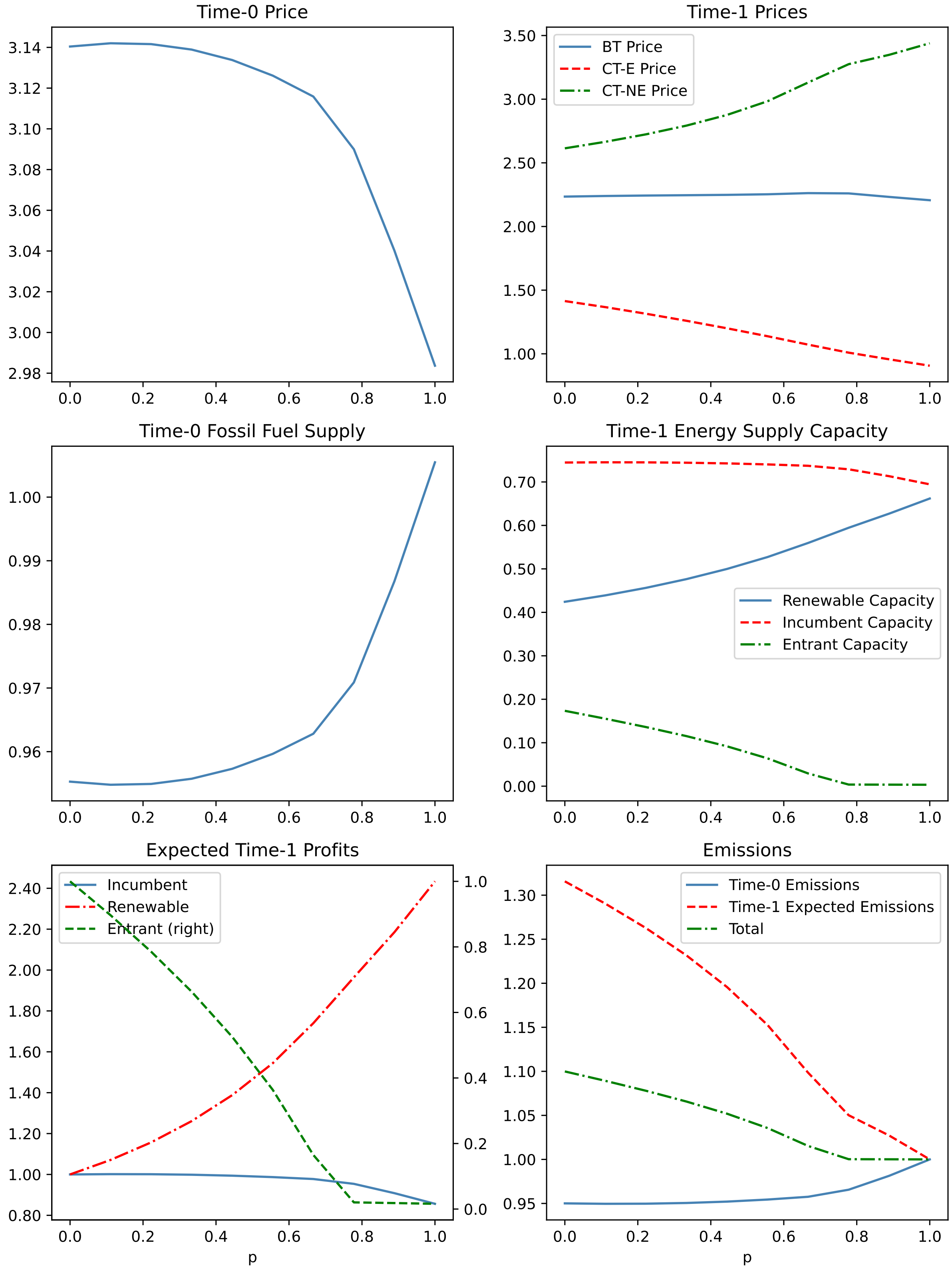

Figure 10: Changes in transition probability with endogenous tax on new capacity.

6 Conclusions

We presented a model that can be used to investigate how transition risks can affect the price of energy. Expectations of carbon taxes in the future have the effect of lowering expected profits for fossil fuel firms, which should incentivize them to increase their current energy supply thus pushing down the price. However, as the economy moves towards a green economy, fossil fuel firms also have less incentive to build new production capacity. In response, existing producers might eventually decide to optimally reduce current fossil fuel supply in the hope of selling in the future at a high price, in a scenario where the renewable sector fails to keep up with the level of technological development that is necessary in order to reliably supply energy to the entire economy. Imposing high carbon taxes in this scenario raises a commitment problem, as this would imply large welfare losses for the economy. Therefore, this mechanism would have the effect of increasing the price of energy before the transition occurs.

Empirically, this counter-intuitive implication of the model on energy prices translates into a positive stock price reaction of fossil fuel producers with large existing capacity, when the market learns about news of future carbon taxes or restrictions on new fossil fuel production capacity. In contrast, technological breakthroughs in renewable technology always depress prices of energy and fossil fuel firms, and all transition risks (breakthroughs, carbon taxes, drilling restrictions) enhance prices of renewable firms. Different transition risks can therefore affect energy prices and sub-sectors differently. We find support in data for heterogeneous effects implied by the model.

We then showed how policy instruments such as carbon taxes and taxes on new fossil fuel capacity can be set optimally in order to minimize this risk. As the renewable sector becomes more technologically sophisticated, the government should react by increasing the tax on new production capacity and lowering the tax on carbon emissions. This should induce the fossil fuel sector to use its existing production capacity in an efficient way over the transition period, thus reducing the risk of energy supply shortages which translate in higher prices.

Our current model can be extended in several interesting directions. First, the model can be set into an infinite horizon setting, in order to obtain additional insights and quantitative estimates of the effects that we have described. Second, we could consider subsidies to the renewable sector as an additional policy instrument, in line with what we are currently seeing in the US. Indeed, our model currently suggests that policies that increase the probability of the Breakthrough Technology scenario should not induce increases in energy prices. Third, we could make the transition probability endogenous to the tax policy, which would capture the idea that as the fossil fuel sector becomes subject to higher taxes, investors in the economy can reallocate resources to the development of green technologies which would accelerate the transition (Acemoglu et al., 2012; Acharya et al., 2023). Finally, while we focused in our empirical work on energy prices and stock prices of energy subsectors, model implications on inventories, investments and production are also worthy of empirical scrutiny.

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Appendix A Model Solution

A.1 Solution to the incumbent fossil fuel producer's problem

Let $\bar{f}_1 = \bar{f}_0 - f_0$. 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

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

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

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

and, consequently,

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

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

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

and

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

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

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

$$f_1^{I,CT,S} = \begin{cases} \kappa_1(1 - \tau_1^{CT})P_1^{CT,S} & if\ P_1^{CT,S} > P_1^{CT,NS} \\ \frac{1}{2}\kappa_1(1 - \tau_1^{CT})P_1^{CT,S} & if\ P_1^{CT,S} = P_1^{CT,NS} \\ 0 & if\ P_1^{CT,S} < P_1^{CT,NS} \end{cases}$$

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

which gives

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

We have therefore different cases to consider.

