Climate Transition Risk and Energy Prices*

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Abstract

We build a general equilibrium model to study how climate transition risks affect energy prices. 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. Such transition risks make it less attractive for fossil fuel firms to create new capacity that might get stranded in the future. However, 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. We show how an optimally implemented tax policy, which sets a lower carbon tax and a higher tax on new fossil fuel production capacity as the green transition becomes more likely, can mitigate the risk of higher energy prices while maximizing social welfare. We present several testable implications based on this counterintuitive effect of transition risk on energy prices and provide preliminary empirical support.

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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 systematically falling valuations of fossil fuel firms (see Figure 1, for example). Similarly, Alekseev et al. (2022) have documented 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 that climate transition risks have on dynamics of prices, investment, production and valuations in the energy sector.

We build a two-period general equilibrium model to better 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) potential entrants who would need to invest today to develop reserves for tomorrow. Renewable firms invest in capacity today 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. 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.

In this environment, we show that transition risks can have the unintended consequence of raising energy prices and fossil-fuel firm valuations. The intuition is that any reduction in investments in additional fossil fuel capacity today—for example, because a potential carbon tax reduces the profitability of producing energy using fossil fuels, or because ESG policies raise the cost of capital for fossil fuel firms—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 the entire 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 can 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 effects 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. In the future period, with some probability a technological breakthrough occurs, which makes the renewable sector capable to provide energy to the entire 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. Then, we also consider the possibility that a social planner might impose taxes, either on carbon emissions or on the creation of new fossil fuel production capacity. These two instruments are meant to capture sources of risk coming from the policy response to the transition.

Our main result is that the transition path to a green economy can 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 supply of energy. 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.

This inventory policy has a countervailing 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.[1] Relatedly, the incentive to undertake this inventory policy implies that fossil fuel firms with large existing reserves are less exposed to transition risk, compared to potential 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, potential entrants to the sector are always hurt.

Finally, we show how the policy response can be tailored in order to minimize the risk of high energy prices over the transition path. Our results suggest that future carbon taxes to be set in the scenario where the technological transition occurs should be decreasing in the transition probability, while taxes on new fossil fuel capacity should be increasing.

[1] The magnitude of this risk has been discussed by McGlade and Ekis (2015), who estimate that, globally, a third of oil reserves, half of gas reserves and over 80 per cent of current coal reserves should remain unused in order to limit global warming to 2°C by 2050.

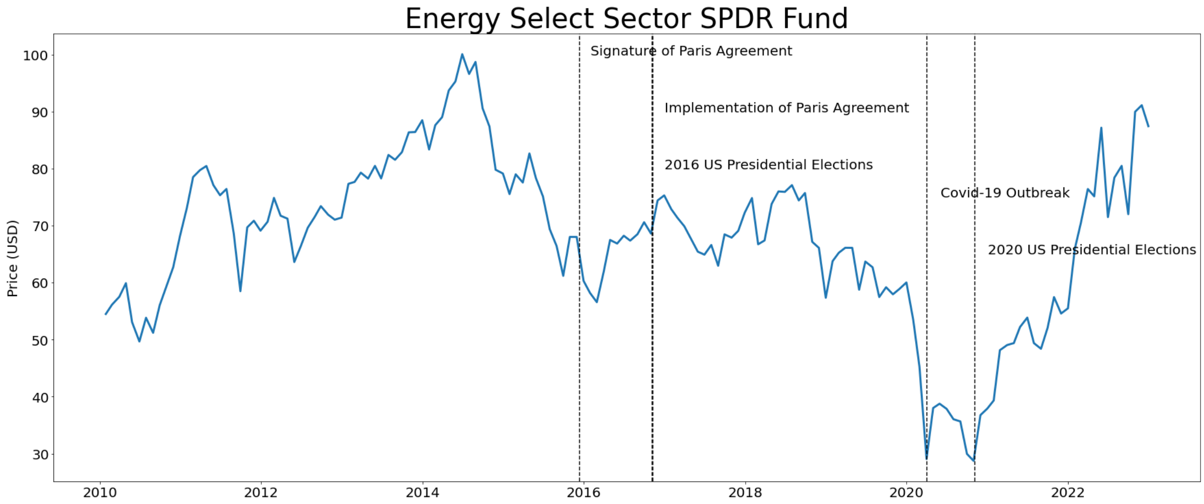

Figure 1: Monthly series of the Energy Select Sector SPDR Fund (XLE) Stock Price. This ETF seeks to provide an effective representation of the energy sector of the S&P 500 Index. Source: CRSP.

The rationale is that, in order to meet the energy needs of the economy, it would be socially optimal to minimize the amount of existing fossil fuel production capacity that remains unused, while discouraging the installment of new capacity.

Our model is also able to provide some empirical implications with respect to the stock price of fossil fuel 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 counterintuitive effect of transition risk on energy prices via the inventory channel, companies with large existing reserves can actually experience an increase in their stock valuations. We find preliminary support for this counterintuitive implication in Figure 2, which plots the monthly correlation of stock returns of eight large firms in the fossil fuel sector with the negative climate risk news index of Alekseev et al. (2022) over the period 2013-22. Consistent with the model's implication, services-providing firms to the fossil fuel sector (Baker Hughes, Halliburton and Schlumberger) – which, in particular, do not have established reserves – are negatively correlated with transition risk news. In contrast, oil majors – with well-established reserves – have either zero correlation (Exxon and Chevron) or positive correlation (Conoco Phillips, Occidental Petroleum, and Devon Energy). The implication is worthy of being tested more fully in future work.

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

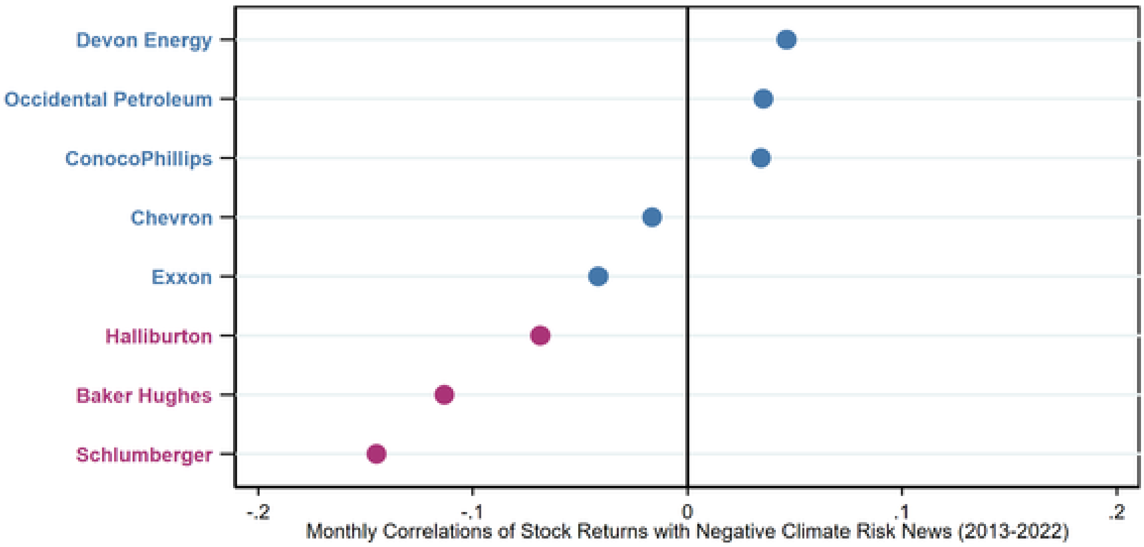

Figure 2: Monthly correlations of stock returns of fossil fuel firms with the negative climate risk news index of Alekseev et al. (2022) over the period 2013-2022.

