Are Renewable Energy Policies Climate Friendly? the Role of Capacity Constraints and Market Power

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Abstract

This paper studies the impacts of renewable energy support policies on energy prices, fossil fuel supply and thus carbon emissions and climate change. We show that the impacts are highly dependent on capacity constraints of renewable energies and market power in the fossil fuel sector. We differentiate renewable energies by whether they face production capacity constraints (solar vs. biofuels) and whether they are already competitive (high cost vs. low cost biofuels). We find that government supports for low cost biofuels are always climate friendly. But for renewable energies that are not yet competitive, the climate change impacts of government supports are often ambiguous and are sensitive to the existence of capacity constraints and to the fossil fuel market structure. Solar subsidies are subject to the Green Paradox under perfect competition, but do delay current fossil fuel use to the future under monopoly. High cost biofuel supports under perfect competition lead to more current fossil fuel supply but delay fossil fuel exhaustion time, and these effects are reversed under monopoly. Our results highlight the importance of long-term effects in renewable policy design and carbon accounting.

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1 Introduction

In response to global climate change and high energy prices, major economies throughout the world are promoting the development of renewable energies such as biofuels, wind power and solar energies. The rationale is rather simple: clean renewable energies will substitute fossil fuels, thereby reducing greenhouse gas (GHG) emissions and alleviating the threat of climate change. However, renewable energy policies are not without controversies, especially when indirect market effects are taken into consideration. For instance in the case of corn based ethanol in the US, Searchinger et al (2008) and Hertel et al (2010) argue that additional carbon emissions due to indirect land use effects can dominate any carbon savings from ethanol replacing gasoline: corn ethanol leads to higher food prices, which in turn will cause more land, including forest land, to be converted into agriculture in developing nations, releasing large amounts of carbon. In fact, much of the debate surrounding ethanol has centered on price changes in the feedstock markets (corn and other commodities) and their effects on food security and land uses. Recently studies on indirect market effects have been extended to include the liquid fuel market, where static international trade models are used to evaluate impacts of US domestic ethanol policies on domestic and international gasoline prices and consumption levels (Rajagopal et al, 2011, de Gorter and Drabik, 2011, and Thompson et al, 2011). Due to the small share of biofuels in the liquid fuel market, these studies typically find rather limited impacts of biofuel policies on gasoline consumption and GHG emissions. Holland et al (2009) further show, in a static model, that even when biofuels do have a lower carbon footprint, a policy such as a low carbon fuel standard that limits carbon intensity of fuels does not necessarily reduce overall carbon emissions.

Fossil energies are nonrenewable resources whose extraction decisions are dynamic in nature, and dynamic considerations can drastically alter the likely effects of renewable energy policies, sometimes leading to impacts opposite to predictions from static models. In a recent important paper, Sinn (2008) shows that government policies that help reduce the demand for fossil fuels, e.g. increasing the tax rate on carbon, improving energy efficiency and increasing the use of renewable energies, could lead to over-extraction of fossil fuels in the near future and thus exacerbate the threat of climate change. The reason is that these demand side policies depress the prices of fossil fuels more in the future than at present, encouraging fossil fuel owners to increase current extraction. Sinn (2008) coined the term Green Paradox to describe this unintended consequence.

There is a growing literature examining the possible presence of Green Paradox for different policies (see Sinn (2012) for a good summary). Hoel (2008) and Van Ploeg and Withagen (2012) show that reducing the cost of a backstop technology has two opposing effects: speeding up fossil fuel extraction and leaving more fossil fuels underground remaining unexploited. Gronwald et al (2010) extend Sinn's work by incorporating endogenous capacity adjustment cost for fossil fuels' extraction and show that Green Paradox may not exist under the new setup. Grafton, et al. (2012) focus on renewable energies with increasing marginal cost and show that when both fossil fuels and renewable energies are in use, the subsidy for renewable energies can reduce fossil fuel demand through direct substitution, but also might increase fossil fuel demand due to depressed energy prices. The subsidy for renewable energies thus generates two couterveiling effects on fossil fuel use and its impact on the date of of exhaustion of fossil fuels depends on the demand elasticity for energy and supply elasticity for renewable energies.

The objective of this paper is to study the price and quantity effects of renewable energy policies in the *energy market* in a dynamic model so as to evaluate the long-term economic and GHG impacts of these policies. Government support for renewable energies takes many forms, such as direct price subsidies and quantity mandates. We show that the GHG effects differ across these policies: subsidies to solar can lead to qualitatively different patterns of fossil fuel use and thus GHG emissions from subsidies to biofuels; and for biofuels, cost subsidies and quantity mandates can lead to qualitatively different impacts as well. More importantly, we show that the dynamic GHG effects and thus the likely presence of the Green Paradox are sensitive to market power in the fossil fuel sector and to the capacity constraints of some renewable energies such as biofuels. For instance, while solar subsidies in a perfectly competitive fossil fuel market might lead to more current supply and earlier exhaustion of fossil fuels and thus suffer from the Green Paradox, they can reduce the current use of fossil fuels when market power exists.

Traditionally renewable energies are modeled as "backstop" resources: once their prices become competitive, they can satisfy the total energy demand and thus drive fossil fuels completely out of the market (see Hoel (1978, 1983), Dasgupta and Stiglitz (1981), Dasgupta et al. (1982, 1983) and Chakravorty et al. (2006, 2008)). Solar energy and nuclear fusion power have been modeled as backstop energies. However many renewable energies have capacity constraints since they cannot supply the entire energy market even when they become competitive. For instance, the capacity of biofuels, including second generation biofuel such as cellulosic ethanol, is limited by land availability and increasing demand for food and feed. Wind power has been the fastest growing renewable energy source in the world, but as the capacity increases, prime wind sites are used up and less favorable sites will have to be utilized, increasing the siting cost. Further, these sites are usually located far away from consumption centers, leading to significant transmission costs and increased pressure on the electricity grid. The cost is thus expected to increase sharply after a threshold. By recognizing the capacity constraints, we distinguish capacity constrained renewable energies such as biofuels, wind power and hydropower from abundant renewable energies such as solar energy and nuclear fusion power.[1] In this paper, we use biofuels and solar to represent these two categories of renewable energies. We further divide biofuels into low cost biofuels such as sugarcane ethanol which is currently competitive on the market, and high cost biofuels such as second generation biofuels which is not competitive yet.

The Green Paradox literature commonly assumes competitive energy markets. But market power exists in many fossil fuel markets, especially in the oil sector. In addition to OPEC, national oil companies, which account for over 55% of world production in 2010, are often given monopoly power in their domestic oil markets, as in the case of Russia, China and Venezuela (USEIA, 2013). In this paper, we consider two extreme cases of market structure: perfect competition in which fossil fuel owners take the energy price as given, and monopoly in which a firm or a cartel controls the fossil fuel supply and sets energy prices. In both models, fossil fuels and renewable energies are perfect substitutes, and the supply of renewable energies is always competitive.

We study the impacts of price policies that subsidize the costs of renewable energies and quantity policies that help raise the capacities of biofuels under each of the two market structures. Specifically, the policies we study include solar cost subsidies, high cost biofuel subsidies, and capacity expansion policies for biofuels.[2] Our policy classification is general and covers many real world renewable energy policies. For example, ethanol blenders in the US currently receives \$0.45 per gallon federal subsidy, and the Energy Independence and Security Act of 2007 requires blending of 36 billion gallons of biofuels by 2022, with 21 billion gallons being next generation biofuels. The US federal and state governments have a variety of supports for solar energy, including tax credits, subsidies for R&D and production (e.g., the PV Incubator project in the Solar America Initiative). Moreover, over 20 states in U.S. have Renewable Portfolio Standards that require utilities to generate a certain percentage of their power from renewable energy sources.

The rest of the paper is organized as follows. In Section 2 we set up the model and study the policy impacts in a perfectly competitive fossil fuel market. We analyze the monopolistic fossil fuel market in Section 3. We discuss the role of capacity constraints and market power in Section 4 and conclude in Section 5. Appendix A provides some additional technical

[1] Amigues at al (1998) and Holland (2003) are the few papers in the literature that show the important role of capacity constraints of renewable resources. They find that capacity constraints could change the order of extraction of heterogeneous resources, for the scarcity rent generated by the capacity constraints changes the cost order of different resources.

[2] Since low cost biofuels are already competitive and thus are supplied at their full capacity from the beginning, further subsidies will not have any impact on the equilibrium energy price and quantities. Therefore we only consider the capacity expansion policies for low cost biofuels.

details and Appendix B contains proofs of the propositions.

2 A competitive fossil fuel market

We consider a partial equilibrium model where energy production costs and government policies are exogenously given. We assume that the four energy products including fossil fuels, low cost biofuels, high cost biofuels and solar are perfect substitutes and the supplies of renewable energies are perfectly competitive.[3] In this section, we assume that the fossil fuel sector is perfectly competitive - we study the case of non-competitive fossil fuel markets in the next section.

Let $q_f(t)$ and $X(t)$ be the supply and remaining reserve of fossil fuels in period t with starting reserve X_0. Let $q_{b,i}(t)$, $i = \{l, h\}$, be the supply of biofuel i in period t and $\overline{q}_{b,i}$ be the (per period) production capacity of biofuel i, with $i = l$ representing low cost and $i = h$ representing high cost biofuels. Thus $q_{b,i}(t) \leq \overline{q}_{b,i}$ for all t. Let $q_b(t) = q_{b,l}(t) + q_{b,h}(t)$ and $\overline{q}_b = \overline{q}_{b,l} + \overline{q}_{b,h}$ denote the total biofuel supply and total biofuel capacity. Finally, let $q_s(t)$ be the supply of solar energy in period t. For simplicity, we assume that all energy products have constant marginal production costs and no fixed costs. Let the unit production costs of fossil fuels, biofuels and solar be c_f, $c_{b,l}$, $c_{b,h}$ and c_s, with $c_f < c_{b,l} < c_{b,h} < c_s$. We study government policies that reduce $c_{b,i}$ and c_s, and/or increase $\overline{q}_{b,i}$, $i = \{l, h\}$.

We consider a stable energy demand function $p(t) = h(Q(t))\ \forall t$ with $h'(Q) \leq 0$ where $p(t)$ denotes the energy price in period t and $Q(t) = q_f(t) + q_{b,l}(t) + q_{b,h}(t) + q_s(t)$ is the total energy consumption. We assume

$$\overline{q}_b < h^{-1}(c_s), \tag{1}$$

i.e., biofuel capacity is sufficiently limited so that solar will not be driven out of the market by biofuels. Similarly, fossil fuels cannot be immediately driven out of the market by biofuels when the latter become competitive:

$$\bar{q}_{b,l} < h^{-1}(c_{b,l}) \quad \text{and} \quad \bar{q}_b < h^{-1}(c_{b,h}). \tag{2}$$

Finally, we assume $c_{b,l} < p(0) < c_{b,h}$ so that at present the low cost biofuel is competitive

[3] The main end uses of these energies are electricity and transportation. The substitution of different energy products requires adjusting the energy contents and conversion to different end uses. For example, oil can be converted to transportation use through gasoline and diesel, and solar can be converted to electricity through photovoltaic technology and then used for transportation through electric cars. Chakravorty et.al (2008) describes such conversions in detail and computes the conversion cost for different energy products and different end uses.

against fossil fuels (i.e., it is supplied at full capacity) but the high cost biofuel is not. The condition depends on the initial stock X_0 as well as production costs, and in Appendix A, we spell out the required range of X_0 for this condition to hold.