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

$$\begin{aligned} \max_{0\leq f_0\leq \bar{f}_0}\ & f_0P_0 - \frac{1}{2\kappa_1}f_0^2 \\ & + p\frac{\kappa_1}{2}(1-\tau_{1,BT})^2(P_{1,BT})^2 \\ & + (1-p)\frac{\kappa_1}{2}(1-\tau_{1,CT})^2(P_{1,*})^2 \end{aligned}$$

   which gives the following interior solution

$$f_0 = \kappa_1 P_0.$$

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

$$\begin{aligned} \max_{0\leq f_0\leq \bar{f}_0}\ & f_0P_0 - \frac{1}{2\kappa_1}f_0^2 \\ & + p\left[(1-\tau_{1,BT})P_{1,BT}(\bar{f}_0 - f_0) - \frac{1}{2\kappa_1}(\bar{f}_0 - f_0)^2\right] \\ & + (1-p)\frac{\kappa_1}{2}(1-\tau_{1,CT})^2(P_{1,*})^2 \end{aligned}$$

   which gives the following interior solution

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

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

$$\begin{aligned} \max_{0\leq f_0\leq \bar{f}_0}\ & f_0P_0 - \frac{1}{2\kappa_1}f_0^2 \\ & + p\frac{\kappa_1}{2}(1-\tau_{1,BT})^2(P_{1,BT})^2 \\ & + (1-p)\left[(1-\tau_{1,CT})P_{1,*}(\bar{f}_0 - f_0) - \frac{1}{2\kappa_1}(\bar{f}_0 - f_0)^2\right] \end{aligned}$$

which gives the following interior solution

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

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

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

which gives the following interior solution

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

A.2 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 $\bar{f}_1 = \hat{f}_1$. We have therefore different cases to consider in period 0.

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

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

which gives the following interior solution

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

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

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

which gives the following interior solution

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

3. Production constraint always binding: this gives

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

which gives the following interior solution

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

Appendix B Proofs

B.1 Proof of Proposition 1

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

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

$$\frac{W}{P_0} = f_0 \tag{16}$$

$$\frac{W}{P_{1,BT}} = C + \bar{f}_0 - f_0 + \hat{f}_1 \tag{17}$$

$$q\frac{W}{P_{1,E}} = C \tag{18}$$

$$(1-q)\frac{W}{P_{1,NE}} = \bar{f}_0 - f_0 + \hat{f}_1 \tag{19}$$

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

$$-\frac{W}{(P_0)^2}\frac{dP_0}{dp} = \frac{df_0}{dp} \tag{20}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{dp} = \frac{dC}{dp} - \frac{df_0}{dp} + \frac{d\hat{f}_1}{dp} \tag{21}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{dp} = \frac{dC}{dp} \tag{22}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{dp} = -\frac{df_0}{dp} + \frac{d\hat{f}_1}{dp} \tag{23}$$

Moreover, optimal quantities are given by

$$\hat{f}_1 = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[pP_{1,BT} + (1-p)P_{1,NE}\Big] \tag{24}$$

$$f_0 = \frac{1}{2}\bar{f}_0 + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\Big[pP_{1,BT} + (1-p)P_{1,NE}\Big] \tag{25}$$

$$C = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big] \tag{26}$$

which implies

$$\frac{d\hat{f}_1}{dp} = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[P_{1,BT} - P_{1,NE} + p\frac{dP_{1,BT}}{dp} + (1-p)\frac{dP_{1,NE}}{dp}\Big] \tag{27}$$

$$\frac{df_0}{dp} = \frac{\kappa_1}{2}\frac{dP_0}{dp} - \frac{\kappa_1}{2}\Big[P_{1,BT} - P_{1,NE} + p\frac{dP_{1,BT}}{dp} + (1-p)\frac{dP_{1,NE}}{dp}\Big] \tag{28}$$

$$\frac{dC}{dp} = \delta\Big[P_{1,BT} - P_{1,E} + p\frac{dP_{1,BT}}{dp} + (1-p)\frac{dP_{1,E}}{dp}\Big] \tag{29}$$

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

$$P_{1,BT} - P_{1,NE} + p\frac{dP_{1,BT}}{dp} + (1-p)\frac{dP_{1,NE}}{dp} > 0 \tag{30}$$

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

Since $\frac{dP_0}{dp} \leq 0$, we can repeat the previous steps to show that $\frac{df_0}{dp} \geq 0$, $\frac{d\hat{f}_1}{dp} \leq 0$, $\frac{dP_{1,NE}}{dp} \geq 0$, and $\frac{dP_{1,BT}}{dp} \leq 0$. Then, suppose again by contradiction that $\frac{dC}{dp} < 0$. From (22), it follows that $\frac{dP_{1,E}}{dp} > 0$, and using (21), we have $\frac{dP_{1,BT}}{dp} > 0$. This is a contradiction, so we must have $\frac{dC}{dp} \geq 0$, and then from (22) it follows immediately that $\frac{dP_{1,E}}{dp} \leq 0$.

□

B.2 Proof of Proposition 3

First, consider the case where $\tau_{1,BT} \to 0$. It follows that the fossil fuel production constraint is binding in both scenarios in period 1, so that (16)-(19) hold. Differentiating both sides of the market clearing conditions with respect to $\tau_{1,BT}$, we obtain

$$-\frac{W}{(P_0)^2}\frac{dP_0}{\tau_{1,BT}} = \frac{df_0}{d\tau_{1,BT}} \tag{31}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} - \frac{df_0}{d\tau_{1,BT}} + \frac{d\hat{f}_1}{d\tau_{1,BT}} \tag{32}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} \tag{33}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\tau_{1,BT}} = -\frac{df_0}{d\tau_{1,BT}} + \frac{d\hat{f}_1}{d\tau_{1,BT}} \tag{34}$$

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

$$\hat{f}_1 = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\Big] \tag{35}$$

$$f_0 = \frac{1}{2}\bar{f}_0 + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\Big] \tag{36}$$

$$C = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big] \tag{37}$$

which implies that we have

$$\frac{d\hat{f}_1}{d\tau_{1,BT}} = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\left[-pP_{1,BT} + p(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,NE}}{d\tau_{1,BT}}\right] \tag{38}$$

$$\frac{df_0}{d\tau_{1,BT}} = \frac{\kappa_1}{2}\frac{dP_0}{d\tau_{1,BT}} - \frac{\kappa_1}{2}\left[-pP_{1,BT} + p(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,NE}}{d\tau_{1,BT}}\right] \tag{39}$$

$$\frac{dC}{d\tau_{1,BT}} = \delta\left[p\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,E}}{d\tau_{1,BT}}\right] \tag{40}$$

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 (31), $\frac{df_0}{d\tau_{1,BT}} < 0$. It follows from (39) that

$$-pP_{1,BT} + p(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0 \tag{41}$$

which in turn implies, using (38), that $\frac{d\hat{f}_1}{d\tau_{1,BT}} > 0$. Using (34), it follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$, which implies, using (41), that $\frac{dP_{1,BT}}{d\tau_{1,BT}} > 0$. It then follows from (32) that $\frac{dC}{d\tau_{1,BT}} < 0$

which in turn implies from (33) that $\frac{dP_{1,E}}{d\tau_{1,BT}} > 0$. But then, (40) implies that $\frac{dC}{d\tau_{1,BT}} > 0$, a contradiction. Therefore, it must be that $\frac{dP_0}{d\tau_{1,BT}} \leq 0$.