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. 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 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.

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 price implications the role of taxes on newly installed fossil fuel production capacity.

The rest of the paper is organized as follows. Section 2 describes the model in detail. Section 3 presents the main results on the effects of transition risk on energy prices, while Section 4 discusses optimal carbon policies. Section 5 concludes.

1 Two-Period Climate Transition Risk Model

1.1 Setup

Time is discrete and there are two periods, $t = 0, 1$, with a gross discount rate $R = 1$. The economy consists of a sector that consumes energy as well as three different types of energy producers: an incumbent fossil fuel-based energy producer, a potential entrant producing fossil fuel-based energy, and a firm producing renewable energy.

In period 0, the incumbent fossil fuel firm arrives with a certain level of reserves (e.g., oil in the ground for which the exploration costs have already been paid). It then chooses how much oil to extract at some cost and how much to leave in the ground to be potentially extracted next period. The potential entrant instead chooses how much new production capacity to install to be used in period 1.[2] The renewable producers can generate clean energy at zero marginal cost. They begin period 0 with no production capacity, and decide 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

[2]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 potential entrants.

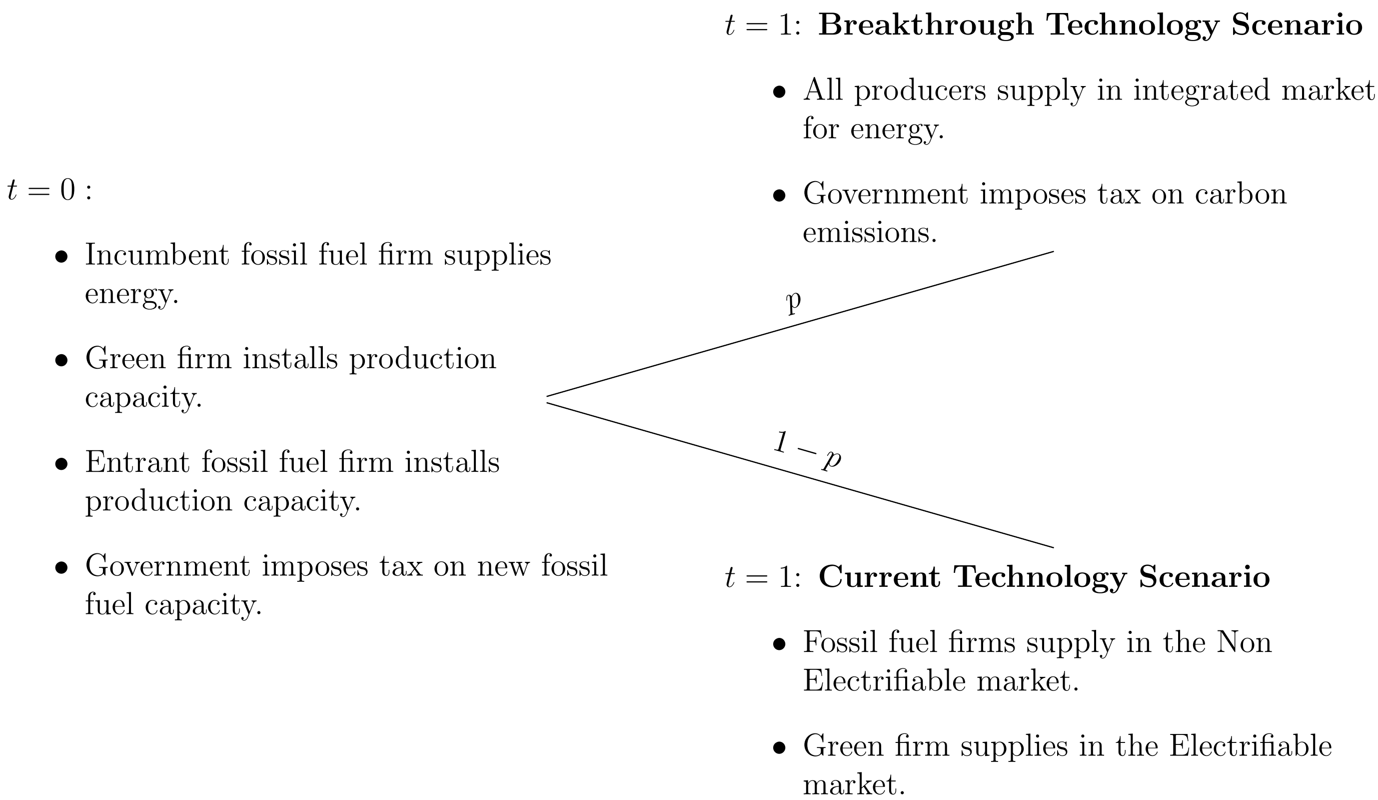

Figure 3: Timeline of the model.

of solar and wind energy production means that 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 can be satisfied by the renewable sector.

We then assume that with some probability p, a breakthrough technology is developed in period 1, which allows renewable energy producers to supply all sectors of the economy.[3] 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 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 will be different across these two markets.

The key externality in this model is that the production of energy by the fossil fuel

[3]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, or could allow in other ways the renewable firms to provide energy to those sectors that were hitherto dependent on fossil fuel sources.

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 the entrant firm. These taxes reflect transition risk affecting the fossil fuel producers in addition to the evolution of renewable technology.

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 3.

1.2 Model

1.2.1 Consumers and Demand for Energy

We keep the consumer side of the economy deliberately simple, in order to focus on the energy supply sector. We assume that in each period there is a uniformly distributed unit mass of 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 in each period that can be used to purchase energy. Wealth cannot be stored across periods. In period 0, consumers solve the following problem

$$\max_{e_0^i} \ \log e_0^i$$
$$s.t. \ P_0 e_0^i \leq W,$$

where e_0^i denotes consumption of energy, and P_0 is the price of energy. It follows immediately that each consumer's demand for energy in period 0 is given by

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

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 $P^i_{1,BT} = P_{1,BT}$ 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 $P^i_{1,CT} = P_{1,E}$ if $i \in [0,q]$, and $P^i_{1,CT} = P_{1,NE}$ 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 given by

$$\begin{aligned} D_0 &= \frac{W}{P_0}, \\ D_{1,BT} &= \frac{W}{P_{1,BT}}, \\ D_{1,E} &= q\frac{W}{P_{1,E}}, \text{ and} \\ D_{1,NE} &= (1-q)\frac{W}{P_{1,NE}}. \end{aligned}$$

1.2.2 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 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 in the respective markets at date 1 where it is able to sell $(P_{1,BT}, P_{1,E})$. 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

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

1.2.3 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 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 a social planner might impose a tax on carbon emissions, τ_1^{BT}, in case the transition occurs in period 1. The fossil fuel incumbent producer therefore solves

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

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

1.2.4 Fossil Fuel Firm: Potential Entrant

We also assume that a potential entrant 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.[4] The fossil fuel entrant producer therefore solves

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

subject to $\hat{f}_1 \geq 0$. The date-1 continuation value V_f^E is equal to $V_f^{E,BT}$ with probability p, given by

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

[4] 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.