2.1 Energy market equilibrium

Given perfect competition and constant marginal production costs, the optimal supplies of biofuels are given by

$$q_{b,i}(t) \begin{cases} = 0, & \text{if } p(t) < c_{b,i} \\ \in \left[0, \overline{q}_{b,i}\right], & \text{if } p(t) = c_{b,i} \\ = \overline{q}_{b,i}, & \text{if } p(t) > c_{b,i} \end{cases}, \quad i = \{l, h\}, \tag{3}$$

and the optimal supply of solar energy is

$$q_s(t) \begin{cases} = 0, & \text{if } p(t) < c_s \\ \geq 0, & \text{if } p(t) = c_s \end{cases}. \tag{4}$$

Since solar is a backstop resource, energy price can never exceed c_s.

When the fossil fuel sector is competitive, the (representative) fossil fuel producer takes the market price trajectory $\{p(t), t \geq 0\}$ as given and chooses its extraction path according to

$$\max_{\{q_f(t)\}} \int_0^{\Gamma} e^{-rt} \left[p(t) q_f(t) - c_f q_f(t)\right] dt$$
$$\text{s.t.} \quad \dot{X}(t) = -q_f(t); \quad \int_0^{\Gamma} q_f(t)\, dt = X_0;$$

where r is the market interest rate, Γ is the ending time when the fossil fuel is driven completely out of the market, $X(t)$ is the remaining stock at time t, and X_0 is the initial stock level. Since the extraction cost is stock independent, stock X_0 will be exhausted. Forming the Hamiltonian and optimizing, we have the firm's optimal supply given by

$$q_f(t) \begin{cases} = 0 & \text{if } p(t) < c_f + \lambda e^{rt} \\ \geq 0 & \text{if } p(t) = c_f + \lambda e^{rt} \end{cases} \tag{5}$$

where λ is the present value Hotelling rent (or in-situ value). The term $c_f + \lambda e^{rt}$, called the augmented marginal cost (AMC) by Holland (2003), measures the "total" marginal cost that includes the scarcity value of fossil fuels in the ground. The firm's extraction decision is made by comparing this cost with the energy price.

The competitive equilibrium is characterized by the supply functions (3), (4), and (5), and the market clearing condition $h\left(q_f\left(t\right)+q_b\left(t\right)+q_s\left(t\right)\right)=p(t)\ \forall t$. From (5), we know $p(t)=c_f+\lambda e^{rt}$ if $q_f(t)>0$: as long as the fossil fuels are still supplied, the AMC completely determines the energy price. During this period, energy price increases overtime and gradually crosses the costs of various renewable energies, at which points these energies start to be supplied at full capacities. Let Γ_1 be the time when the energy price reaches the cost of high cost biofuels, i.e., $c_{b,h}=c_f+\lambda e^{r\Gamma_1}$. We can divide the equilibrium path into several stages.

During the first stage $t\in[0,\Gamma_1)$, $p(t)<c_{b,h}$: the high cost biofuel is not competitive but the low cost biofuel supplies at its full capacity. The fossil fuels supply the residual market at rates

$$q_f\left(t\right)=h^{-1}\left(c_f+\lambda e^{rt}\right)-\overline{q}_{b,l},\quad t\in[0,\Gamma_1). \tag{6}$$

During the second stage $t\in[\Gamma_1,\Gamma)$, $c_{b,h}\leq p(t)<c_s$ with $p(\Gamma)=c_s$: both types of biofuels are competitive and supplied at their full capacities, but solar is still not competitive. The supply of fossil fuels is given by

$$q_f\left(t\right)=h^{-1}\left(\lambda e^{rt}+c_f\right)-\overline{q}_b,\quad t\in[\Gamma_1,\Gamma). \tag{7}$$

Since solar is a backstop resource, fossil fuels are exhausted at time Γ, at which point solar becomes competitive and supplies the market together with biofuels. For $t\geq\Gamma$, $p(t)=c_s$, $q_f\left(t\right)=0$, $q_{b,i}\left(t\right)=\overline{q}_{b,i}$, $i=\{l,h\}$, and solar supplies the residual demand: $q_s(t)=h^{-1}\left(c_s\right)-\overline{q}_b$.

Figure 1 illustrates the price and supply paths of fossil fuels (solid curves). The paths are characterized by three variables, $\{\lambda,\Gamma_1,\Gamma\}$, which are determined by

$$\begin{aligned}
\int_0^{\Gamma_1}\left[h^{-1}\left(c_f+\lambda e^{rt}\right)-\bar{q}_{b,l}\right]dt+\int_{\Gamma_1}^{\Gamma}\left[h^{-1}\left(c_f+\lambda e^{rt}\right)-\bar{q}_{b,h}-\bar{q}_{b,l}\right]dt &= X_0, && (8)\\
c_f+\lambda e^{r\Gamma_1} &= c_{b,h}, && (9)\\
c_f+\lambda e^{r\Gamma} &= c_s. && (10)
\end{aligned}$$

2.2 Impacts of renewable energy policies

Through comparative analysis of (8) — (10), we can evaluate the impacts of renewable energy policies on fossil fuel supply and the associated GHG emissions. Strictly speaking, a policy is climate friendly if it reduces the net present value (NPV) of GHG damages, and is subject to Green Paradox if it raises the NPV of GHG damages. Specific damage functions and CO_2 accumulation equations are needed to numerically evaluate the climate impacts of these policies. In this paper, we resort to more qualitative definitions of climate friendliness and Green Paradox. Since CO_2 is a stock pollutant with a low rate of dissipation, and since fossil fuels have larger carbon footprints than renewable energies, we say that a policy is *climate friendly* if it delays the current extraction of fossil fuels, i.e., if it reduces fossil fuel supply in early periods (which naturally means that it increases the supply in later periods), *and* it postpones the time Γ at which the fossil fuels are exhausted.[4] Delaying current fossil fuel supply is beneficial since future climate damages are discounted, and since early carbon emissions accumulate in the atmosphere leading to damages both now and in the future. Similarly, later exhaustion of fossil fuels means delaying the release of all stored carbon in the fossil fuel stock. Conversely, Green Paradox arises if fossil fuel supply rises in the near future *and* the stock is exhausted earlier in response to a renewable energy policy.[5] As we show below, there are some *intermediate cases* where only one of the two conditions is satisfied or violated. In these cases, no definite conclusions can be drawn on the effects of the policies unless numerical parameter values are used. We leave this more accurate assessment of the climate effects of the policies to future work.

To study the changes in the supply path of fossil fuels, we first evaluate the changes in energy prices.

Proposition 1 *Suppose the energy market is perfectly competitive. Then*

(1) $\partial\lambda/\partial c_s > 0$, $\partial\Gamma_1/\partial c_s < 0$ *and* $\partial\Gamma/\partial c_s > 0$*: solar subsidies reduce the value of fossil fuels and thus the energy price, delay the arrival time of high cost biofuels and speed up the exhaustion of fossil fuels;*

(2) $\partial\lambda/\partial c_{b,h} > 0$, $\partial\Gamma_1/\partial c_{b,h} > 0$ *and* $\partial\Gamma/\partial c_{b,h} < 0$*: high cost biofuel subsidies reduce energy price, speed up the arrival time of high cost biofuels and delay the exhaustion of fossil fuels; and*

(3) $\partial\lambda/\partial\overline{q}_{b,i} < 0$, $\partial\Gamma_1/\partial\overline{q}_{b,i} > 0$ *and* $\partial\Gamma/\partial\overline{q}_{b,i} > 0$, $i = \{l, h\}$*: capacity expansion policies for both types of biofuels reduce energy price, and delay the arrival time of biofuels and the exhaustion time of fossil fuels.*

The proof is in Appendix B. Proposition 1 is illustrated in Figures 1(a) - 3(a), with the bold dashed lines representing price paths after policy implementation. Since the renewable energies and fossil fuels are substitutes, renewable energy policies will render the fossil fuels

[4] Hoel (2008) derives a general condition under which delaying current GHG emissions to the future would be beneficial and argues that the condition is easily satisfied.

[5] Most papers in the literature define Green Paradox as arising when one of the two conditions is true. For instance, Sinn (2008) defines Green Paradox as increased fossil fuel use in early periods, and Grafton et al (2012) defines Green Paradox as the speed up of fossil fuel exhaustion time.

less competitive and thus reduce the Hotelling rent and the energy prices. Price reductions tend to increase fossil fuel supply and speed up their exhaustion, leading to Green Paradox. However, as illustrated in Figures 1(b) - 3(b), this is not always the case due to biofuels' capacity constraints.

Figures 1(b) - 3(b) describe the quantity paths and can be derived directly from Proposition 1 and Figures 1(a)-3(a). From Figure 1(b), Green Paradox arises for solar policies: due to the reduction in energy prices, fossil fuel supplies increase for all periods, including early periods, and consequently fossil fuel exhaustion occurs sooner. Although the reduction of $c_{b,h}$ pushes up fossil fuel supplies in earlier periods, it also speeds up the arrival time of the high cost biofuel. There is thus a period $[\Gamma', \Gamma]$ in Figure 2(b) during which fossil fuel supplies are reduced. In fact, the supply reduction dominates the supply increase in other periods so that the fossil fuel is exhausted at a later time. In Figure 3(b), an increase in capacity $\bar{q}_{b,h}$ raises fossil fuel supplies in earlier periods and reduces the supplies in later periods. Again, the supply reduction dominates so that fossil fuels are exhausted at a later time. Thus price and quantity supports for high cost biofuels have ambiguous qualitative impacts: they are not entirely climate friendly and Green Paradox does not arise either.

Since low cost biofuels are already competitive (and thus supplied at their full capacity), further reduction of its cost $c_{b,l}$ does not have any impact on fossil fuel supply. If its capacity $\bar{q}_{b,l}$ expands, the exhaustion time of fossil fuels is delayed and there are two opposing effects on q_f. On one hand, q_f decreases given fixed total energy demand since biofuel is a perfect substitute for the fossil fuel. On the other hand, since the energy price decreases, the total energy demand rises. Further, since $\partial\lambda/\partial\bar{q}_{b,l} < 0$, and the energy price is $p(t) = c_f + \lambda e^{rt}$, the energy price is reduced more in future periods. Thus, we expect that the energy price effect dominates in future periods, and the substitution effect dominates in earlier periods. We can formally establish this result when the demand function is linear.