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

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

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

$$\frac{W}{P_{1,BT}} = C + f^I_{1,BT} + \hat{f}_1 \tag{43}$$

$$q\frac{W}{P_{1,E}} = C \tag{44}$$

$$(1-q)\frac{W}{P_{1,NE}} = \bar{f}_0 - f_0 + \hat{f}_1 \tag{45}$$

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

$$-\frac{W}{(P_0)^2}\frac{dP_0}{d\tau_{1,BT}} = \frac{df_0}{d\tau_{1,BT}} \tag{46}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} + \frac{df^I_{1,BT}}{d\tau_{1,BT}} + \frac{d\hat{f}_1}{d\tau_{1,BT}} \tag{47}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} \tag{48}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\tau_{1,BT}} = -\frac{df_0}{d\tau_{1,BT}} + \frac{d\hat{f}_1}{d\tau_{1,BT}} \tag{49}$$

Optimal quantities are given by

$$f_0 = \frac{\kappa_1}{2-p}P_0 - \frac{(1-p)\kappa_1}{2-p}P_{1,NE} + \frac{1-p}{2-p}\bar{f}_0 \tag{50}$$

$$\hat{f}_1 = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\Big[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\Big] \tag{51}$$

$$f^I_{1,BT} = \kappa_1(1-\tau_{1,BT})P_{1,BT} \tag{52}$$

$$C = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big] \tag{53}$$

which implies

$$\frac{df_0}{d\tau_{1,BT}} = \frac{\kappa_1}{2-p}\frac{dP_0}{d\tau_{1,BT}} - \frac{(1-p)\kappa_1}{2-p}\frac{dP_{1,NE}}{d\tau_{1,BT}} \tag{54}$$

$$\frac{d\hat{f}_1}{d\tau_{1,BT}} = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\left[-pP_{1,BT} + p(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,NE}}{d\tau_{1,BT}}\right] \tag{55}$$

$$\frac{df^I_{1,BT}}{d\tau_{1,BT}} = \kappa_1\left[-P_{1,BT} + (1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}}\right] \tag{56}$$

$$\frac{dC}{d\tau_{1,BT}} = \delta\left[p\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,E}}{d\tau_{1,BT}}\right] \tag{57}$$

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 (48) we have $\frac{dP_{1,E}}{d\tau_{1,BT}} > 0$. This implies, using (57), that $\frac{dP_{1,BT}}{d\tau_{1,BT}} < 0$. Using (56) we then have $\frac{df^I_{1,BT}}{d\tau_{1,BT}} < 0$, and using (47) we have $\frac{d\hat{f}_1}{d\tau_{1,BT}} > 0$. Then, from (55) we find $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, which implies using (49) that $\frac{df_0}{d\tau_{1,BT}} > 0$. But then (46) implies $\frac{dP_0}{d\tau_{1,BT}} < 0$ and (54) 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, (47) implies $\frac{d\hat{f}_1}{d\tau_{1,BT}} < 0$, and using (55) we get $\frac{d\hat{P}_{1,NE}}{d\tau_{1,BT}} < 0$. But then (49) implies $\frac{df_0}{d\tau_{1,BT}} < 0$, (46) implies $\frac{dP_0}{d\tau_{1,BT}} > 0$, and (54) implies $\frac{d\hat{P}_{1,NE}}{d\tau_{1,BT}} > 0$, a contradiction. Hence, $\frac{df^I_{1,BT}}{d\tau_{1,BT}} \leq 0$.

Then, suppose that $\frac{d\hat{f}_1}{d\tau_{1,BT}} > 0$. From (55) we have $\frac{d\hat{P}_{1,NE}}{d\tau_{1,BT}} > 0$, from (49) we have $\frac{df_0}{d\tau_{1,BT}} > 0$, from (46) we have $\frac{dP_0}{d\tau_{1,BT}} < 0$ and from (54) we have $\frac{d\hat{P}_{1,NE}}{d\tau_{1,BT}} < 0$, a contradiction. Therefore, $\frac{d\hat{f}_1}{d\tau_{1,BT}} \leq 0$

For the next step, suppose that $\frac{d\hat{P}_{1,NE}}{d\tau_{1,BT}} < 0$. Then, using (49) we have $\frac{df_0}{d\tau_{1,BT}} < 0$, using (46) we have $\frac{dP_0}{d\tau_{1,BT}} > 0$, and using (54) we get $\frac{d\hat{P}_{1,NE}}{d\tau_{1,BT}} > 0$, a contradiction. Therefore, $\frac{d\hat{P}_{1,NE}}{d\tau_{1,BT}} \geq 0$.

Finally, suppose that $\frac{dP_0}{d\tau_{1,BT}} < 0$. Using (46), this implies that $\frac{df_0}{d\tau_{1,BT}} > 0$. From (54), it then follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$, a contradiction. This proves that we must have $\frac{dP_0}{d\tau_{1,BT}} \geq 0$.

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

$$\frac{W}{P_0} = f_0 \tag{58}$$

$$\frac{W}{P_{1,BT}} = C + f^I_{1,BT} + f^E_{1,BT} \tag{59}$$

$$q\frac{W}{P_{1,E}} = C \tag{60}$$

$$(1-q)\frac{W}{P_{1,NE}} = \bar{f}_0 - f_0 + \hat{f}_1 \tag{61}$$

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

$$-\frac{W}{(P_0)^2}\frac{dP_0}{d\tau_{1,BT}} = \frac{df_0}{d\tau_{1,BT}} \tag{62}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} + \frac{df^I_{1,BT}}{d\tau_{1,BT}} + \frac{df^E_{1,BT}}{d\tau_{1,BT}} \tag{63}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\tau_{1,BT}} = \frac{dC}{d\tau_{1,BT}} \tag{64}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\tau_{1,BT}} = -\frac{df_0}{d\tau_{1,BT}} + \frac{d\hat{f}_1}{d\tau_{1,BT}} \tag{65}$$

Optimal quantities are now given by

$$f_0 = \frac{\kappa_1}{2-p}P_0 - \frac{(1-p)\kappa_1}{2-p}P_{1,NE} + \frac{1-p}{2-p}\bar{f}_0 \tag{66}$$

$$\hat{f}_1 = \frac{(1-p)\kappa_1\kappa_2}{\kappa_1+(1-p)\kappa_2}P_{1,NE} \tag{67}$$

$$f^I_{1,BT} = f^E_{1,BT} = \kappa_1(1-\tau_{1,BT})P_{1,BT} \tag{68}$$

$$C = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big] \tag{69}$$

which implies

$$\frac{df_0}{d\tau_{1,BT}} = \frac{\kappa_1}{2-p}\frac{dP_0}{d\tau_{1,BT}} - \frac{(1-p)\kappa_1}{2-p}\frac{dP_{1,NE}}{d\tau_{1,BT}} \tag{70}$$

$$\frac{d\hat{f}_1}{d\tau_{1,BT}} = \frac{(1-p)\kappa_1\kappa_2}{\kappa_1+(1-p)\kappa_2}\frac{dP_{1,NE}}{d\tau_{1,BT}} \tag{71}$$

$$\frac{df^I_{1,BT}}{dd\tau_{1,BT}} = \frac{df^E_{1,BT}}{dd\tau_{1,BT}} = \kappa_1\Big[-P_{1,BT} + (1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}}\Big] \tag{72}$$

$$\frac{dC}{d\tau_{1,BT}} = \delta\Big[p\frac{dP_{1,BT}}{d\tau_{1,BT}} + (1-p)\frac{dP_{1,E}}{d\tau_{1,BT}}\Big] \tag{73}$$

Suppose first that $\frac{dP_0}{d\tau_{1,BT}} < 0$. Using (62), this implies that $\frac{df_0}{d\tau_{1,BT}} > 0$. From (70), it then follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} < 0$. This implies, from (65), that $\frac{d\hat{f}_1}{d\tau_{1,BT}} > 0$. But then, from (71), 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 (62), this implies that $\frac{df_0}{d\tau_{1,BT}} < 0$. From (70), it then follows that $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$. Then, from (65), this $\frac{d\hat{f}_1}{d\tau_{1,BT}} < 0$. But it then follows from (71) 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 $\frac{df_0}{d\tau_{1,BT}} = \frac{d\hat{f}_1}{d\tau_{1,BT}} = \frac{dP_{1,NE}}{d\tau_{1,BT}} = 0$

□

B.3 Proof of Proposition 5

Suppose that the period-1 production constraint is binding for both fossil fuel producers, so that (16)-(19) hold. Differentiating both sides of the market clearing conditions with respect to $\hat{\tau}_0$, we obtain

$$-\frac{W}{(P_0)^2}\frac{dP_0}{\hat{\tau}_0} = \frac{df_0}{d\hat{\tau}_0} \tag{74}$$

$$-\frac{W}{(P_{1,BT})^2}\frac{dP_{1,BT}}{d\hat{\tau}_0} = \frac{dC}{d\hat{\tau}_0} - \frac{df_0}{d\hat{\tau}_0} + \frac{d\hat{f}_1}{d\hat{\tau}_0} \tag{75}$$

$$-\frac{qW}{(P_{1,E})^2}\frac{dP_{1,E}}{d\hat{\tau}_0} = \frac{dC}{d\hat{\tau}_0} \tag{76}$$

$$-\frac{(1-q)W}{(P_{1,NE})^2}\frac{dP_{1,NE}}{d\hat{\tau}_0} = -\frac{df_0}{d\hat{\tau}_0} + \frac{d\hat{f}_1}{d\hat{\tau}_0} \tag{77}$$