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

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

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

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

1.2.5 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 therefore 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 problems (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).*

In 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.

2 Model Analysis

We can now use our model to understand how the endogenous quantities of interest, in particular the price of energy, 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, $\hat{\tau}_0$.

2.1 Changes in the Climate Transition Probability

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 research in the private sector or, from a policy perspective, we can view p as a parameter depending on the size of government subsidies to R&D in the green energy sector.

Figure 4 shows how the model outcomes change as p increases.[5] 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 in period 1. Similarly, the expectation of increasing competition from the renewable producer in period 1 induces the new 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

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

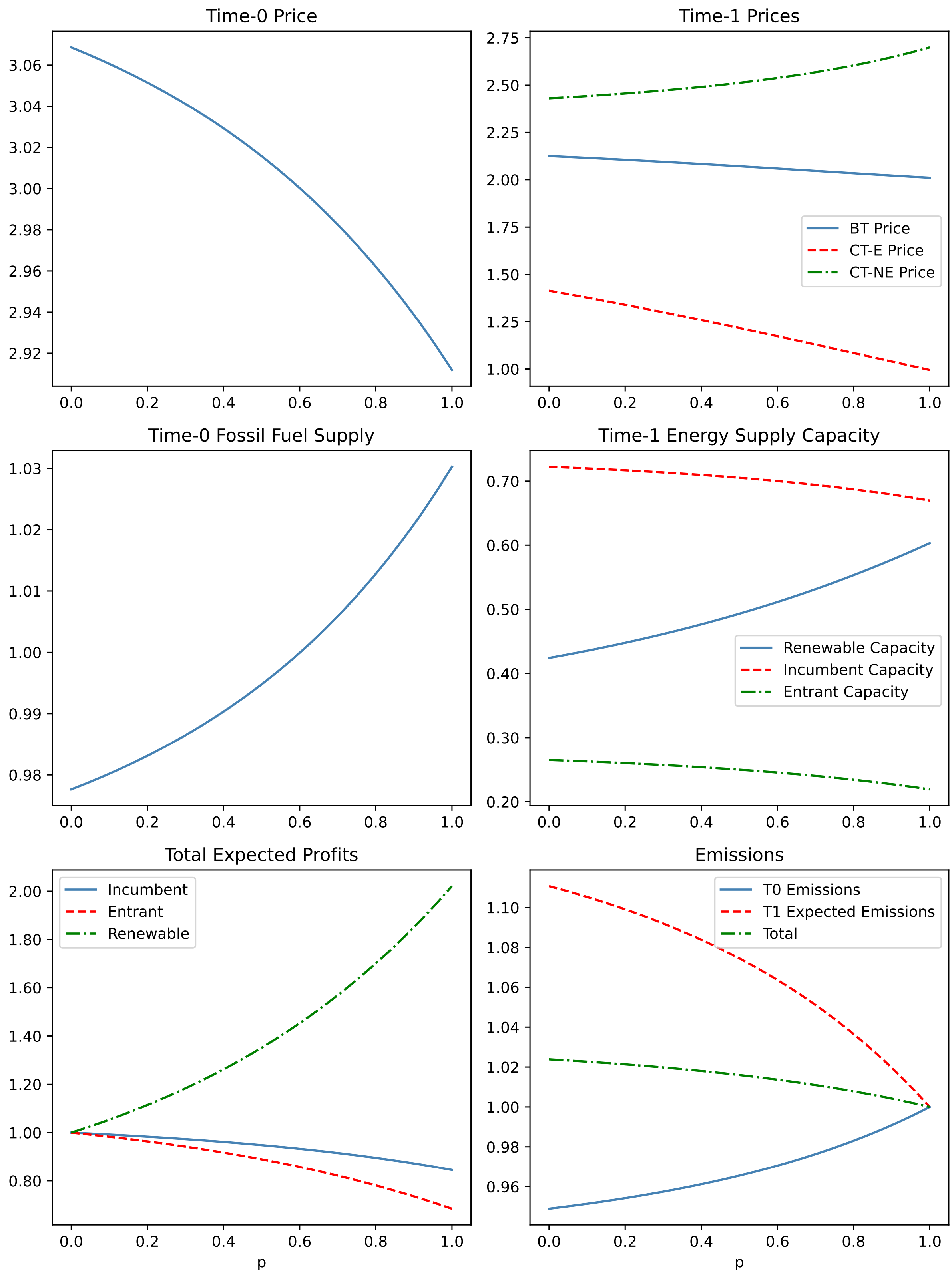

Figure 4: Equilibrium effects of changes in the transition probability. Profits are normalized by first period's values, while emissions by last period's values.

in the relative attractiveness of producing oil today vs. 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 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 available to the incumbent firm, push up the price in the non-electrifiable market of the CT scenario. The different dynamics of the 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 available production capacity. These results are summarized in the following Proposition.

Proposition 1. *Suppose that taxes are set to zero. Then, 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 have the following empirical prediction of our model:

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.*

2.2 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, hence understanding their effect on energy prices in our framework is particularly important.