Corollary 2 *Suppose the fossil fuel market is perfectly competitive and the energy demand function is linear. Then capacity expansion policies for low cost biofuels reduce fossil fuel supply in early periods.*

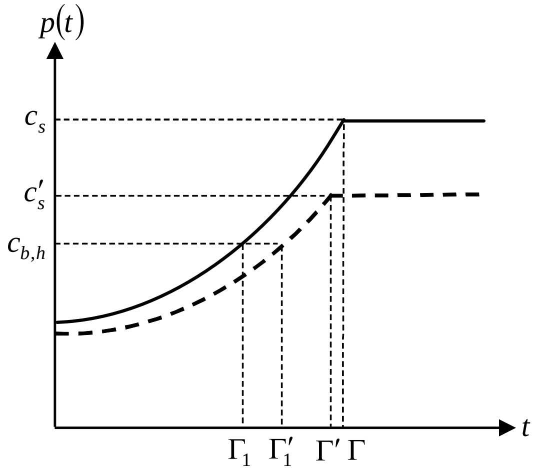
As shown in Figure 4, low cost biofuel capacity expansion delays fossil fuel supply and delays its date of exhaustion, and is thus climate friendly. In summary,

Proposition 3 *If the energy market is perfectly competitive, then*

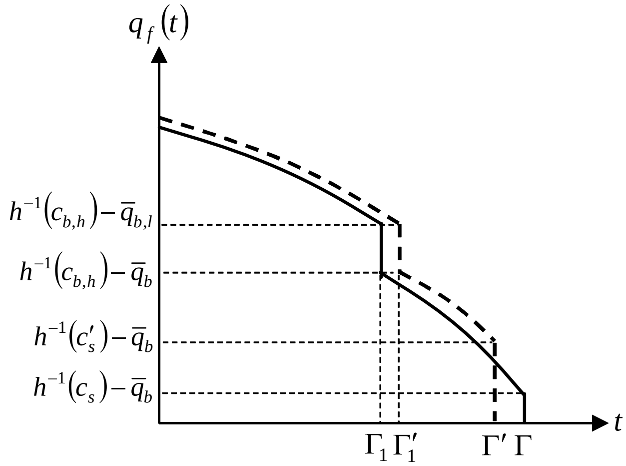
(1) Green Paradox arises for solar cost reduction policies;

(2) Under linear demand, capacity expansion policies for low cost biofuels are climate friendly; and

(3) The climate change effects of the two high cost biofuel policies are ambiguous.

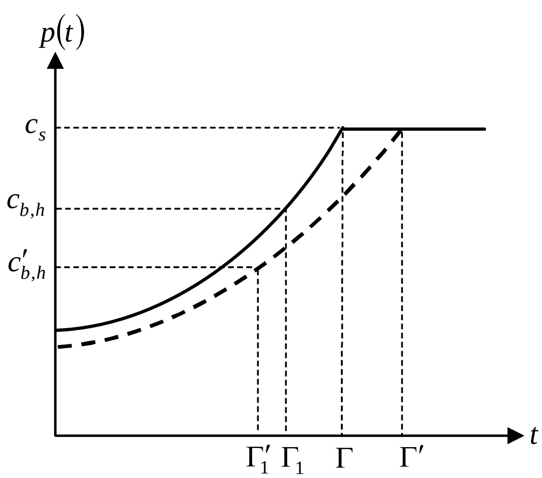


(a) Impact on prices

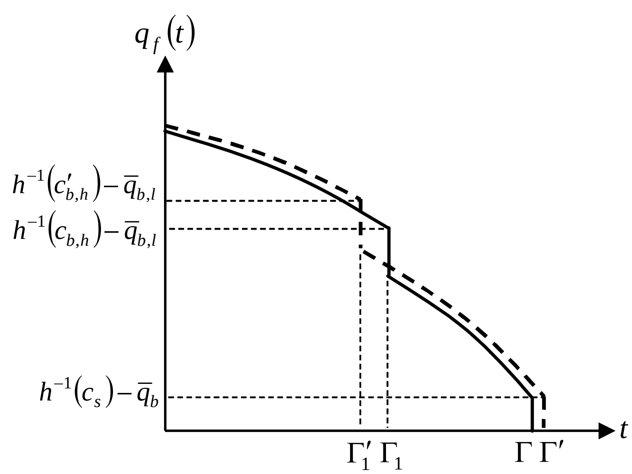


(b) Impact on fossil fuel supply

Figure 1: Impacts of solar subsidies: perfect competition

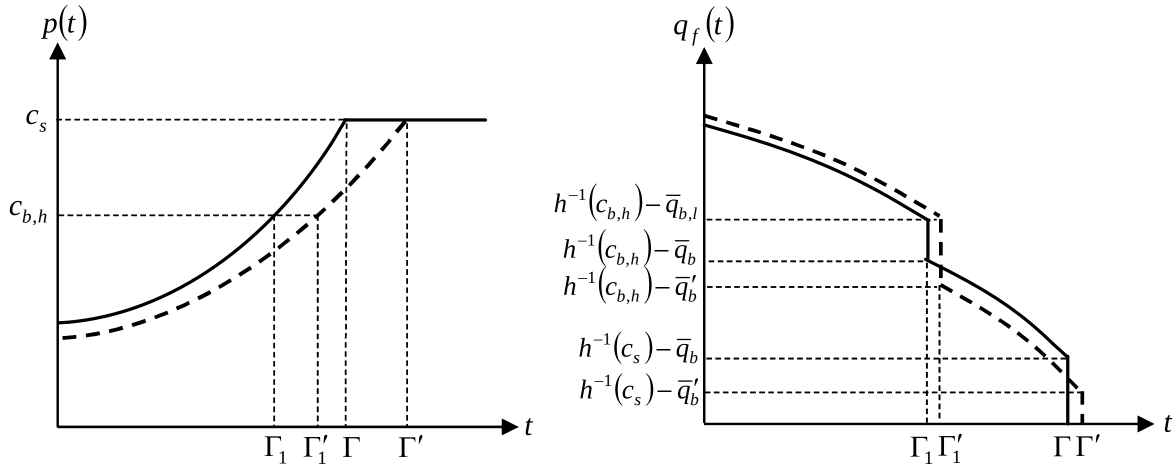


(a) Impact on prices



(b) Impact on fossil fuel use

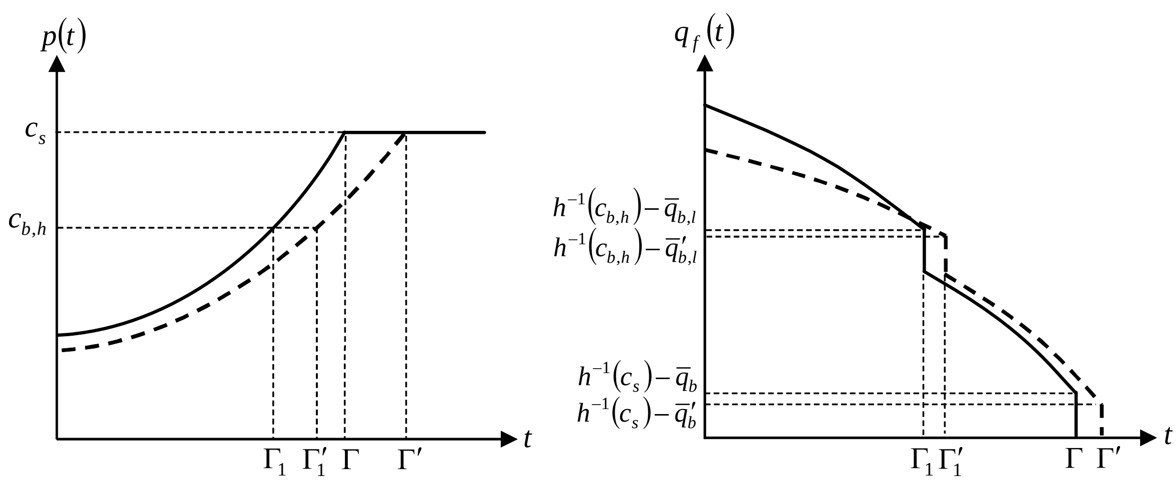
Figure 2: Impacts of high cost biofuel subsidies: perfect competition



(a) Impact on prices

(b) Impact on fossil fuel supply

Figure 3: Impacts of high cost biofuel capacity expansion policies: perfect competition



(a) Impact on prices

(b) Impact on fossil fuel supply

Figure 4: Impacts of low cost biofuel capacity expansion policies: perfect competition

Although solar and biofuels are assumed to be perfect substitutes, they have strikingly different impacts on fossil fuel supplies due to the existence or absence of capacity constraints. Despite the controversy surrounding the indirect land use change effects of biofuels, Proposition 3 shows that, *if* the oil sector is competitive, capacity expansion of low cost biofuels such as sugar ethanol (or corn ethanol if it is already competitive) can have beneficial impacts on climate change through indirect effects on oil supply, and capacity expansion policies such as quantity mandates in the Energy Independence and Security Act are preferred to cost reduction policies such as biofuel blending subsidies.

3 Non-competitive fossil fuel market

Fossil fuel markets are often characterized by imperfect competition (Loury, 1986; Polasky, 1992). In this section, we show that imperfect competition can significantly affect the climate change impacts of renewable energy policies. To sharpen our analysis, we focus on an extreme scenario where the fossil fuel sector is controlled by a monopolist while maintaining the assumption that the renewable energies are supplied by competitive firms.

3.1 Energy market equilibrium

The optimal supplies of renewable energies are still given by (3) and (4). The monopolist acts as a Stackelberg leader in the energy market and its optimization problem is

$$\max_{\{q_f(t)\}} \int_0^T e^{-rt} \left[h\left(q_f(t) + q_{b,h}(t) + q_{b,l}(t) + q_s(t)\right) q_f(t) - c_f q_f(t) \right] dt \tag{11}$$

$$\text{s.t.} \quad \dot{X}(t) = -q_f(t)\,; \; \int_0^T q_f(t)\, dt = X_0;\; (3);\; (4),$$

where T is the exhaustion time of the fossil fuel stock. Since the fossil fuel firm is the Stackelberg leader, it needs to incorporate the responses of renewable energies in choosing $q_f(t)$ to maximize (11). We assume the revenue function $h(q_f + q_b + q_s)\, q_f$ is concave in q_f given q_b and q_s.