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

$$\hat{f}_1 = \frac{(1-\hat{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\hat{\tau}_0)\kappa_2}\Big[pP_{1,BT} + (1-p)P_{1,NE}\Big] \tag{78}$$

$$f_0 = \frac{1}{2}\bar{f}_0 + \frac{\kappa_1}{2}P_0 - \frac{\kappa_1}{2}\Big[pP_{1,BT} + (1-p)P_{1,NE}\Big] \tag{79}$$

$$C = \delta\Big[pP_{1,BT} + (1-p)P_{1,E}\Big] \tag{80}$$

which implies

$$\begin{aligned}\frac{d\hat{f}_1}{d\hat{\tau}_0} = &-\frac{\kappa_1^2\kappa_2}{[\kappa_1 + (1-\hat{\tau}_0)\kappa_2]^2}\Big[pP_{1,BT} + (1-p)P_{1,NE}\Big] \\ &+ \frac{(1-\hat{\tau}_0)\kappa_1\kappa_2}{\kappa_1 + (1-\hat{\tau}_0)\kappa_2}\Big[p\frac{dP_{1,BT}}{d\hat{\tau}_0} + (1-p)\frac{dP_{1,NE}}{d\hat{\tau}_0}\Big]\end{aligned} \tag{81}$$

$$\frac{df_0}{d\hat{\tau}_0} = \frac{\kappa_1}{2}\frac{dP_0}{d\hat{\tau}_0} - \frac{\kappa_1}{2}\Big[p\frac{dP_{1,BT}}{d\hat{\tau}_0} + (1-p)\frac{dP_{1,NE}}{d\hat{\tau}_0}\Big] \tag{82}$$

$$\frac{dC}{d\hat{\tau}_0} = \delta\Big[p\frac{dP_{1,BT}}{d\hat{\tau}_0} + (1-p)\frac{dP_{1,E}}{d\hat{\tau}_0}\Big] \tag{83}$$

We want to show that $\frac{dP_0}{d\hat{\tau}_0} \geq 0$. We proceed again by contradiction, and suppose that the opposite holds. From (74), this implies $\frac{df_0}{d\hat{\tau}_0} > 0$. It follows from (82) that

$$p\frac{dP_{1,BT}}{d\hat{\tau}_0} + (1-p)\frac{dP_{1,NE}}{d\hat{\tau}_0} < 0 \tag{84}$$

which implies, using (81) that $\frac{d\hat{f}_1}{d\hat{\tau}_0} < 0$. From (77), it then follows that $\frac{dP_{1,NE}}{d\hat{\tau}_0} > 0$, which implies, using (84), that $\frac{dP_{1,BT}}{d\hat{\tau}_0} < 0$. From (75), we then have $\frac{dC}{d\hat{\tau}_0} > 0$, which implies, from (76), that $\frac{dP_{1,E}}{d\hat{\tau}_0} < 0$. But then, (83) implies $\frac{dC}{d\hat{\tau}_0} < 0$, which is a contradiction. Therefore, we must have $\frac{dP_0}{d\hat{\tau}_0} \geq 0$.

□

B.4 Proof for taxes in both technology scenarios

Consider a generic concave utility function u. If the Breakthrough Technology scenario realizes, then the planner solves

$$\max_{\tau_{1,BT} \in [0,1]} u\left(\frac{W}{P_{1,BT}(\tau_{1,BT})}\right) - \frac{\lambda}{2}(f_{1,BT}(\tau_{1,BT}))^2$$

where $f_{1,BT}$ denotes aggregate fossil fuel production. Using the market clearing condition (5), this is equal to

$$\max_{\tau_{1,BT} \in [0,1]} u(C + f_{1,BT}(\tau_{1,BT})) - \frac{\lambda}{2}(f_{1,BT}(\tau_{1,BT}))^2$$

which gives the following first order condition

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

where we have used the fact that supply from the renewable sector C is price-inelastic, hence it is not sensitive to the tax (conditional on being in period 1).

If the Current Technology scenario realizes, then the planner solves

$$\max_{\tau_{1,CT} \in [0,1]} qu\left(\frac{W}{P_{1,E}(\tau_{1,CT})}\right) + (1-q)u\left(\frac{W}{P_{1,NE}(\tau_{1,CT})}\right) - \frac{\lambda}{2}(f_{1,CT}(\tau_{1,CT}))^2$$

By using market clearing conditions and the fact that fossil fuel firms only supply in the non-electrifiable market, then we have the following first order condition

$$u'\left(\frac{f_{1,CT}(\tau_{1,CT})}{1-q}\right) = \lambda f_{1,CT}(\tau_{1,CT})$$

hence, by combining the optimality conditions across the two scenarios we obtain

$$\frac{f_{1,BT}(\tau_{1,BT})}{f_{1,CT}(\tau_{1,CT})} = \frac{u'(C + f_{1,BT}(\tau_{1,BT}))}{u'\left(\frac{f_{1,CT}(\tau_{1,CT})}{1-q}\right)}$$

Finally, using the concavity of the utility function and taking the limit as $q \to 0$, we have

$$\frac{f_{1,BT}(\tau_{1,BT})}{f_{1,CT}(\tau_{1,CT})} < \frac{u'(f_{1,BT}(\tau_{1,BT}))}{u'\left(\frac{f_{1,CT}(\tau_{1,CT})}{1-q}\right)} \to \frac{u'(f_{1,BT}(\tau_{1,BT}))}{u'(f_{1,CT}(\tau_{1,CT}))}$$

Suppose now that $f_{1,BT} > f_{1,CT}$. Then, we have $u'(f_{1,BT}) < u'(f_{1,CT})$. But this implies, using the previous condition, that $f_{1,BT} < f_{1,CT}$. This is a contradiction, hence we must have $f_{1,BT} \leq f_{1,CT}$, which implies that the carbon tax should be higher in the BT scenario (since emissions are decreasing in the tax rate). We have equality when $q = 1$, in which case there is no difference between the two technology scenarios. Moreover, if the optimal tax function is monotone in q, then this results holds for each $q \in [0, 1]$.

□

B.5 Proof for results on Firm Profits and drilling restrictions

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

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

which implies that total expected profits in period 0 are

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

It follows that

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

Therefore, we want to show that

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

Recall that in section B.3 we showed that

$$\frac{dP_0}{d\hat{\tau}_0} \geq 0, \ \frac{df_0}{d\hat{\tau}_0} \leq 0$$

It follows then immediately, using (82), that

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

We now want to show that $\frac{dC}{d\hat{\tau}_0} \geq 0$. By contradiction, suppose that the opposite holds. Then, using (76), we have $\frac{dP_{1,E}}{d\hat{\tau}_0} > 0$ which in turn implies, using (83), that $\frac{dP_{1,BT}}{d\hat{\tau}_0} < 0$. But then, subtracting (76) from (75), we find that $\frac{d\hat{f}_1}{d\hat{\tau}_0} - \frac{df_0}{d\hat{\tau}_0} > 0$, which in turn implies, using (59), that $\frac{dP_{1,NE}}{d\hat{\tau}_0} < 0$. But then it follows that

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

which is a contradiction, hence it must be $\frac{dC}{d\hat{\tau}_0} \geq 0$. Then, using (76) we find $\frac{dP_{1,E}}{d\hat{\tau}_0} \leq 0$ which in turn implies, using (83), that $\frac{dP_{1,BT}}{d\hat{\tau}_0} \geq 0$. It then follows, using (75), that $\frac{d\hat{f}_1}{d\hat{\tau}_0} \leq 0$. Finally, using (81), we obtain

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

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

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

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

and total expected profits in period 0 are

$$\begin{aligned}\Pi_0^I = {} & f_0 P_0 - \frac{1}{2\kappa_1}f_0^2 \\ & + \left[pP_{1,BT} + (1-p)P_{1,NE}\right](\bar{f}_0 - f_0) \\ & - \frac{1}{2\kappa_1}(\bar{f}_0 - f_0)^2\end{aligned}$$

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

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

Hence, it follows that

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

Using (79), $P_0 - P_1 = \frac{2}{\kappa_1}\left(f_0 - \frac{1}{2}\bar{f}_0\right)$, hence

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

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

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

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

using

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

we have

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

Therefore, this implies

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

where the results follows from $\frac{dC}{d\hat{\tau}_0} \geq 0$ and (83).