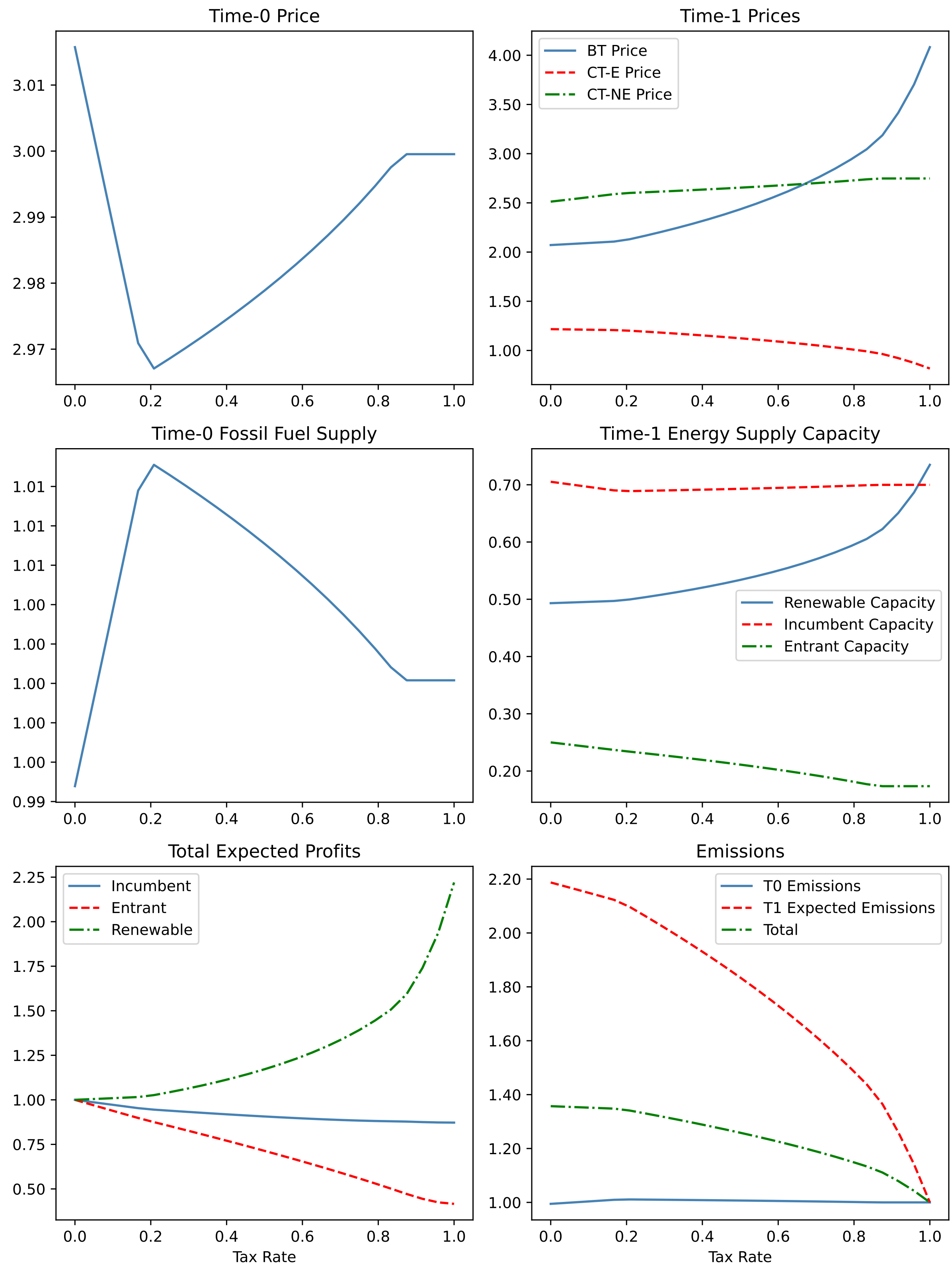

Figure 5: Equilibrium effects of changes in BT tax rate. Profits are normalized by first period's values, while emissions by last period's values. BT scenario probability is fixed at $p = 0.5$.

Figure 5 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 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.

On the other hand, a future carbon tax reduces investment in new fossil fuel production capacity by new potential 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 decrease current supply of energy, 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 new 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 region where the price response 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 when deciding how much capacity to install. Therefore, further changes in the tax rate do not change the optimally installed

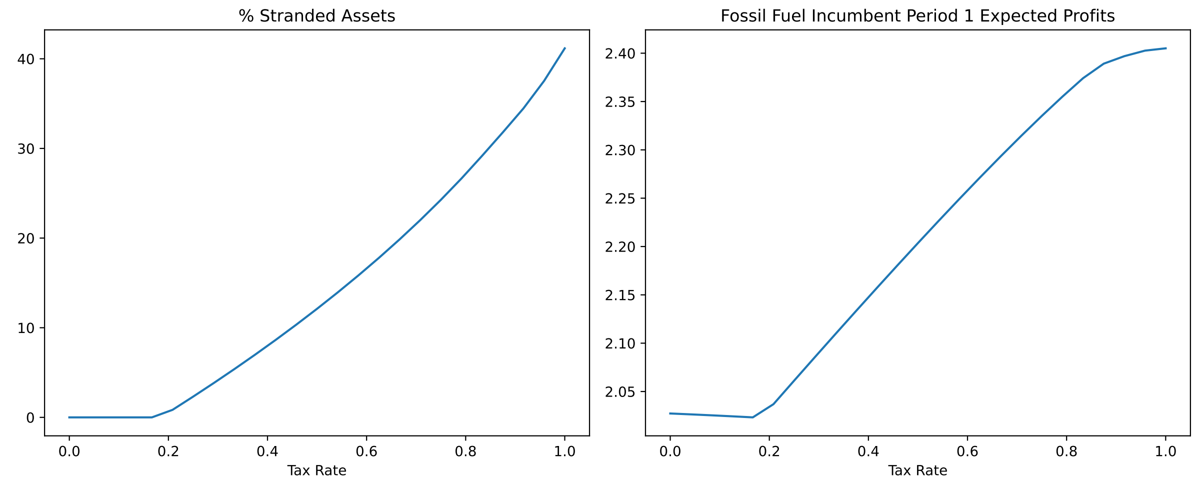

Figure 6: Fossil fuel stranded assets in the BT scenario, and future expected profits, as a function of the tax rate. BT scenario probability is fixed at $p = 0.5$.

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 6 illustrates this result, showing how the proportion of initial reserves of the fossil fuel sector that remain unused is increasing in the carbon tax rate. However, despite its assets becoming stranded, the incumbent fossil fuel firm experiences an increase in its period 1 expected profits, due to the high profits in the Current 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 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 empirical prediction related to the stock prices of the fossil fuel sector, where we can identify the potential entrant fossil fuel firm in the model with firms having 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.*

2.2.1 Taxes on production rather than on sales

Up to this point, 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 7 shows the same exercise as in the previous section, and we can see that the results are qualitatively the same. We therefore maintain the initial model formulation.

2.3 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. 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 8 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 tax only affects the potential entrant firm, but not the incumbent producer, whose reserves of fossil fuels are already in place.