The present value Hamiltonian of (11) can be written as

$$H_t = h\left(q_f(t) + q_b(t) + q_s(t)\right) q_f(t) - c_f q_f(t) - \mu e^{rt} q_f(t) \tag{12}$$

where μ is the present value Hotelling rent. Free choice of exhaustion time T leads to the

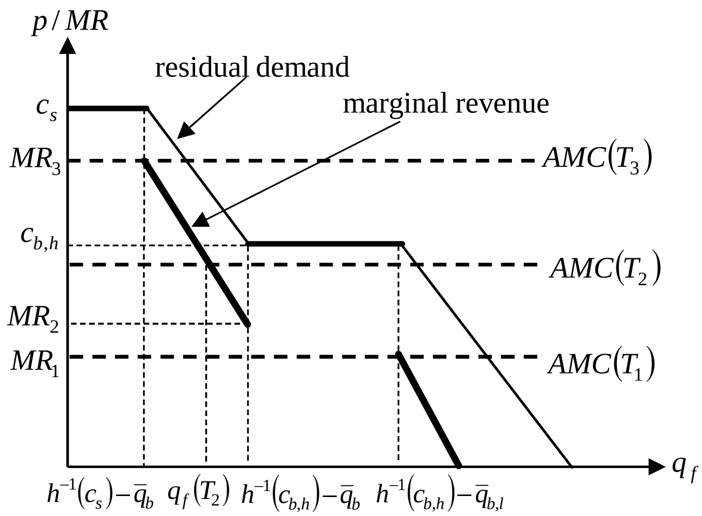


Figure 5: The residual demand and marginal revenue for the monopolist

transversality condition

$$H_T = h\left(q_f\left(T\right) + q_b\left(T\right) + q_s\left(T\right)\right) q_f\left(T\right) - c_f q_f\left(T\right) - \mu e^{rT} q_f\left(T\right) = 0. \tag{13}$$

If the optimal $q_f(t)$ is an interior solution, it is determined from (12) by equating the marginal revenue with AMC:

$$h'\left(q_f\left(t\right) + q_b\left(t\right) + q_s\left(t\right)\right) q_f\left(t\right) + h\left(q_f\left(t\right) + q_b\left(t\right) + q_s\left(t\right)\right) = c_f + \mu e^{rt} \tag{14}$$

However, as we show below, the optimal decision does not always involve interior solutions. Figure 5 illustrates the residual demand curve facing the monopolist and the associated marginal revenue curve (the bold curve), which equals $h'q_f + h$ when the residual demand function is differentiable. Note that the marginal revenue curve is discontinuous at $p = c_{b,h}$ and $p = c_s$. At the two price levels, the residual demand curve is flat so that the monopolist can reduce its supply without raising the energy price since the high cost biofuel or solar will simply "make up" the rest of the total demand. Alternatively, the monopolist can increase its supply up to the total demand without decreasing the energy price since the supply of high cost biofuel or solar will be decreased correspondingly. Thus when high cost biofuel or solar just becomes competitive, the marginal revenue jumps from $h'q_f + h$ up to h.

The monopolist's output decision q_f and thus the market equilibrium are determined by comparing the (residual) marginal revenue and AMC $c_f + \mu e^{rt}$. As shown in Figure 5, $AMC(t)$ is a horizontal line and continuously increases over time. But the marginal revenue curve is not continuous, so that the equilibrium might occur at interior or corner solutions. Depending on the nature of the solutions, we divide the equilibrium paths into several stages: Figure 5 shows representative levels of AMC corresponding to these stages, and Figure 6(a) (solid curves) illustrates the equilibrium price path.

During the first stage $t \in [0, T_1)$, where T_1 is such that $AMC(T_1) = MR_1$ in Figure 5, $p(t) < c_{b,h}$ and the high cost biofuel is not competitive. The optimal q_f is given by an interior solution at the intersection of AMC and the marginal revenue curve below MR_1:

$$h'\left(q_f(t) + \overline{q}_{b,l}\right) q_f(t) + h\left(q_f(t) + \overline{q}_{b,l}\right) = c_f + \mu e^{rt}. \tag{15}$$

During this stage, low cost biofuels are supplied at their full capacity and fossil fuels supply the residual demand. High cost biofuels and solar do not enter the market.

At $t = T_1$, $p(T_1) = c_{b,h}$ so that high cost biofuels become competitive. As discussed earlier, the monopolist's (residual) marginal revenue jumps up while $AMC(t)$ still continuously increases. Therefore after T_1, the marginal revenue, which is equal to $c_{b,h}$, would be higher than $AMC(t)$ for a while, and the optimal q_f takes a corner solution: $q_f(t) = h^{-1}(c_{b,h}) - \bar{q}_{b,l}$, supplying the entire residual market with low cost biofuels supplying at their capacity. During this period, the monopolist floods the market and staves off high cost biofuels.

Note that as the monopolist floods the market, the market price remains flat at $c_{b,h}$. This is optimal for the monopolist because if the price is higher, high cost biofuels would supply the market at full capacity and the fossil fuel supply would drop dramatically, leading to a plummet of profit. However, as $AMC(t)$ further rises, the profit margin of flooding the market $(p(t) - AMC(t))$ decreases and at a certain point of time, it pays to raise the price above $c_{b,h}$ and have the high cost biofuels in the market: the increased profit margin more than offsets the reductions in market share. In fact, as shown in Figure 5, there is a period of time during which $AMC(t)$ remains between $[MR_2, c_{b,h}]$ and still intersects with the marginal revenue curve. Thus, there are two possible solutions for $q_f(t)$: the corner solution as before and the interior solution determined by equating marginal revenue to $AMC(t)$. As shown in Wang and Zhao (2013), there is a time T_2 before $AMC(t)$ reaches $c_{b,h}$ so that at $t = T_2$, the monopolist switches to the interior solution, energy price jumps from $c_{b,h}$ up, high cost biofuel supply jumps from zero to its full capacity $\bar{q}_{b,h}$, and consequently the fossil fuel supply jumps down. Further, T_2 is determined by

$$q_f(T_2)\left[h\left(q_f(T_2) + \overline{q}_b\right) - c_f - \mu e^{rT_2}\right] = \left[h^{-1}(c_{b,h}) - \overline{q}_{b,l}\right]\left(c_{b,h} - c_f - \mu e^{rT_2}\right) \tag{16}$$

where $q_f(T_2)$ is the residual demand for fossil fuels at T_2 at the interior solution. Equation (16) states that at T_2 the Hamiltonian associated with the interior solution (the left hand side) should equal that associated with the corner solution (the right hand side).

We summarize the above results in the following:

Summary 4 *As the energy price rises to the cost of high cost biofuels at* T_1*, the monopolist would stave off high cost biofuels for a while by flooding the market and keeping the energy price flat at* $c_{b,h}$*. Eventually, at* $T_2 > T_1$*, the monopolist lets the energy price jump up above the cost of high cost biofuels. The monopolist's supply jumps down while that of the high cost biofuel jumps up to its full capacity.*

During stage three $t \in [T_2, T_3)$ where T_3 is such that $AMC(T_3) = MR_3$ in Figure 5, high cost biofuels are supplied at full capacity and $q_f(t)$ is determined by an interior solution equating the marginal revenue to AMC:

$$h'\left(q_f\left(t\right) + \overline{q}_b\right) q_f\left(t\right) + h\left(q_f\left(t\right) + \overline{q}_b\right) = c_f + \mu e^{rt}. \tag{17}$$

Energy price continuously increases and $q_f(t)$ continuously decreases, until T_3 when energy price reaches c_s. As the solar energy becomes competitive, the monopolist again picks the corner solution and floods the market, staving solar energy from the market for a certain period. It does so until its stock is exhausted at T. For $t \in [T_3, T)$, $p(t) = c_s$ and the optimal fossil fuel supply is given by

$$q_f\left(t\right) = h^{-1}\left(c_s\right) - \overline{q}_b. \tag{18}$$

Intuitively, since energy price cannot exceed c_s, any delay of fossil fuel extraction would incur the interest cost without any benefit. Therefore, during this stage the monopolist would extract its stock as soon as possible, i.e., it produces at the maximum rate given in (18).

$[T, \infty)$ is the final stage, during which the energy price remains constant at c_s, $q_f\left(t\right) = 0$, $q_{b,l}\left(t\right) = \overline{q}_{b,l}$, $q_{b,h}\left(t\right) = \overline{q}_{b,h}$ and solar supplies the rest of the demand at $h^{-1}\left(c_s\right) - \overline{q}_b$. Since at the exhaustion time T, $p\left(T\right) = c_s$, equation (13) implies

$$c_s = c_f + \mu e^{rT} \tag{19}$$

Figure 6 illustrates the energy price path and fossil fuel supply path over the different stages.

The equilibrium price and quantity paths are fully characterized by $\{\mu, T_1, T_2, T_3, T, q_f\left(T_2\right)\}$, which are determined by (19), (16) and

$$\int_0^{T_1} q_f(t)\,dt + \left[h^{-1}(c_{b,h}) - \overline{q}_{b,l}\right](T_2 - T_1) + \int_{T_2}^{T_3} q_f(t)\,dt + X_{T_3} = X_0 \tag{20}$$

$$h'\left(h^{-1}(c_{b,h})\right)\left[h^{-1}(c_{b,h}) - \overline{q}_{b,l}\right] + c_{b,h} - c_f - \mu e^{rT_1} = 0 \tag{21}$$

$$h'(q_f(T_2) + \overline{q}_b)\, q_f(T_2) + h(q_f(T_2) + \overline{q}_b) - c_f - \mu e^{rT_2} = 0 \tag{22}$$

$$h'\left(h^{-1}(c_s)\right)\left[h^{-1}(c_s) - \overline{q}_b\right] + c_s - c_f - \mu e^{rT_3} = 0 \tag{23}$$

Equation (20) is the resource exhaustion condition for fossil fuels, and the corresponding fossil fuel supply, $q_f(t)$, in (20) is derived from (15) and (17). Equations (21), (22) and (23) respectively represent the optimal conditions at times T_1, T_2 and T_3, i.e., the marginal revenue at these times should equal the corresponding augmented marginal costs.