□

B.6 Proof for results on Firm Profits and probability of Breakthrough Technology State

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

$$\hat{f}_1 = \frac{\kappa_1\kappa_2}{\kappa_1 + \kappa_2}\left[pP_{1,BT} + (1-p)P_{1,NE}\right]$$

which implies that total expected profits in period 0 are

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

It follows that

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

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

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

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

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

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

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

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

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

using

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

we have

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

Therefore, this implies

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

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

$\square$

B.7 Proof for results on Firm Profits and carbon tax in BT scenario

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

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

and, consequently, profits are

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

It follows that

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

Recall that in section B.2 we showed that, when the carbon tax rate is low, $\frac{dP_0}{d\tau_{1,BT}} \leq 0$. This in turn implies, using (31), that $\frac{df_0}{d\tau_{1,BT}} \geq 0$. Therefore, using (39) it follows immediately that

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

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

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

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

and, consequently, profits are

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

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

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

Note that

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

and, using (36), $P_0 - P_1 = \frac{2}{\kappa_1}(f_0 - \bar{f}_0)$. It then follows that

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

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

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

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

using

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

we have

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

Therefore, this implies

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

We now argue that $\frac{dC}{d\tau_{1,BT}} \geq 0$. Suppose that the opposite holds. Then, using (33), $\frac{dP_{1,NE}}{d\tau_{1,BT}} > 0$, which in turn implies, using (40), that $\frac{dP_{1,BT}}{d\tau_{1,BT}} < 0$. But then, it follows from (32) that $\frac{dC}{d\tau_{1,BT}} > 0$, which is a contradiction. Therefore, it must be $\frac{dC}{d\tau_{1,BT}} \geq 0$. But then, using (40), it immediately follows that $\frac{d\Pi_0^R}{d\tau_{1,BT}} \geq 0$.

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

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

$$\hat{f}_1 = \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\left[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\right]$$

and profits are

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

It then follows that

$$\begin{aligned}\frac{d\Pi_0^E}{d\tau_{1,BT}} &= \frac{\kappa_1\kappa_2}{\kappa_1+\kappa_2}\left[p(1-\tau_{1,BT})P_{1,BT} + (1-p)P_{1,NE}\right] \\ &\times \left[p\left((1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} - P_{1,BT}\right) + (1-p)\frac{dP_{1,NE}}{d\tau_{1,BT}}\right]\end{aligned}$$

Recall that in section B.2 we showed that $\frac{d\hat{f}_1}{d\tau_{1,BT}} \leq 0$, which immediately implies, using (55), that $\frac{d\Pi_0^E}{d\tau_{1,BT}} \leq 0$. We now turn to the incumbent firm. Optimal quantities are

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

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

and profits are

$$\begin{aligned}\Pi_0^I &= f_0P_0 - \frac{1}{2\kappa_1}f_0^2 \\ &+ p\frac{\kappa_1}{2}(1-\tau_{1,BT})^2(P_{1,BT})^2 \\ &+ (1-p)\left[P_{1,NE}(\bar{f}_0 - f_0) - \frac{1}{2\kappa_1}(\bar{f}_0-f_0)^2\right]\end{aligned}$$

It then follows that

$$\begin{aligned}\frac{d\Pi_0^I}{d\tau_{1,BT}} &= \frac{df_0}{d\tau_{1,BT}}P_0 + f_0\frac{dP_0}{d\tau_{1,BT}} - \frac{1}{\kappa_1}f_0\frac{df_0}{d\tau_{1,BT}} \\ &+ p\kappa_1(1-\tau_{1,BT})\left[(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} - P_{1,BT}\right]P_{1,BT} \\ &+ (1-p)\left[\frac{dP_{1,NE}}{d\tau_{1,BT}}(\bar{f}_0-f_0) - P_{1,NE}\frac{df_0}{d\tau_{1,BT}} + \frac{1}{\kappa_1}(\bar{f}_0-f_0)\frac{df_0}{d\tau_{1,BT}}\right]\end{aligned}$$

which can be rewritten as

$$\frac{d\Pi_0^I}{d\tau_{1,BT}} = p\kappa_1(1-\tau_{1,BT})\left[(1-\tau_{1,BT})\frac{dP_{1,BT}}{d\tau_{1,BT}} - P_{1,BT}\right]P_{1,BT} + f_0\frac{dP_0}{d\tau_{1,BT}} + (1-p)(\bar{f}_0 - f_0)\frac{dP_{1,NE}}{d\tau_{1,BT}}$$

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

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

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

$$\hat{f}_1 = \frac{\kappa_1\kappa_2}{\kappa_1 + (1-p)\kappa_2}(1-p)P_{1,NE}$$

and profits are

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

It then follows that

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

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

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

Appendix C Carbon tax on production rather than on sales

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

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

subject to $0 \leq f^I_{1,BT} \leq \bar{f}_0 - f_0$, 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 $0 \leq f^E_{1,BT} \leq \hat{f}_1$.

Note that this formulation of the model is equivalent to our main specification, as if the government where to set a tax on fossil fuel emissions higher than the equilibrium price, then both firms would choose not to produce in that scenario. Indeed, Figure 11 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.