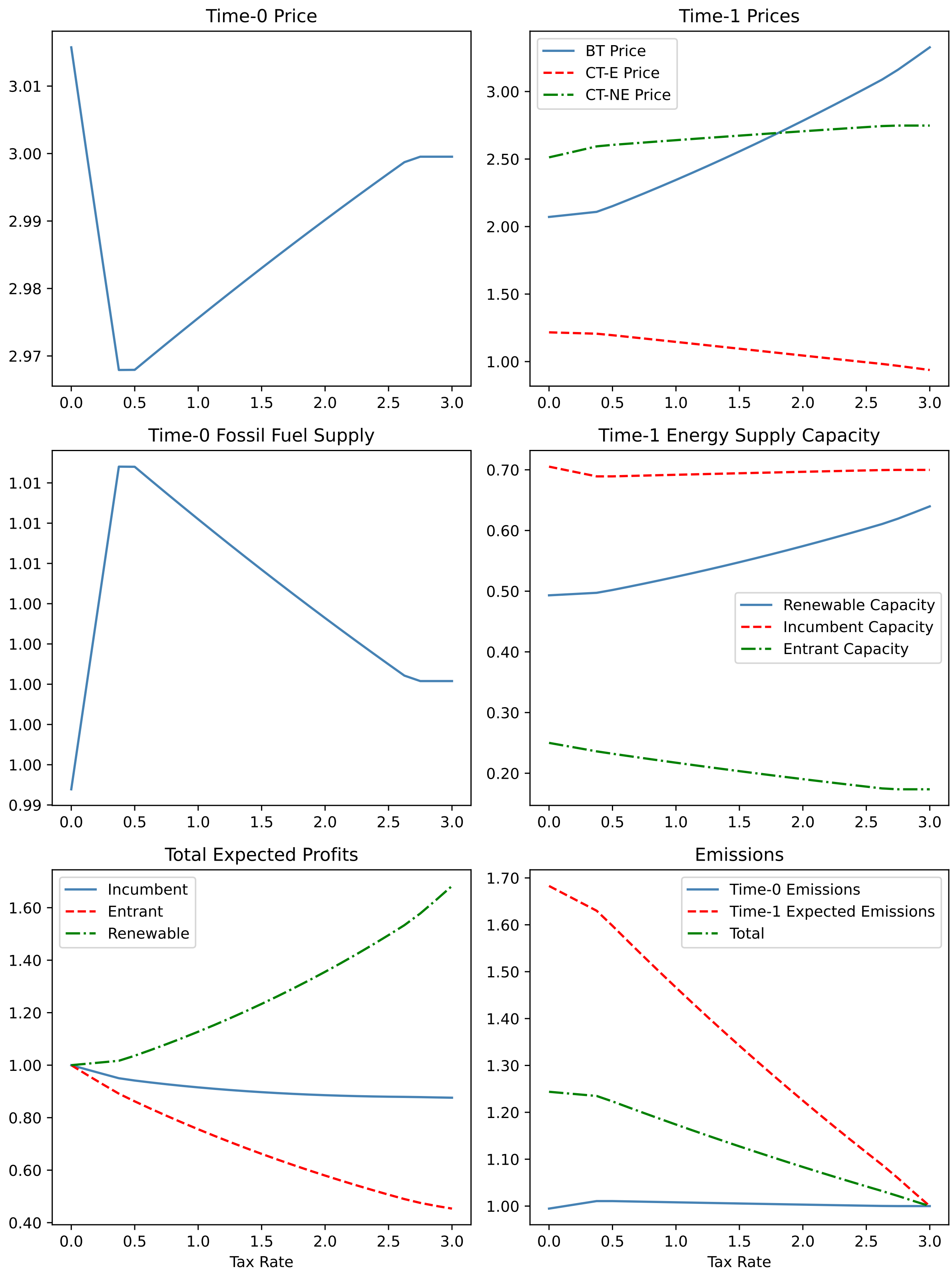

Figure 7: Equilibrium effects of changes in BT tax rate. Profits are normalized by first period's values, while emissions by last period's values. BT scenario probability is fixed at $p = 0.5$.

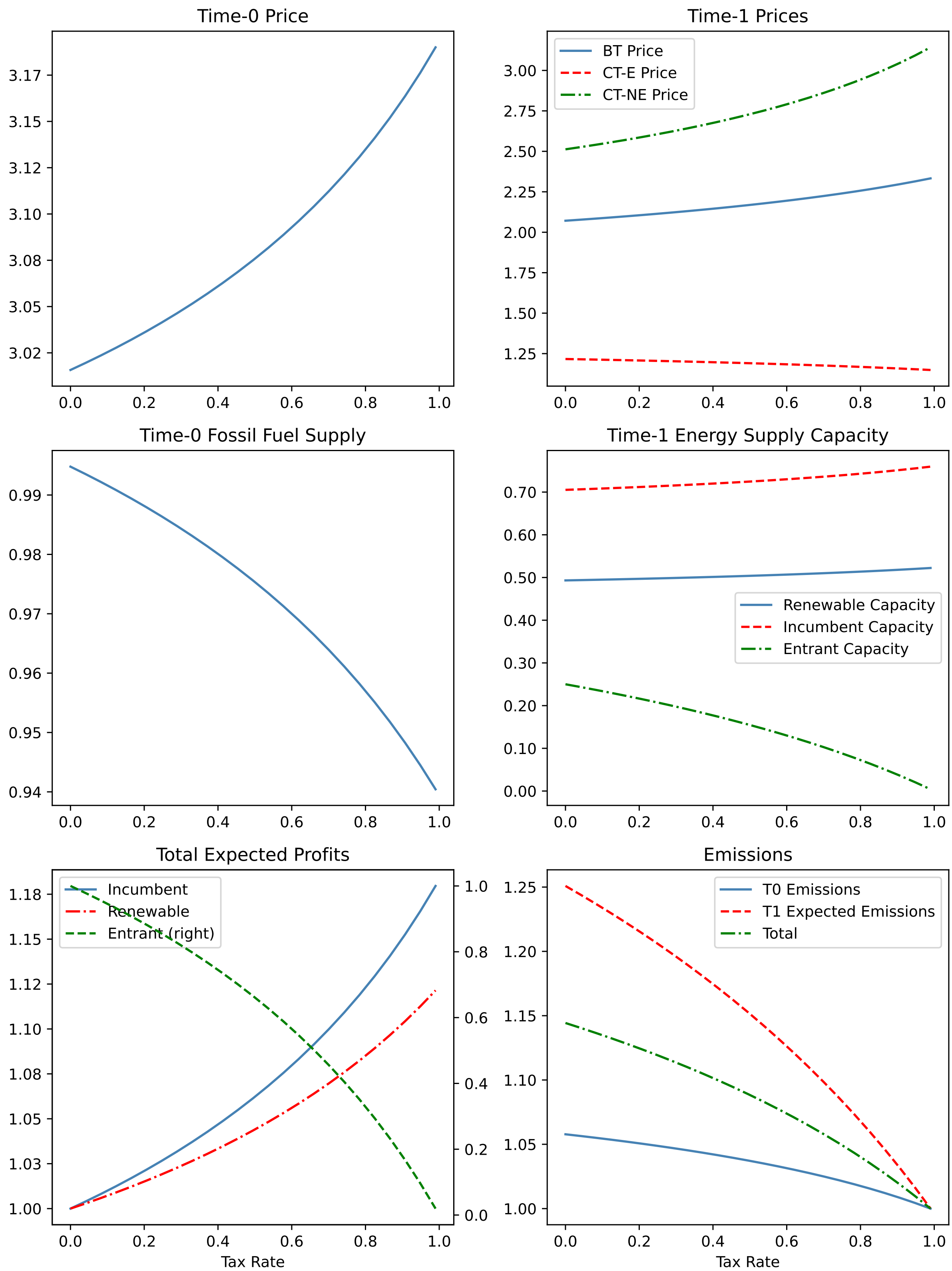

Figure 8: Equilibrium effects of changes in new production capacity tax rate. Profits are normalized by first period's values, while emissions by last period's values. BT scenario probability is fixed at $p = 0.5$.