3.2 Impacts of renewable energy policies

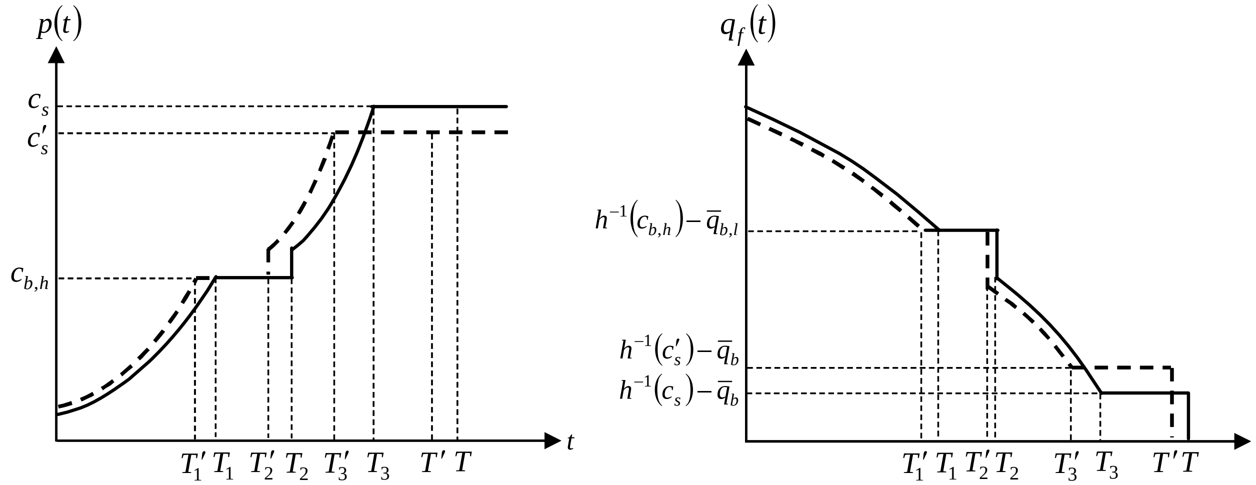
Given the equilibrium paths of fossil fuel prices and supplies determined above, we study how these paths respond to the renewable energy policies. We first consider policies that reduce the cost of solar energy.

Proposition 5 *Under monopoly, solar subsidies*

(1) raise the present shadow value of fossil fuels, i.e. $\partial\mu/\partial c_s < 0$, and thus reduces fossil fuel production $q_f(t)$ in early periods (for $t < T_1$); and

(2) bring forward $\{T_1, T_2, T_3, T\}$, i.e. $\partial T_i/\partial c_s > 0$, $i = \{1, 2, 3\}$, and $\partial T/\partial c_s > 0$.

These results generalize Hoel (1978) who studies an energy market without biofuels and with a constant elasticity demand function. Figure 6 illustrates the impacts of solar subsidies on energy prices and quantities. Opposite to the case of perfect competition (cf. Proposition 1(1)), the monopolist fossil fuel owner *raises*, not reduces, energy prices in response to solar cost reduction in periods before solar becomes competitive. This might seem surprising given that solar is modeled as a perfect substitute to fossil fuels. To understand the intuition, note that the monopolist, unlike a competitive producer, always has incentives to reduce its output in order to raise energy prices. This incentive is "mitigated" by the inherent dynamic nature of its decision problem: current extraction reductions will necessarily lead to future extraction increases, and current price hikes will be traded with future price reductions. The current vs. future trade-off is affected by, among other factors, the relative elasticities of the residual demand function facing the monopolist in different periods. Other things equal, the monopolist has incentive to extract more in periods with higher residual demand elasticities because it is more difficult to raise prices during these periods - it has to cut its production



(a) Impact on prices (b) Impact on fossil fuel supply

Figure 6: Impacts of solar subsidies: monopoly

by a larger amount. During period $[T_3, T)$ the residual demand elasticity is infinite, and as a result the monopolist extracts the maximum possible amount, effectively staving off solar energy from the market. As c_s decreases, the period of infinite residual demand elasticity starts earlier (Figures 7(a) and 6(a)): T_3 decreases to T_3' so that for period $[T_3', T_3]$, the residual demand elasticity increases from finite levels to infinite. Further, since $p(t) = c_s' < c_s$ during $t \geq T_3'$, the lower solar cost implies that the monopolist can produce more to flood the market. In response to the two changes, the monopolist has to reduce its extraction in early periods so as to increase its extraction for periods $t \geq T_3'$.

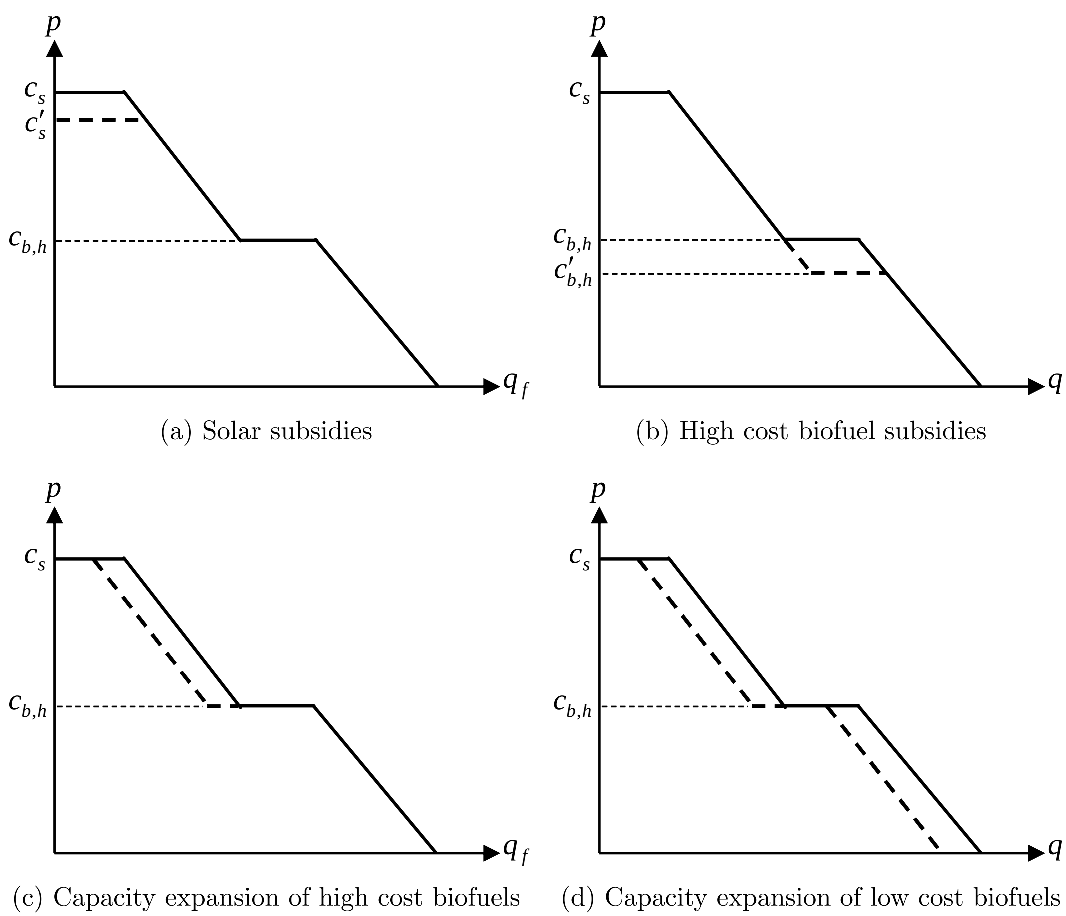
Figure 6(b) shows that although solar subsidies reduce the early use of fossil fuels, the stock of fossil fuels is also exhausted earlier. The net effect of such policies on global climate change is ambiguous, allowing the possibility that solar policies help mitigate climate change if the damages from increased carbon emissions in the future are more than offset by gains from reduced carbon emissions in early periods. Further, the effects under monopoly differs sharply from the case of perfect competition: with the existence of market power, solar subsidies are not necessarily subject to Green Paradox.

We next show that the impacts of high cost biofuel subsidies are similar to those of solar subsidies.

Proposition 6 *Under monopoly, high cost biofuel subsidies*

(1) raise the present shadow value of fossil fuels, i.e. $\partial \mu / \partial c_{b,h} < 0$*, and thus reduces fossil fuel production* $q_f(t)$ *in early periods (for* $t < T_1$*); and*

(2) bring forward $\{T_1, T_2, T_3, T\}$*, i.e.* $\partial T_i / \partial c_{b,h} > 0$*,* $i = \{1, 2, 3\}$*, and* $\partial T / \partial c_{b,h} > 0$*.*