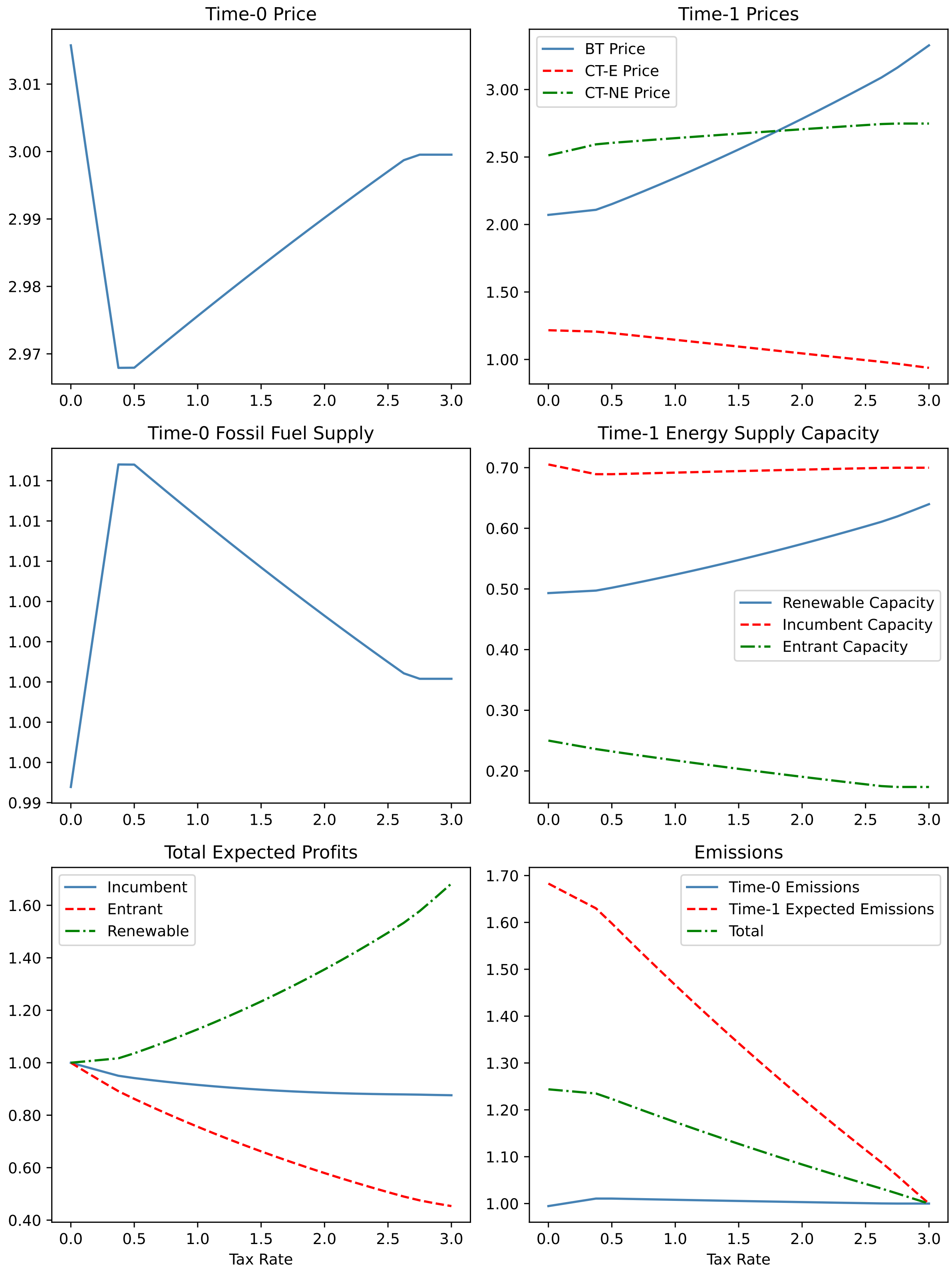

Figure 11: Equilibrium effects of changes in BT tax rate. Note that profits for each producer are normalized by their profits for $p = 0$, whereas emissions are normalized for each period and total by the corresponding value for $p = 1$. BT scenario probability is fixed at $p = 0.5$.

Appendix D Summary of Mechanisms at Work

Table 4: Summary of mechanisms at work.

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

Appendix E Additional Data Details

E.1 Measuring Climate Transition Risks By GPT

We construct several indices to measure the climate transition risks we mentioned in the model applying the state-of-the-art large language models (LLMs) on news reported in the New York Times (NYT). LLMs are a type of artificial intelligence (AI) model designed to understand, generate, and interact with human-like text. LLMs are leading in performance across a range of natural language processing (NLP) tasks, largely due to their extensive scale. We utilize GPT-4, one of the most advanced LLMs pre-trained by OpenAI.[17]

E.1.1 Pre-processing

We obtained historical news articles from the NYT through LexisNexis, covering a 10-year period from 2012 to 2022. We first need to identify news articles that cover the climate transition risks we are measuring, which are the cost of emissions and the possibility of a technological breakthrough that improves renewable energy firms' ability to provide energy to all sectors. We filtered all NYT articles that contain at least one of the following terms: "carbon" and "renewable". We believe these terms provide a comprehensive dataset, capturing most articles relevant to our topics. For instance, articles discussing carbon emissions pricing likely mentioned the term "carbon" at least once. While this approach might also include some irrelevant articles, such as those about drilling on Mars, the capability of the GPT model to filter out irrelevant information, as demonstrated in Table 5, ensures these articles do not compromise our index construction.

The LexisNexis dataset includes both electronic (online) and printed versions of news articles, which sometimes feature different titles and slight sentence adjustments. For example, the article titled "Seismic Survey of Alaskan Arctic Refuge Won't Move Forward"

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[17] The OpenAI model we used is gpt-4-0125-preview.

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.[18]

E.1.2 Article-level Analysis by GPT

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

Here is a news article:

“%s”

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

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

\- - -

Question1: Does this article discuss U.S. carbon pricing policy, or factors related to U.S. carbon

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

pricing policy?
(a) Yes
(b) No

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

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

Question4: How significant do you anticipate the impact of this news about U.S. carbon pricing policy will be on the market prices and operational strategies of companies in oil/gas industry?
(a) Highly Significant Impact[19]
(b) Moderate Impact[20]
(c) Minimal Impact[21]
(d) No Impact[22]

We analyzed a total of 15,415 news articles, filtered by the above keywords over our 10-year sample period. We analyzed each article in five topics:

- U.S. carbon pricing policy
- U.S. regulatory or financial cost of carbon emissions
- Renewable energy or battery storage technology breakthroughs probability
- Actual technology breakthroughs on renewable energy or battery storage
- Policies subsidize or support the production of renewable energy

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

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[19] We also provide detailed instructions to the GPT model to identify articles that should be considered of highly significant impact. This news will have a profound impact on oil/gas industry. It's likely to lead to considerable fluctuations in market prices and may prompt these companies to re-evaluate and significantly alter their long-term operational strategies and investment plans.

[20] 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.

[21] This news is unlikely to have a substantial impact on the oil and gas 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.

[22] The article has negligible impact on both the prices and operational strategies of oil and gas firms.

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

	Responses from GPT-4				
Headline	Relevance	Direction	Strength	Importance	Explanation
Using Executive Powers, Obama Begins His Last Big Push on Climate Policy	Yes	Tightening	Extremely Likely	Highly Significant Impact	The article discusses President Obama's plan to tackle climate change by imposing regulations to curb carbon emissions from power plants, using authority already embedded in law. This indicates a tightening of U.S. carbon pricing policy, making it extremely likely to impact the market and operational strategies of companies in the oil/gas industry significantly.
Trump Lays Plans to Reverse Obama's Climate Change Legacy	Yes	Loosening	Extremely Likely	Highly Significant Impact	The article discusses President Trump's plans to dismantle Obama-era climate change policies, including the Clean Power Plan aimed at closing polluting power plants and reducing emissions. This indicates a loosening of U.S. carbon pricing policy, making it 'Extremely Likely' due to direct presidential action, with a 'Highly Significant Impact' on the oil/gas industry by potentially lowering operational costs and regulatory burdens.
A Kit With Few Instructions Inspires an Improv Act	No	Neutral	Neutral	No Impact	The article does not discuss U.S. carbon pricing policy or factors related to it. It focuses on an individual's hobby project of building a three-wheeled car, which is unrelated to carbon pricing policy.

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

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

	Responses from GPT-4				
Headline	Relevance	Direction	Strength	Importance	Explanation
Administration to Press Ahead With Carbon Limits	Yes	Increase	Extremely Likely	Highly Significant Impact	The article discusses the implementation of the first federal carbon limits on the nation's power companies, indicating an increase in the regulatory or financial cost of carbon emissions in the U.S. This is a significant policy change, making the likelihood of this change 'Extremely Likely' and its impact on the oil/gas industry 'Highly Significant' due to the potential for increased operational costs and the need for strategic adjustments.
Supreme Court Limits E.P.A.'s Ability to Restrict Power Plant Emissions	Yes	Decrease	Very Likely	Highly Significant Impact	The article discusses the Supreme Court's decision limiting the EPA's ability to regulate carbon emissions, which indirectly affects the regulatory or financial cost of carbon emissions in the U.S. The ruling is seen as a setback for broader regulatory efforts to combat climate change, implying a decrease in regulatory costs for carbon emissions.
In Liguria's Coastal Hills, A Storm's Fury Brings A Struggle for Restoration	No	Neutral	Neutral	No Impact	The article does not address the regulatory or financial cost of carbon emissions in the U.S. It is centered on local recovery efforts in a specific Italian region following severe weather damage.