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.

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 describes the empirical predictions of our model for fossil fuel producers' stock prices, based on the fact that future profits in period 1 are increasing for the incumbent firm, and 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 actually experience an increase in their stock valuations.*

3 Optimal Climate Policy

In the previous section, we took the two tax instruments $(\tau_{1,BT}, \hat{\tau}_0)$ as exogenously given. We now consider the problem of a benevolent 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.

3.1 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 in each period and technology scenario as

$$W_0 := \log\left(\frac{W}{P_0}\right) - \frac{\lambda}{2} f_0^2 \tag{12}$$

$$W_{1,BT} := \log\left(\frac{W}{P_{1,BT}}\right) - \frac{\lambda}{2}(f_{1,BT}^I + f_{1,BT}^E)^2 \tag{13}$$

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

where λ is a parameter that captures the extent to which emissions are socially costly, and we associate to it a quadratic loss function. In period 0, we can define a measure of expected total welfare as

$$W := W_0 + pW_{1,BT} + (1-p)W_{1,CT} \tag{15}$$

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 (15). 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 (13). 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 9 plots the optimal tax predicted by our model in the BT scenario as a function of the transition probability p, fixing a value for the penalty parameter λ. 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 9 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

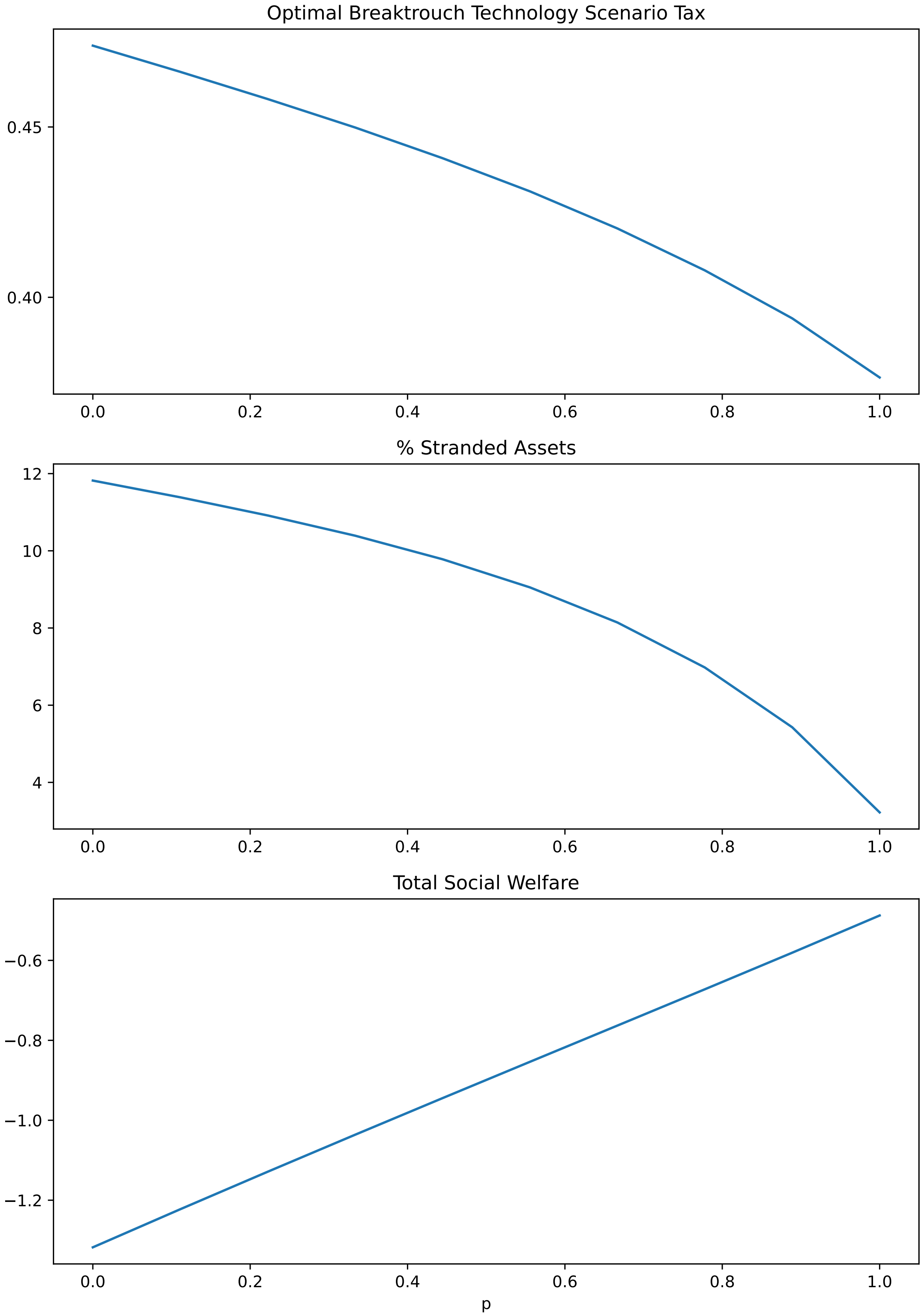

Figure 9: Optimal carbon tax and fossil fuel stranded assets. The value for the carbon emissions penalty parameter is fixed at $\lambda = 1$.

a green economy through the optimal tax policy.

Finally, Figure 10 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 can see that, through the optimal tax rate path, 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, but it is actually decreasing in p.

Therefore, an optimal carbon tax policy, where the optimal tax rate in the Breakthrough Technology scenario is inversely related to the ex-ante transition probability p, allows the economy to experience a decreasing energy price over the transition path. Recall from our results in Section 3 that the economy can experience an increase in the price of energy in period 0 if the carbon tax rate in the BT scenario is very high. Indeed, the high tax rate discourages investment in new production capacity by potential entrant fossil fuel firms, and can therefore induce the incumbent firms to reduce current supply, for the possibility of capturing higher profits in the future in case the BT scenario does not realize. However, as explained before, as p increases then investment in new capacity decreases. A tax rate increasing in p would therefore amplify this effect, and might make the non-electrifiable market in the CT state a very attractive scenario for the incumbent producer, even though this state becomes less likely as p increases, by discouraging competition from potential entrants even more. If instead the tax is decreasing in p, then the reduction in newly installed capacity is not as strong. It then follows that the incumbent fossil fuel sector has no incentive to cut the present supply of energy, thus inducing a reduction in the current price of energy as p increases.

3.1.1 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. Indeed, we show in the appendix 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. It follows that taxes on carbon emissions would have a larger negative welfare effect on the economy compared to the case 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, compared to the scenario where the technological breakthrough does realize, as high carbon taxes would be hard to implement in the Current Technology scenario. We thus abstract for now from this issue, and leave it as a future extension of the model.