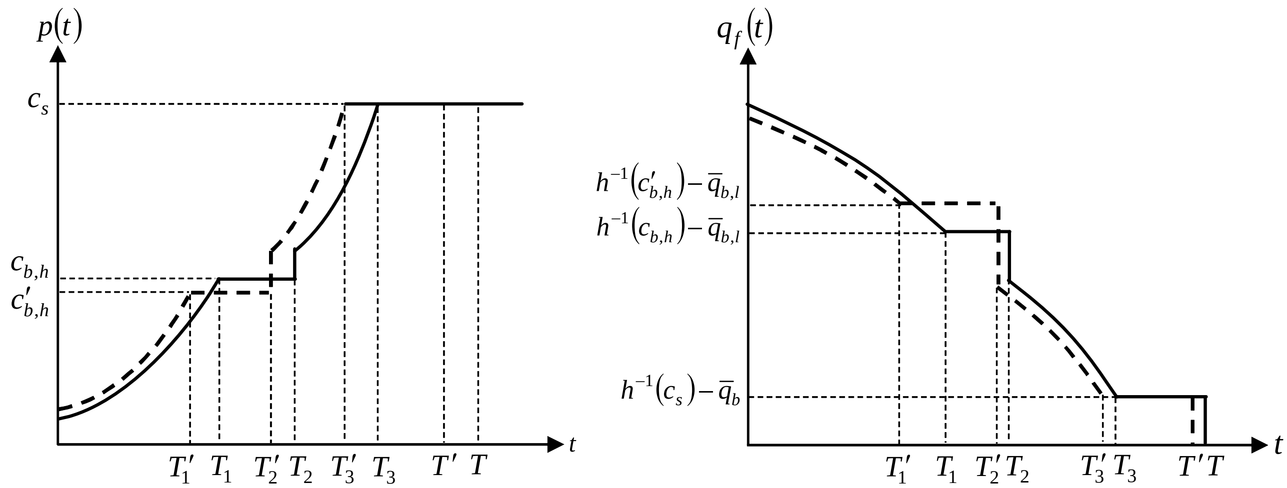
(a) Solar subsidies

(b) High cost biofuel subsidies

(c) Capacity expansion of high cost biofuels

(d) Capacity expansion of low cost biofuels

Figure 7: Policy impacts on the residual demand for the monopolist



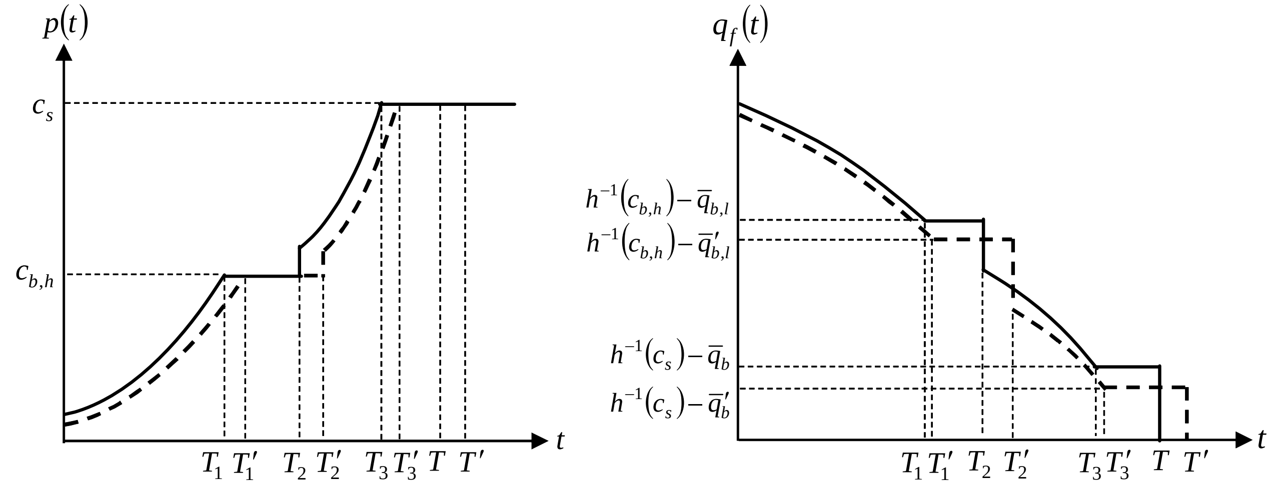
(a) Impact on prices

(b) Impact on fossil fuel supply

Figure 8: Impacts of high cost biofuel subsidies: monopoly

Figure 8 illustrates the impacts on the price and quantity paths. The intuition is again similar to that in Proposition 5. As $c_{b,h}$ decreases, two changes occur related to the residual demand elasticities: (i) the period of infinite elasticity when the monopolist floods the market to stave off high cost biofuels occurs earlier, and (ii) the monopolist needs to produce more in order to stave off high cost biofuels ($h^{-1}(c_{b,h}) - \bar{q}_{b,l}$ is decreasing in $c_{b,h}$). Both changes imply that the monopolist has incentive to reduce its output before high cost biofuels become competitive, so that it can raise its output during the "stave-off" period $[T_1, T_2)$. In fact, as shown in Figure 8(b), the monopolist's output also decreases after T_2 to compensate for increased production during $[T_1, T_2)$.

Finally we examine the effects of biofuel capacity expansion policies. Again the impacts will depend on how cross-period comparisons of the residual demand elasticities change as the capacities expand, and we argue that capacity expansions will raise the elasticities relatively more in future periods than in current periods. Consider, for instance, the expansion of low cost biofuels' capacity $\bar{b}_{b,l}$ when the demand function is linear. Figure 7(d) shows how the residual demand curve shifts in. For the two downward slopping segments of the demand curve, it is straightforward to show that the residual demand elasticity increases as $\bar{b}_{b,l}$ increases: the elasticity equals $(dq/dp)(p/q)$, and inward parallel shifts of the demand curve raises the ratio p/q while the slope dq/dp is unchanged. Moreover, the elasticities increase relatively more when price is higher and quantity is lower, i.e., in future periods than in current periods. Therefore, at least the the case of linear demand, we expect that low cost biofuel capacity expansion will lead the monopolist to produce less in current periods and



(a) Impact on prices

(b) Impact on fossil fuel supply

Figure 9: Impacts of low cost biofuel capacity expansion policies: monopoly

more in future periods.

Proposition 7 *Under monopoly and for linear energy demand functions, capacity expansion policies for low cost biofuels*

(1) reduce the present shadow value of fossil fuels, i.e., $\partial\mu/\partial\overline{q}_{b,h} < 0$*;*

(2) delay $\{T_1, T_2, T_3, T\}$*, i.e.* $\partial T_i/\partial\overline{q}_{b,h} > 0$*,* $i = \{1, 2, 3\}$*, and* $\partial T/\partial\overline{q}_{b,h} > 0$*; and*

(3) reduce fossil fuel production $q_f(t)$ *for early periods* $t < T_1$*.*

Figure 9 shows the changes in price and quantity paths in response to capacity expansion of low cost biofuels. Current production of fossil fuels is delayed to future periods and the fossil fuel stock is exhausted at a later time. Thus, low cost biofuel capacity expansion policies are indeed climate friendly.

The effects of high cost biofuel capacity expansion on the residual demand elasticities are similar to those of low cost biofuel capacity expansion: as shown in Figure 7(c), it also tends to make future residual demand elasticities increase more than current elasticities. However, partly due to the existence of the "stave-off" periods, we cannot obtain analytical results even for linear demand functions and instead rely on a numerical approach. We assume a linear energy demand function $p_t = \overline{p} - \beta Q_t$. Parameter values of c_f, $c_{b,h}$, c_s, and $\overline{p}$ are set at \$20, \$250, \$380 and \$450. We set the initial fossil fuel reserve X_0 at the world proved oil reserve of 2013, which is around 1670 billion barrels (BP, 2013). We set the low cost biofuel capacity $\overline{q}_{b,l}$ at the level of current world biofuel production, which is around 0.5 billion barrels. As standard in the literature, we set the interest rate at $r = 0.05$. Finally

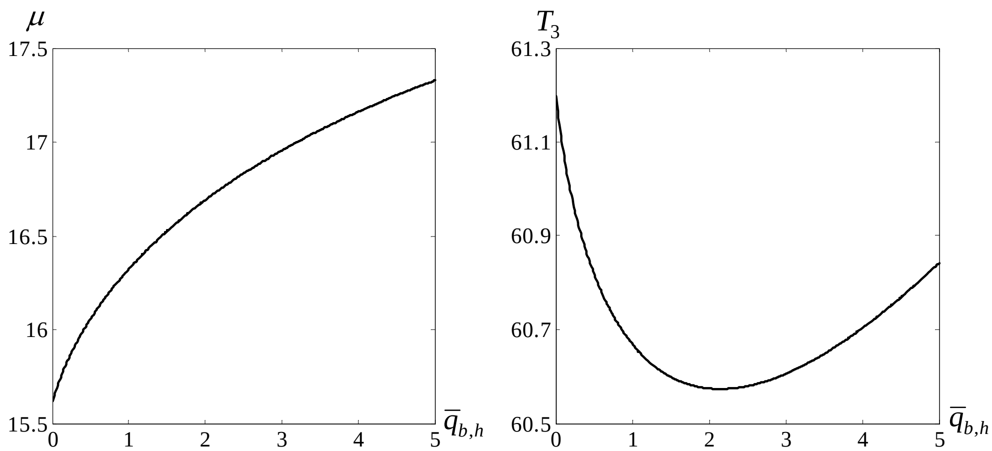


Figure 10: Impacts of capacity expansion policies for high cost biofuels on μ and T_3

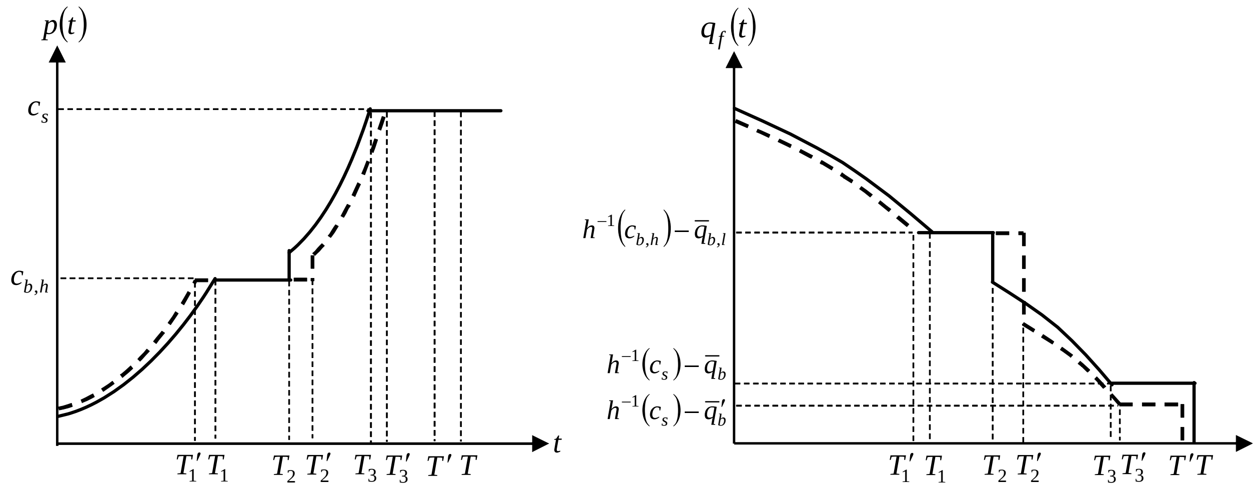
we let $\beta = 6$ so that current fossil fuel production $q_f(0)$ in a benchmark case of our model with $\bar{q}_{b,h} = \bar{q}_{b,l}$ matches the current worldwide oil consumption of about 31 billion barrels per year (BP, 2013).

As shown in Figure 10, expansion of the high cost biofuel capacity tends to raise the Hotelling rent μ, but its effect on T_3 is ambiguous.[6] Sensitivity analysis shows that these results are robust. Figure 11 shows the effects of the capacity expansion on the price and quantity paths. Given that μ is higher, energy price increases and thus fossil fuel supply decreases in early periods. A higher μ also implies that T decreases, i.e., the fossil fuel stock is exhausted earlier. Thus, the net climate impacts of high cost biofuel capacity expansion are ambiguous, unlike the case of low cost biofuels.

4 The role of capacity constraints and market power

Table 1 summarizes the "climate friendliness" of the various renewable energy policies under the two types of market structures, where "+" and "−" represent climate friendly and unfriendly impacts respectively. A policy is climate friendly if its impacts are positive in terms of both current fossil fuel production (i.e., it reduces or delays current production) and exhaustion time (i.e., it delays exhaustion of fossil fuels), and is subject to Green Paradox if both impacts are negative. Thus, capacity expansion policies for low cost biofuels are climate friendly regardless of the market structure, and solar subsidies are subject to Green Paradox

[6] The impacts on T_1 and T can be easily derived from (21) and (19). Both T_1 and T are monotonically decreasing in μ and consequently are also decreasing in $\bar{q}_{b,h}$. Further, the numerical example shows that T_2 is monotonically increasing in $\bar{q}_{b,h}$.



(a) Impact on prices (b) Impact on fossil fuel supply

Figure 11: Impacts of high cost biofuel capacity expansion policies: monopoly

when the fossil fuel market is competitive. The results indicate that when both exhaustion time and early production of fossil fuels are considered, few policies have unambiguous impacts, and most of them are not subject to the Green Paradox. Detailed and careful numerical studies are thus needed to evaluate the net climate impacts of renewable energy policies.