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

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

	Responses from GPT-4				
Headline	Relevance	Direction	Strength	Importance	Explanation
Projects to Add Wind Power for City Gain Momentum	Yes	Increase	Very Likely	Moderate Impact	The article discusses renewable energy, specifically wind power projects in New York City, indicating an increase in renewable energy technology breakthrough probabilities. It mentions zoning changes to facilitate wind turbines and a major offshore wind farm proposal.
Japanese Cabinet Proposes Energy Sector Overhauls	Yes	Increase	Very Likely	Moderate Impact	The article mentions Japan's efforts to foster competition in the electricity industry and encourage the use of renewable energy, indicating an increase in renewable energy or battery storage technology breakthrough probabilities.
Trump Budget Proposes Deep Cuts in Energy Innovation Programs	Yes	Decrease	Very Likely	Highly Significant Impact	Cuts in energy research programs, particularly in renewable energy and battery storage technology, indicate a decrease in breakthrough probabilities, with a 'Very Likely' chance due to the budget proposal, significantly impacting the oil/gas industry.

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

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

	Responses from GPT-4		
Headline	Discussed Actual BT?	Importance	Explanation
Scientists to Announce Big Breakthrough in Fusion Energy	Yes	Highly Significant Impact	The article details an actual breakthrough in fusion energy research, where ignition was achieved, indicating a significant step towards renewable energy or battery storage technology. This breakthrough represents a realized advancement, not just plans or investments.
A Physics Magic Trick: Take 2 Sheets of Carbon and Twist	Yes	Highly Significant Impact	The article details actual scientific breakthroughs in the study of graphene, particularly its superconductivity when twisted at a 'magic angle.' This represents a significant advancement in materials science with potential implications for renewable energy and battery storage technologies.
Soap, Detergent and Even Laxatives Could Turbocharge a Battery Alternative	Yes	Moderate Impact	The article details an actual technology breakthrough in supercapacitors. This breakthrough involves a new class of electrolytes that could significantly enhance energy storage capabilities, which could have a moderate impact on the oil and gas industry by potentially altering long-term operational strategies.

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

Table 9: Responses From GPT - Policies that Subsidize or Support the Production of Renewable Energy

	Responses from GPT-4				
Headline	Relevance	Direction	Strength	Importance	Explanation
U.S. Approves Wind Power Transmission Project	Yes	Loosening	Extremely Likely	Moderate Impact	The federal decision to allow the wind energy transmission project to proceed indicates a policy that supports the production of renewable energy.
Major Climate Action at Stake in Fight Over Twin Bills Pending in Congress	Yes	Loosening	Extremely Likely	Highly Significant Impact	The article details policies supporting renewable energy production, such as tax incentives for electric vehicles and clean energy, which are extremely likely to significantly impact the oil/gas industry.
Britain Plans to Cut Subsidies for Renewable Energy	Yes	Tightening	Extremely Likely	Moderate Impact	The article details the British government's intention to reduce subsidies for renewable energy, indicating a tightening of policies that support renewable energy production. This change is extremely likely given the government's announcement and expected parliamentary approval. The impact on the oil/gas industry is considered moderate because while it may reduce competitive pressure from renewables in the short term, the long-term implications for the industry's operational strategies remain uncertain.

Note: Sample responses from GPT-4 on topic policies subsidize or support the production of renewable energy.

E.1.3 Aggregation

To measure the overall views of climate transition news in a given week, we construct news indices by aggregating article-level scores to a weekly level. Compared with daily scores, weekly scores are more likely to capture discussions around the event date. They also better capture reflections in the stock market in the days following the event when we connect these indices to stock returns later. We include news from Saturday and Sunday in the following week since this news would only be reflected on Monday when the market opens. Before aggregation, we map textual responses into numerical scores. For direction responses, tightening carbon policies, more drilling restrictions, and increased renewable technology breakthrough probability are mapped to "+1". Loosening carbon policies, fewer drilling restrictions, and decreased renewable technology breakthrough probability are mapped to "-1". For the question measuring the strength of direction, responses range from neutral to extremely likely, spanning from 0 to 4. 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, spanning from 0 to 3.

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

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

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

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

E.2 Oil Futures Price

Table 10: Data Description and Sources

Variable	Description	Source	Frequency	Processing
CL.hh	WTI crude oil futures *hh*-month contract (settlement price)	Bloomberg	Daily	End of week/month % change
CPIAUCSL	U.S. CPI for all urban consumers: all items	FRED	Monthly	% change
GDPC1	U.S. Real Gross Domestic Product	FRED	Quarterly	% change
M1SL	M1 money supply	FRED	Monthly	% change
M2SL	M2 money supply	FRED	Monthly	% change
CFNAI	Chicago Fed National Activity Index	Chicago FED	Monthly	constructed to be stationary
IGREA	Kilian's (2009) index of global real economic activity	Dallas FED	Monthly	constructed to be stationary
LW.hh	*hh*-month zero-coupon treasury yields by Liu and Wu (2019)	Wu's webpage	Daily	End of week/month % change
OECD ConsChg	OECD liquid fuel consumption change	EIA	Quarterly	

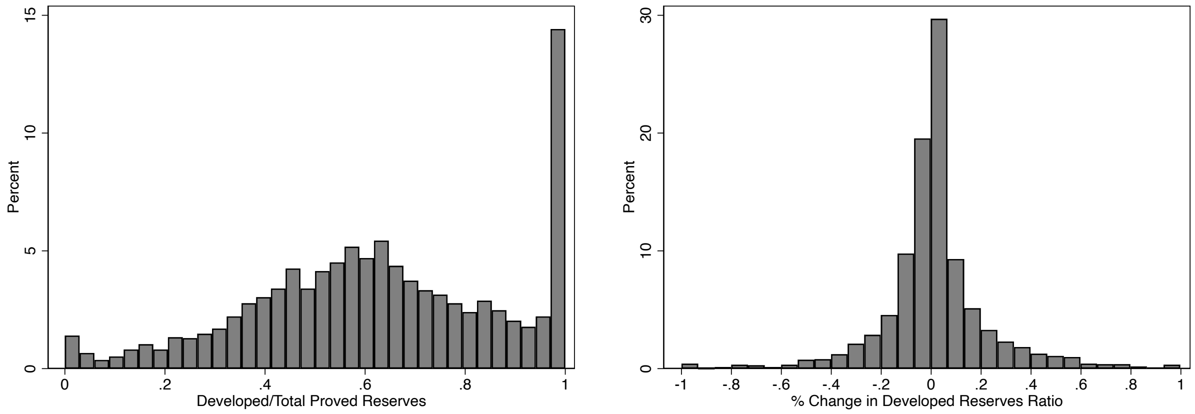
Note: Table provides descriptions, sources, and the frequency of the variables utilized in our study of oil futures prices (Section 4.2). The last column details the processing methods applied to convert raw data into the variables used in our analysis.

E.3 Correlation with Stock Returns

We next examine how news is reflected in the stock returns of energy firms and how these reflections differ among three types of firms in our model: entrants, incumbents, and renewable firms. We merge the constructed NYT news indices with individual stock data from the Center for Research in Security Prices (CRSP) and Global Industry Classification Standard (GICS) industry codes for firms from Compustat. For fossil fuel firms, we focus on integrated oil companies engaged in the exploration and production of oil and gas (GICS codes 10102010 and 10102020), excluding manufacturers of drilling equipment (GICS code 10101020), drilling contractors (GICS code 10101010), oil marketing (GICS code 10102030), and storage and transportation companies (GICS code 10102040) that are not directly involved in oil production.