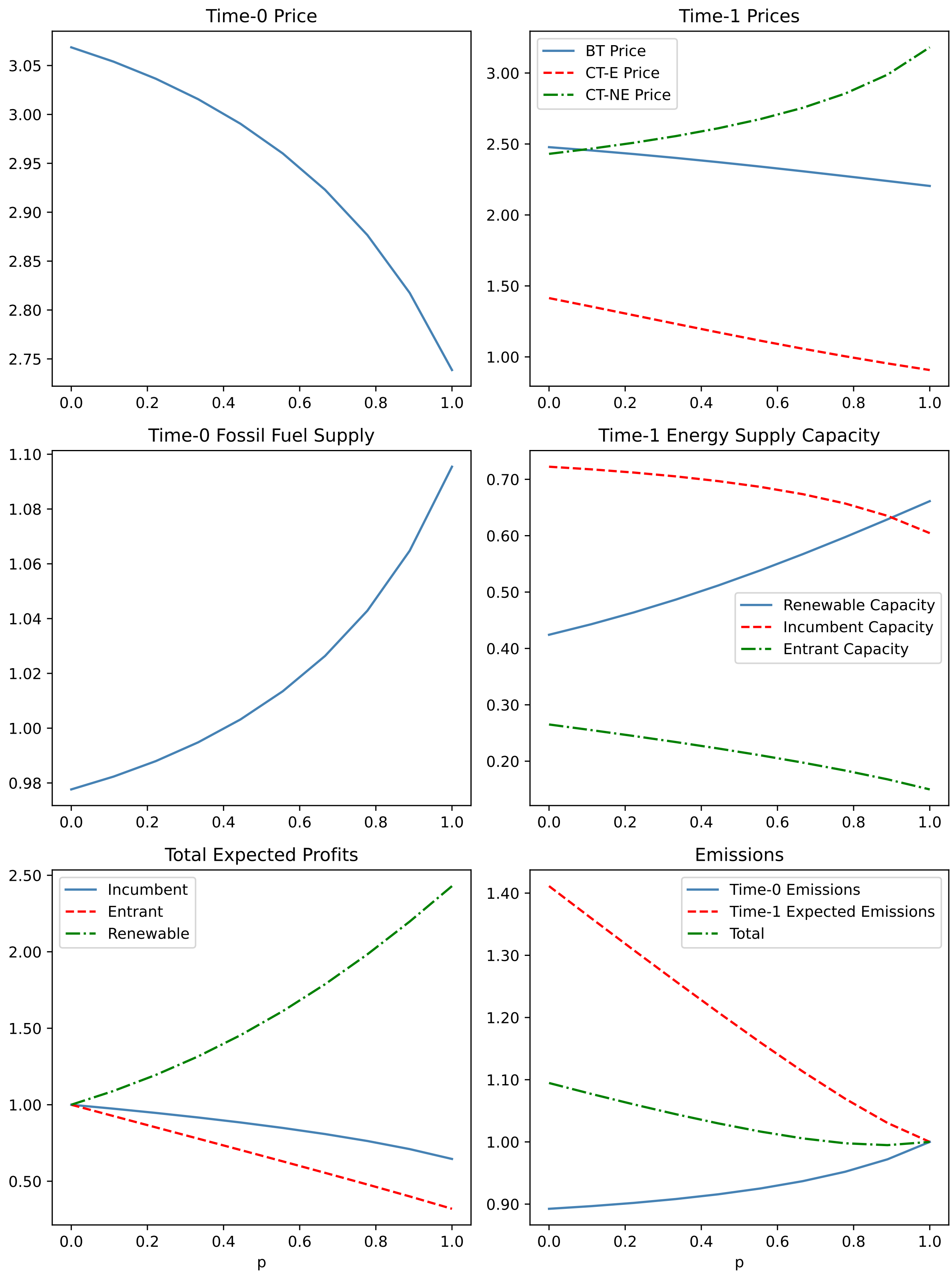

Figure 10: Changes in transition probability with endogenous BT carbon tax. The value for the carbon emissions penalty parameter is fixed at $\lambda = 1$.

3.2 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 11 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 the previous case, the tax is increasing in the 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, as the renewable sector will be able to satisfy future demand for energy. In our numerical simulation of the model, for high enough transition probabilities, it is actually optimal not to have newly installed capacity at all.

Figure 12 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 as the breakthrough scenario becomes more likely. Therefore, the increase in p, which makes the Current Technology state less likely thus inducing the incumbent fossil fuel producer to increase current supply, is able to compensate for the effect of an increasing capacity tax, which pushes instead the incumbent producer to reduce current supply.

This result, together with the result on the optimal carbon tax in the previous section, suggests that in order to minimize the damage to the economy represented by 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 11, where carbon taxes are not imposed, we can see that the fraction of stranded assets is always equal to zero over the transition.

The intuition is that, until the renewable sector is developed enough so that it can reliably supply energy to the entire economy, energy production still has to be carried out by the fossil fuel sector. However, this energy production should rely as much as possible on existing fossil fuel reserves, rather than installing new production capacity which would then become stranded as technological progress in the renewable sector occurs. Our results in Section 3 showed that this transition can generate an increase in the price of energy. However, our results on optimal policy suggest that taxes can be set in an optimal way as a function of the degree to which the renewable sector is innovating, in order to mitigate this risk.