Table 1: Summary of climate change impacts of renewable policies

	Competitive Market		Non-competitive Market	
	Current production	Exhaustion time	Current production	Exhaustion time
c_s	−	−	+	−
$c_{b,h}$	−	+	+	−
$\overline{q}_{b,h}$	−	+	+	−
$\overline{q}_{b,l}$	+	+	+	+

Comparison of the climate impacts of solar and biofuel subsidies indicates that capacity constraints play a significant role in determining the policy effects in the case of perfect competition. Although solar subsidies are subject to Green Paradox, biofuel subsidies can delay the exhaustion of fossil fuels. Even in the case of monopoly power, comparing Figures 6(b) and 8(b) shows that solar subsidies tend to move fossil fuel supplies to the far future (after T_3) while biofuel subsidies move the supplies to the intermediate future (between T_1 and T_2), including moving fossil fuel consumption from after T_2 to the intermediate future $[T_1, T_2)$.

The difference is again due to the capacity constraints of high cost biofuels.[7]

The impacts of capacity expansion policies are sensitive to biofuel costs, i.e., to whether the biofuels are currently in the market or not. While capacity expansion of low cost biofuels are always climate friendly, capacity expansion of high cost biofuels leads to more current fossil fuel production under perfect competition, and speeds up the exhaustion of fossil fuels under monopoly. That is, *future* capacity expansion of (high cost) biofuels can lead to adverse effects while *current* capacity expansion (of low cost biofuels) is always climate friendly.

Table 1 also shows that the climate change impacts are sensitive to market structure. The climate impacts of high cost biofuel policies under competition, including subsidies and capacity expansion, are opposite to those under monopoly. While solar subsidies raise current fossil fuel supply under competition, the opposite is true under monopoly. Only when the renewable energy is already competitive, as in the case of low cost biofuels, are the impacts similar across competition and monopoly.

The existence of the "stave-off" periods under monopoly is a major factor driving the difference between competition and monopoly. As shown in Figure 6(b), the reason that solar subsidies under monopoly lead to reduced fossil fuel production in early periods is that the monopolist needs to produce more during the "stave-off" period $[T_3, T)$ when it floods the market to keep solar off. Similarly in the case of biofuel subsidies, as shown in Figure 8(b), increased fossil fuel supply during the "stave-off" period $[T_1, T_2)$ causes the monopolist to reduce its production in earlier periods and leads to earlier exhaustion of the fossil fuel stock. In the case of capacity expansion of high cost biofuels, Figure 11(b) shows that it is again the increased fossil fuel supply during the "stave-off" period $[T_1, T_2)$ that causes reduced supply during $[0, T_1)$ and earlier exhaustion time. The existence of "stave-off" periods is not merely a theoretical conjecture: some argue that OPEC intensionally keeps oil prices low to keep renewable energies off the market (Indiviglio, 2010), and many renewable energies remain "almost" competitive for prolonged time periods. What we show in this paper is that the "stave-off" periods in fact play a crucial role in determining the climate impacts of renewable policies.

5 Discussion and Conclusions

This paper provides a comprehensive study of the impacts of renewable energy policies on energy prices, fossil fuel supply and thus carbon emissions and climate change, highlighting

[7] To the extent that capacity constraints represent the shape of the production costs of biofuels, the sensitivity to capacity constrains is similar to the sensitivity to production cost functions found in Grafton et al (2012).

the role of capacity constraints of renewable energies and the market power in the fossil fuel sector. To capture the climate change impacts, we define climate friendliness (resp. Green Paradox) as delaying (resp. speeding up) current fossil fuel use as well as fossil fuel exhaustion time. We differentiate renewable energies by whether they face production capacity constraints (solar vs. biofuels) and whether they are already competitive (high cost vs. low cost biofuels). We consider two extreme cases of market structure in the fossil fuel sector: perfect competition and monopoly or cartel. The policies include subsidies that reduce production costs of renewable energies and capacity expansions of biofuels. Since we treat these policies as exogenous changes of cost or capacities, our study can also be used to analyze the impacts of technology innovations of renewable energies.

We find that capacity expansion of low cost biofuels, i.e., renewable energies with capacity constraints that are already competitive in the market, are always climate friendly. But for renewable energies that are not yet competitive, the climate change impacts of their support policies are often ambiguous and are sensitive to the existence of capacity constraints and to the fossil fuel market structure. Solar subsidies are subject to the Green Paradox under perfect competition, but does delay current fossil fuel use to the future under monopoly. High cost biofuel supports under perfect competition lead to more current fossil fuel supply but delays fossil fuel exhaustion time, and these effects are reversed under monopoly. A critical factor determining the climate impacts under monopoly is the monopolist's practice of flooding the market to stave off high cost biofuel or solar when they just become competitive.

Our findings have important implications for the debate on the carbon footprints of renewable energies, especially biofuels such as corn ethanol, as well as for renewable energy policy design. Despite the controversy over indirect land use changes associated with corn based ethanol, the dynamic fuel market effects are climate friendly given that corn ethanol in certain production regions is already competitive. On the other hand, precisely because corn ethanol is competitive, price subsidy has no effects but its capacity expansion has positive dynamic climate impacts. These findings favor quantity policies and R&D subsidies that expand the feedstock for ethanol production. When the fossil fuel sector is under monopoly, policy supports for renewable energies that are not yet competitive can reduce current fossil fuel supplies, and can have positive climate impacts if concerns about short-term carbon emissions dominate concerns about long-term carbon emissions associated with earlier depletion of fossil fuels.

We made a number of simplifying assumptions in the paper, including linear production costs for all energies. Allowing the extraction cost of fossil fuels to be convex and stock dependent will not affect our major conclusions. When fossil fuels are competitively supplied, renewable energies inevitably reduce the in-situ value of fossil fuel stocks regardless of the extraction cost structure, so that the qualitative impacts of renewable energies remain unchanged as the cost structure varies. In the case of fossil fuel monopoly, the driving force in determining the climate change impacts of fossil fuels is the existence of "stave-off" periods when the monopolist floods the market to prevent the immediate entry of renewable energies. Wang and Zhao (2013) shows that such "stave-off" periods still exist when fossil fuel extraction costs are convex and stock dependent. Consequently climate change impacts of renewable policies remain sensitive to market structures under convex and stock dependent extraction costs.

When fossil fuel extraction costs are decreasing in stock levels, i.e., $c_f(c_s)$ being decreasing in c_s, solar subsidies might have an additional benefit of leaving more fossil fuels in the ground without ever being extracted. Specifically, the stock of $c_f^{-1}(c_s)$ will never be extracted, since the extraction cost is higher than solar cost c_s if the stock drops below this level. However, if solar cost is high such that $c_s > c_f(0)$, the entire stock of fossil fuels will be exhausted. Ploeg and Withagen (2012) has more discussion about this issue.

In this paper we choose to model biofuel production costs as linear facing capacity constraints, the setup being an approximation to convex cost functions. This representation enables us to distinguish price policies such as subsidies from quantity policies such as mandatory quantity or blending requirements. We showed that the two kinds of policies can lead to qualitatively different climate impacts even though both encourage biofuel production. The setup, however, is by no means only a convenient modeling simplification but represents real world cost functions when land is the limiting factor. For instance, Stavins (1999) shows that land based carbon sequestration cost functions become vertical at a certain level of carbon sequestration since after that prime agricultural lands have to be converted to forests in order to supply the additional sequestered carbon. If we maintain the existence of capacity constraints, our results remain valid if the production costs below the capacity constraints are convex rather than linear.

Finally, we considered two extreme versions of fossil fuel market structures, perfect competition and monopoly, to highlight the sensitivity of policy impacts to market forces. The literature has studied two additional, and more realistic, market structures, oligopoly with a limited number of fossil fuel producers, and cartel-fringe where a cartel such as OPEC coexists with price-taking fringe fossil fuel firms. The additional realism is important if one attempts to quantitatively assess the climate impacts of renewable energies, e.g., through calibrated cost and demand functions. It is less important in our study since our focus is on the qualitative impacts, i.e., whether renewable policies can move fossil fuel supplies to the future and/or delay their exhaustion.

A Starting fossil fuel stock

In this section we identify the two threshold values of fossil fuel stock $X_{0,l}$ and $X_{0,h}$ ($X_{0,l} < X_{0,h}$) such that for any $X_0 \in [X_{0,l}, X_{0,h}]$, the condition $c_{b,l} < p(0) < c_{b,h}$ holds. In other words, $X_{0,l}$ (or $X_{0,h}$) is the value that guarantees $p(0) = c_{b,h}$ (or $c_{b,l}$). Below we define the two stock values under the two market structures of perfect competition and monopoly.

Competitive fossil fuel market. By setting $\Gamma_1 = 0$ in (8), (9) and (10), we can define $X_{0,l}$ by

$$X_{0,l} = \int_0^y h^{-1}\left(c_f + (c_{b,h} - c_f)\, e^{rt}\right) dt - \overline{q}_b y, \tag{24}$$

where y is determined by $c_f + (c_{b,h} - c_f)\, e^{ry} = c_s$. Note that if $X_0 = X_{0,l}$, the current shadow value of fossil fuels equals $c_{b,h} - c_f$ and $p(0) = c_{b,h}$. Similarly

$$X_{0,h} = \int_0^y h^{-1}\left(c_f + (c_{b,l} - c_f)\, e^{rt}\right) dt - \overline{q}_{b,l} y - \overline{q}_{b,h}(y - z) \tag{25}$$

where y and z are respectively determined by $c_f + (c_{b,l} - c_f)\, e^{ry} = c_s$ and $c_f + (c_{b,l} - c_f)\, e^{rz} = c_{b,h}$.

Monopolistic fossil fuel market. We define $X_{0,l}$ by

$$X_{0,l} = X_{T_3} + \left[h^{-1}(c_{b,h}) - \overline{q}_{b,l}\right] y + \int_y^z q_f(t)\, dt \tag{26}$$

where, given $\mu = h'\left(h^{-1}(c_{b,h})\right)\left[h^{-1}(c_{b,h}) - \overline{q}_b\right] + c_{b,h} - c_f$, $q_f(t)$ is determined by (17), z is the solution for T_3 in (23) and y is the solution for T_2 in (16) and (22). Similarly, the upper bound of the stock size is

$$X_{0,h} = X_{T_3} + \left[h^{-1}(c_{b,h}) - \overline{q}_{b,l}\right](y - x) + \int_0^x q_f(t)\, dt + \int_y^z q_f(t)\, dt \tag{27}$$

where, given $\mu = h'\left(h^{-1}(c_{b,l})\right)\left[h^{-1}(c_{b,l}) - \overline{q}_{b,l}\right] + c_{b,l} - c_f$, $q_f(t)$ in the first and second integration is determined by (15) and (17) respectively, x solves T_1 in (21), and y and z are defined in the same way as in (26).