To classify entrants and incumbents, we compute a proved developed reserves ratio by dividing the dollar amount of proved developed reserves for oil, natural gas, and natural gas liquids by the dollar amount of total proved reserves for these resources. We obtain the proved developed reserves and total proved reserves from the Industry Specific Annual section of Compustat. This ratio indicates the extent to which a firm has capitalized on its reserves: firms with a higher ratio have developed more of theirs, suggesting they are incumbents with established operations. Conversely, firms with a lower ratio are classified as entrants: in line with the model, these are firms that have not yet built the infrastructure to develop a large fraction of the reserves that they own. We use the medium developed reserves ratio to classify incumbents and entrants. Figure 12 shows the histogram of developed reserves ratio.

Figure 12: Distribution of Developed Reserves Ratio



(a) Developed Reserves Ratio

(b) % Change in Developed Reserves Ratio

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

For renewable firms, we use the holding firms of the Invesco WilderHill Clean Energy ETF, which include publicly traded companies in the United States engaged in the advancement of cleaner energy and conservation. To avoid skewing the data with anomalous price movements, we have excluded Tesla, given its significant price increase since 2020. The number of firms that have been classified as entrants, incumbents and renewable are 107, 143 and 41 respectively.

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

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

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

$$R_{i,t} = \alpha_k + \gamma_i + \beta_{1,k}\nu_{k,t} + \beta_{2,k}\mathrm{Inc}_{i,t} + \beta_{3,k}\mathrm{Ren}_{i,t} + \beta_{4,k}\nu_{k,t}\mathrm{Inc}_{i,t} + \beta_{5,k}\nu_{k,t}\mathrm{Ren}_{i,t} + \epsilon_{k,i,t},$$

where $R_{i,t}$ is the market-hedged return of stock i at week t. We compute rolling 3-year market beta for each firm, and use it to hedge the market exposure of each stock. γ_i represents firm fixed effects. $\nu_{k,t}$ is the AR(1) innovations of index k (either the NYT-Emission Cost News Index or the NYT-Renewable Breakthrough News Index) at week t. We focus on AR(1) innovations because returns should reflect the unexpected component of the news, though the results are similar if we include the index directly instead of the innovations. We scale the residuals by their standard deviation. We also include dummies for whether firm i at time t is an incumbent ($\mathrm{Inc}_{i,t}$) or a renewable company ($\mathrm{Ren}_{i,t}$); entrants will have both dummies set to zero and will therefore represent the baseline in the regression. Finally, we include in the regression the interaction of the type of firm (incumbent, entrant, renewable) with the index. Table 3 reports the results from the regression.

E.4 Robustness

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

We used the medium of the developed ratio to split fossil fuel firms into incumbents and entrants. Table 12 shows the results when firms are split by different developed ratio percentiles.

Table 11: Stock Returns and NYT Index - Robustness

	Cost of Emission						Renewable BT					
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Index AR(1) Innovation	-0.0023***	-0.0026***	-0.0027***	-0.0025***		-0.0019**	-0.0035***	-0.0036***	-0.0042***	-0.0040***		-0.0029***
	(0.0009)	(0.0009)	(0.0009)	(0.0009)		(0.0008)	(0.0010)	(0.0010)	(0.0010)	(0.0010)		(0.0010)
Incumbent × Index AR(1) Innovation	0.0028***	0.0029**	0.0030***	0.0029***	0.0019*	0.0031***	0.0027**	0.0027**	0.0029**	0.0026**	0.0018*	0.0024**
	(0.0010)	(0.0011)	(0.0011)	(0.0010)	(0.0010)	(0.0011)	(0.0011)	(0.0011)	(0.0011)	(0.0012)	(0.0009)	(0.0011)
Renewable × Index AR(1) Innovation	0.0042***	0.0044***	0.0046***	0.0046***	0.0036**	0.0057***	0.0042***	0.0044***	0.0051***	0.0052***	0.0030**	0.0044***
	(0.0014)	(0.0015)	(0.0015)	(0.0014)	(0.0014)	(0.0015)	(0.0013)	(0.0013)	(0.0013)	(0.0014)	(0.0013)	(0.0014)
Company FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Time FE	No	No	No	No	Yes	No	No	No	No	No	Yes	No
Remove Market from Stock Returns	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	No
Remove FF3 from Stock Returns	No	No	No	No	No	Yes	No	No	No	No	No	Yes
Specification	Dir	Dir×Str	Dir×Str×Imp	Dir×Imp, PCA	Dir×Imp	Dir×Imp	Dir	Dir×Str	Dir×Str×Imp	Dir×Imp, PCA	Dir×Imp	Dir×Imp
R^2	0.47	0.47	0.47	0.47	16.2	0.45	0.48	0.48	0.50	0.50	16.2	0.43
Observations	34,670	34,670	34,670	34,670	34,670	34,670	34,670	34,670	34,670	34,670	34,670	34,670

Note: This is a robustness table of Table 3. Regressions (1)-(6) show coefficients of regressing stock returns on AR(1) innovations of NYT-Emission Cost News Index and the interaction terms with dummies indicating incumbents and renewable firms, controlling for firm fixed effects. Regressions (7)-(12) instead show coefficients of regressing stock returns on AR(1) innovations of NYT-Renewable Breakthrough News 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 focus on energy firms in these regressions. Entrants serve as the benchmark, and the interaction terms test the differences between incumbents or renewable firms and entrants. The news indices were constructed by scaling direction based on the news's importance to market prices and oil industry operation strategies. This table includes several scaling methods: direction only ((1) and (7)), direction scaling by signal strength ((2) and (8)), and direction scaling by both signal strength and importance ((3) and (9)). In the main table, we combined multiple indices by taking their arithmetic average. In this robustness table, versions using the first principal component are included in (4) and (10). Versions with time fixed effects are shown in (5) and (11), and those hedging against the FF3 factors of stock returns are in (6) and (12). Standard errors are in parentheses and are clustered at the company level. Significance levels: * (p<0.10), ** (p<0.05), *** (p<0.01).

Table 12: Stock Returns and NYT Index - Robustness (Developed Ratio)

	Cost of Emission				Renewable BT			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Index AR(1) Innovation	-0.0030**	-0.0031***	-0.0023***	-0.0017***	-0.0033**	-0.0041***	-0.0036***	-0.0030***
	(0.0013)	(0.0011)	(0.0007)	(0.0007)	(0.0013)	(0.0012)	(0.0008)	(0.0007)
Incumbent × Index AR(1) Innovation	0.0029**	0.0034***	0.0030***	0.0025**	0.0013	0.0024*	0.0024**	0.0015
	(0.0014)	(0.0012)	(0.0010)	(0.0011)	(0.0014)	(0.0013)	(0.0011)	(0.0011)
Renewable × Index AR(1) Innovation	0.0051***	0.0052***	0.0044***	0.0039***	0.0041**	0.0049***	0.0044***	0.0037***
	(0.0018)	(0.0016)	(0.0014)	(0.0013)	(0.0016)	(0.0015)	(0.0012)	(0.0012)
Company FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Remove Market from Stock Returns	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Developed Ratio Split Percentile	P30	P40	P60	P70	P30	P40	P60	P70
R^2	0.46	0.48	0.47	0.48	0.48	0.49	0.49	0.49
Observations	34,670	34,670	34,670	34,670	34,670	34,670	34,670	34,670

Note: Regressions (1)-(4) show coefficients of regressing stock returns on AR(1) innovations of NYT-Emission Cost News Index and the interaction terms with dummies indicating incumbents and renewable firms, controlling for firm fixed effects. Regressions (5)-(8) instead show coefficients of regressing stock returns on AR(1) innovations of NYT-Renewable Breakthrough News Index. 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 focus on energy firms in these regressions. Entrants serve as the benchmark, and the interaction terms test the differences between incumbents or renewable firms and entrants. We test the robustness of using different percentiles (30th to 70th percentile) of the developed ratio to classify incumbents and new entrants in this table. Standard errors are in parentheses and are clustered at the company level. Significance levels: * ($p<0.10$), ** ($p<0.05$), *** ($p<0.01$).