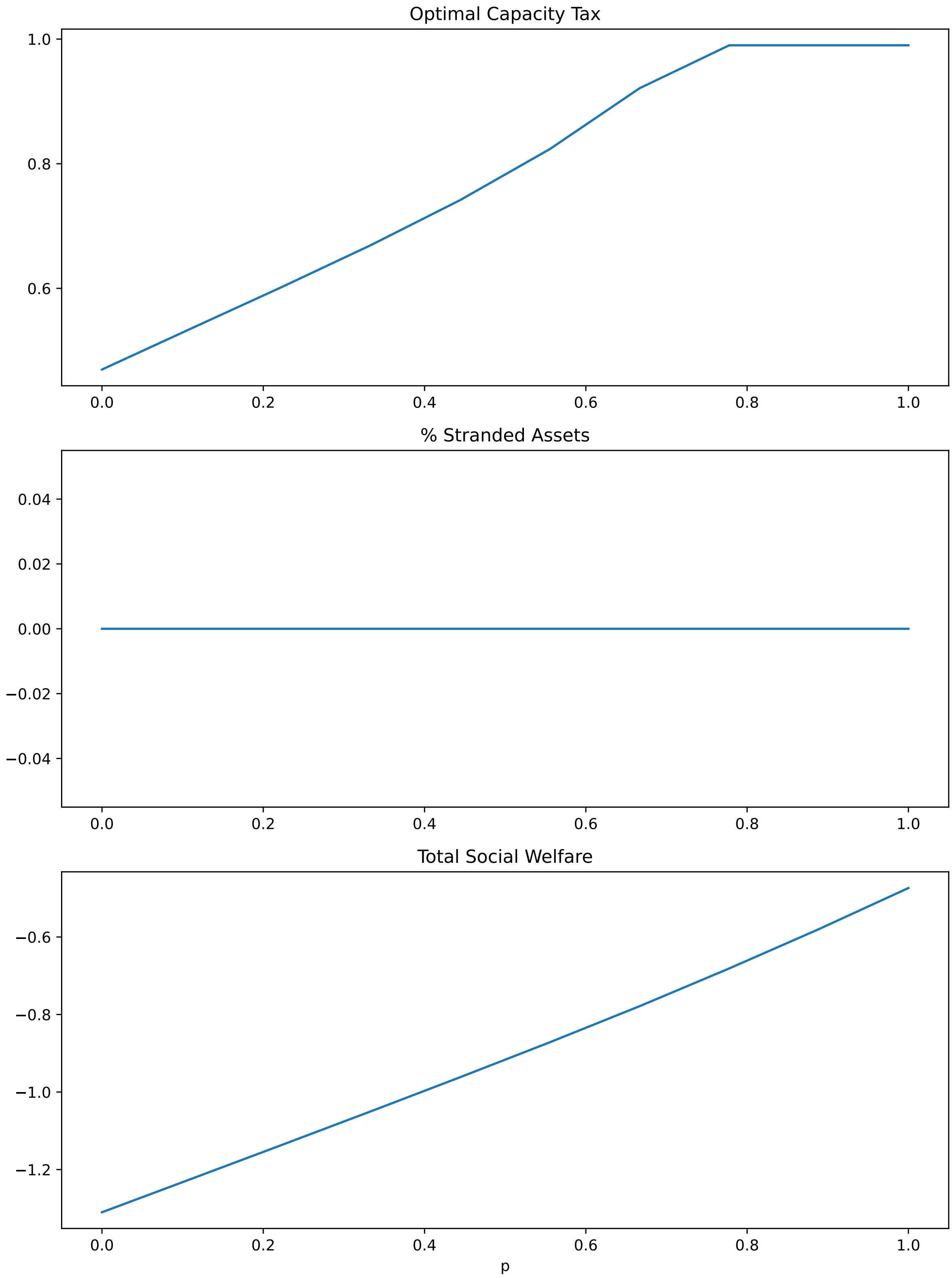

Figure 11: Optimal tax on new capacity and fossil fuel stranded assets. The value for the carbon emissions penalty parameter is fixed at $\lambda = 1$.

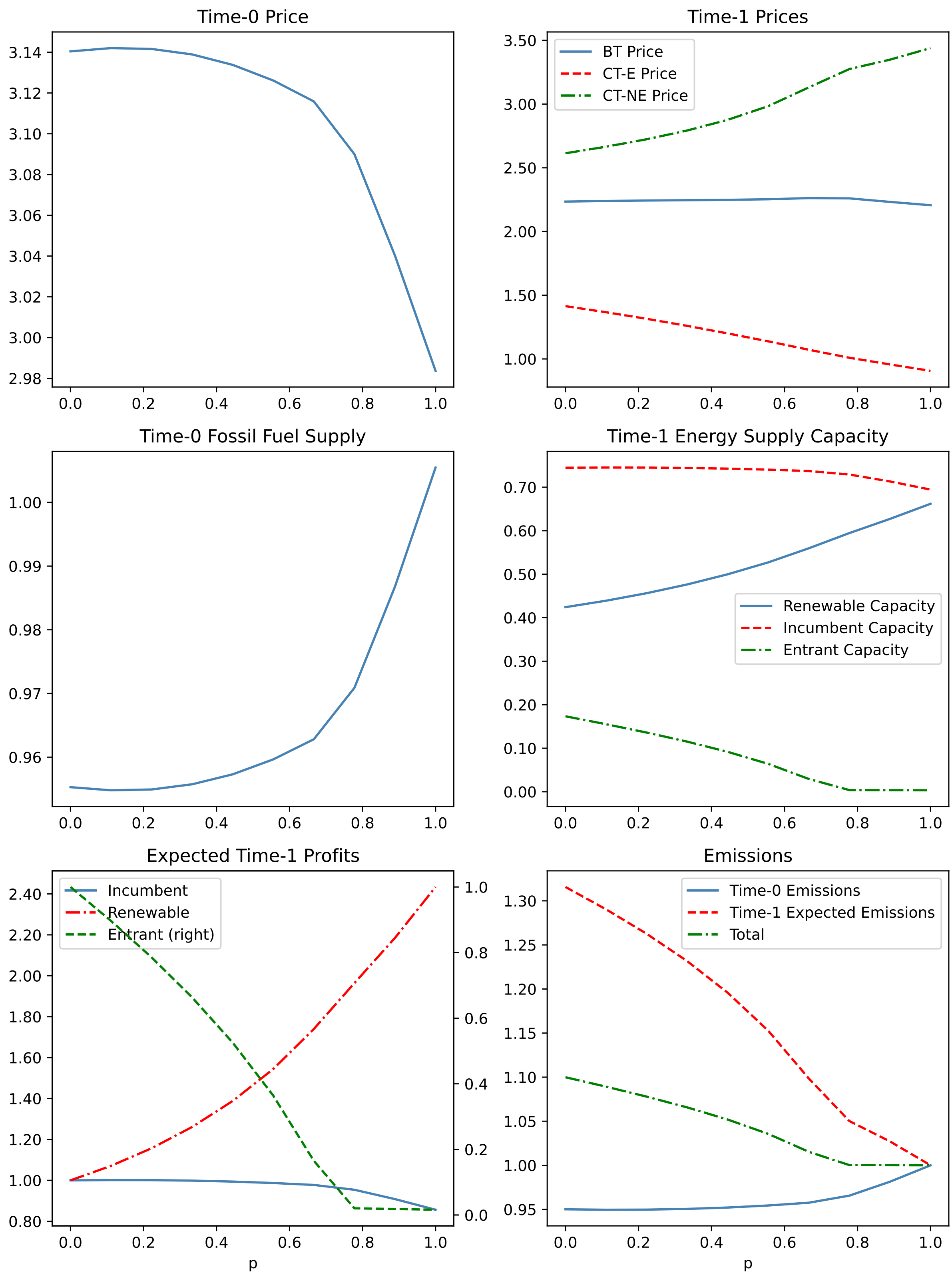

Figure 12: Changes in transition probability with endogenous tax on new capacity.

4 Conclusions

We presented a model that can be used to investigate how transition risk 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. Therefore, 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 can translate 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.

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, the empirical implications of the model can be brought to the data (beyond our preliminary evidence in Figure 2), analyzing in particular how the stock prices of fossil fuel firms react to different climate policy announcements, and investigating whether the stocks of firms with large existing capacities react positively to transition policies (such as taxes on new production capacity) that might at first sight be considered bad for them.

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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

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

   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

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

   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

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

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 $\frac{dP_{1,E}}{dp} \leq 0$.

$\square$

B.2 Proof of Proposition 3

First, consider the case where $\tau_{1,BT} \rightarrow 0$. 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

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

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

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

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

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

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

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

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

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

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

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

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

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 $\frac{dP_0}{d\hat{\tau}_0} \geq 0$.

$\square$

B.4 Proof for section 3.1.1.

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

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

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

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

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

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

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

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

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

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

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

and profits are

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

It then follows that

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

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

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

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.