B Proofs

Proof of Proposition 1. We first consider the case of solar subsidies. Applying implicit function theorem to (8) - (10), we obtain

$$\begin{pmatrix} \int_0^{\Gamma} \frac{e^{rt}}{h'(h^{-1}(p(t)))}dt & \overline{q}_{b,h} & h^{-1}(c_s) - \overline{q}_b \\ e^{r\Gamma_1} & r\lambda e^{r\Gamma_1} & 0 \\ e^{r\Gamma} & 0 & r\lambda e^{r\Gamma} \end{pmatrix} \begin{pmatrix} \frac{\partial \lambda}{\partial c_s} \\ \frac{\partial \Gamma_1}{\partial c_s} \\ \frac{\partial \Gamma}{\partial c_s} \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}. \tag{28}$$

Using Cramer rule then yields

$$\begin{aligned} \frac{\partial \lambda}{\partial c_s} &= -r\lambda e^{r\Gamma_1}\left[h^{-1}(c_s) - \overline{q}_b\right]/\Phi > 0, \\ \frac{\partial \Gamma_1}{\partial c_s} &= e^{r\Gamma_1}\left[h^{-1}(c_s) - \overline{q}_b\right]/\Phi < 0, \\ \frac{\partial \Gamma}{\partial c_s} &= \left[r\lambda e^{r\Gamma_1}\int_0^{\Gamma}\frac{e^{rt}}{h'(h^{-1}(p(t)))}dt - \overline{q}_{b,h}e^{r\Gamma_1}\right]/\Phi > 0, \end{aligned}$$

where Φ is the determinant of the square matrix in (28), given by

$$\Phi = r\lambda e^{r(\Gamma_1+\Gamma)}\left[r\lambda\int_0^{\Gamma}\frac{e^{rt}}{h'(h^{-1}(p(t)))}dt - h^{-1}(c_s) + \overline{q}_{b,l}\right] < 0.$$

Following the same approach, we can easily obtain the effects of high cost biofuel subsidies,

$$\begin{aligned} \frac{\partial \lambda}{\partial c_{b,h}} &= -\overline{q}_{b,h}r\lambda e^{r\Gamma}/\Phi > 0, \\ \frac{\partial \Gamma_1}{\partial c_{b,h}} &= \left\{r\lambda e^{r\Gamma}\int_0^{\Gamma}\frac{e^{rt}}{h'(h^{-1}(p(t)))}dt - e^{r\Gamma}\left[h^{-1}(c_s) - \overline{q}_b\right]\right\}/\Phi > 0, \\ \frac{\partial \Gamma}{\partial c_{b,h}} &= \overline{q}_{b,h}e^{r\Gamma}/\Phi < 0, \end{aligned}$$

the effects of capacity expansion policies for high cost biofuels,

$$\begin{aligned} \frac{\partial \lambda}{\partial \overline{q}_{b,h}} &= (r\lambda)^2 e^{r(\Gamma_1+\Gamma)}(\Gamma - \Gamma_1)/\Phi < 0, \\ \frac{\partial \Gamma_1}{\partial \overline{q}_{b,h}} &= -(\Gamma - \Gamma_1)\, r\lambda e^{r(\Gamma_1+\Gamma)}/\Phi > 0, \\ \frac{\partial \Gamma}{\partial \overline{q}_{b,h}} &= -(\Gamma - \Gamma_1)\, r\lambda e^{r(\Gamma_1+\Gamma)}/\Phi > 0, \end{aligned}$$

and the effects of capacity expansion policies for low cost biofuels,

$$\frac{\partial \lambda}{\partial \overline{q}_{b,l}} = (r\lambda)^2 e^{r(\Gamma_1+\Gamma)}\Gamma/\Phi < 0, \ \frac{\partial \Gamma_1}{\partial \overline{q}_{b,l}} = -\Gamma r\lambda e^{r(\Gamma_1+\Gamma)}/\Phi > 0, \ \frac{\partial \Gamma}{\partial \overline{q}_{b,l}} = -\Gamma r\lambda e^{r(\Gamma_1+\Gamma)}/\Phi > 0.$$

■

Proof of Corollary 2. To prove the corollary, we only need to characterize the sign of $\partial q_f(t)/\partial \overline{q}_{b,l}$ at $t = 0$. First, we can derive the policy impacts on fossil fuel supply by applying the implicit function theorem to (6) and (7)

$$\frac{\partial q_f(t)}{\partial \overline{q}_{b,l}} = \frac{e^{rt}\frac{\partial \lambda}{\partial \overline{q}_{b,l}}}{h'\left(h^{-1}\left(\lambda e^{rt} + c_f\right)\right)} - 1.$$

Further for all $t \in [0, \Gamma]$, we have,

$$\frac{\partial^2 q_f(t)}{\partial \overline{q}_{b,l}\partial t} = \frac{re^{rt}\frac{\partial \lambda}{\partial \overline{q}_{b,l}}\left\{h'\left(h^{-1}\left(\lambda e^{rt} + c_f\right)\right) - \frac{h''\left(h^{-1}\left(\lambda e^{rt}+c_f\right)\right)\left(p_t - c_f\right)}{h'\left(h^{-1}\left(\lambda e^{rt}+c_f\right)\right)}\right\}}{\left[h'\left(h^{-1}\left(\lambda e^{rt} + c_f\right)\right)\right]^2}.$$

If the demand function is linear, evidently $\partial^2 q_f(t)/\partial \overline{q}_{b,l}\partial t > 0$. Suppose $\partial q_f(t)/\partial \overline{q}_{b,l} \geq 0$ at $t = 0$, then $\partial q_f(t)/\partial \overline{q}_{b,l} \geq 0$ for all $t \in [0, \Gamma]$. That means fossil fuel extraction increases for all periods. However this result would violate the resource exhaustion condition due to the fact that $\partial \Gamma/\partial \overline{q}_{b,l} > 0$. Hence we must have $\partial q_f(t)/\partial \overline{q}_{b,l} < 0$ at $t = 0$. ■

Proof of Proposition 5. The proof is based on comparative dynamic analysis of (19), (16) and (20) - (23). There are five unknown variables in the five equations of (20) - (23) and (16), we can derive policy effects on $\{\mu, T_1, T_2, T_3, q_f(T_2)\}$ first and then use (19) to obtain the policy effect on T. Applying the implicit function theorem to equations (20) - (23) and (16), we have

$$\Omega \times \frac{\partial w}{\partial c_s} = \begin{pmatrix} -\frac{\partial X_{T_3}}{\partial c_s} \\ 0 \\ 0 \\ -\frac{\partial MR(T_3)}{\partial c_s} \\ 0 \end{pmatrix}, \quad (29)$$

where

$$
\begin{aligned}
\Omega &= \begin{pmatrix} A & 0 & B & h^{-1}(c_s) - \overline{q}_b & 1 \\ -e^{rT_1} & -r\mu e^{rT_1} & 0 & 0 & 0 \\ -e^{rT_2} & 0 & -r\mu e^{rT_2} & 0 & \frac{\partial MR(T_2)}{\partial q_f(T_2)} \\ -e^{rT_3} & 0 & 0 & -r\mu e^{rT_3} & 0 \\ e^{rT_2}B & 0 & r\mu e^{rT_2}B & 0 & 0 \end{pmatrix}, \\
w &= (\mu, T_1, T_2, T_3, q_f(T_2))',
\end{aligned}
$$

and

$$
\begin{aligned}
A &= \int_0^{T_1} \frac{e^{rt}}{\partial MR(t)/\partial q_f(t)} dt + \int_{T_2}^{T_3} \frac{e^{rt}}{\partial MR(t)/\partial q_f(t)} dt < 0, \\
B &= h^{-1}(c_{b,h}) - \overline{q}_{b,l} - q_f(T_2), \\
\frac{\partial MR(T_2)}{\partial q_f(T_2)} &= h''(q_f(T_2) + \overline{q}_b) q_f(T_2) + 2h'(q_f(T_2) + \overline{q}_b) < 0, \\
\frac{\partial X_{T_3}}{\partial c_s} &= \frac{\ln\left(\frac{c_s - c_f}{MR(T_3)}\right) + h'(h^{-1}(c_s))(h^{-1}(c_s) - \overline{q}_b)\left[\frac{1}{c_s - c_f} - \frac{\partial MR(T_3)}{\partial c_s}/MR(T_3)\right]}{rh'(h^{-1}(c_s))}, \\
\frac{\partial MR(T_3)}{\partial c_s} &= \frac{(h^{-1}(c_s) - \overline{q}_b) h''(h^{-1}(c_s))}{h'(h^{-1}(c_s))} + 2 > 0.
\end{aligned}
$$

Term A is derived by differentiating (20) with respect to μ, in which $\partial q_f(t)/\partial\mu$ is obtained by applying implicit function theorem to (15) and (17). Since the revenue function for the monopolist is concave, it is easy to check signs of A, $\partial MR(T_3)/\partial c_s$ and $\partial MR(T_2)/\partial q_f(T_2)$. Denote the determinant of the square matrix Ω as $\det(\Omega)$. We have

$$
\det(\Omega) = Br^2\mu^2 e^{r(T_1+T_2+T_3)} \left[h^{-1}(c_s) - \overline{q}_b + B - r\mu A\right] \frac{\partial MR(T_2)}{\partial q_f(T_2)} < 0.
$$

Then applying Cramer rule in (29), we obtain

$$
\begin{aligned}
\frac{\partial\mu}{\partial c_s} &= Br^2\mu^2 e^{r(T_1+T_2)} \frac{\frac{\partial MR(T_2)}{\partial q_f(T_2)}\left[r\mu e^{rT_3}\frac{\partial X_{T_3}}{\partial c_s} + (h^{-1}(c_s) - \overline{q}_b)\frac{\partial MR(T_3)}{\partial c_s}\right]}{\det(\Omega)}, \\
\frac{\partial T_1}{\partial c_s} &= \frac{\partial T_2}{\partial c_s} = \frac{\partial T}{\partial c_s} = -\frac{\partial\mu}{\partial c_s}/(r\mu), \\
\frac{\partial q_f(T_2)}{\partial c_s} &= 0.
\end{aligned}
$$

Evidently the signs of $\partial\mu/\partial c_s$ and $\partial T_i/\partial c_s$, $i=\{1,2\}$ depend on the sign of

$$r\mu e^{rT_3}\frac{\partial X_{T_3}}{\partial c_s}+\left(h^{-1}(c_s)-\overline{q}_b\right)\frac{\partial MR(T_3)}{\partial c_s},$$

which, by substituting in $\partial X(T_3)/\partial c_s$, $\partial MR(T_3)/\partial c_s$ and (23), can be simplified to

$$\left(h^{-1}(c_s)-\overline{q}_b\right)\left[-(1+\theta)\ln\left(1+\frac{1}{\theta}\right)+1+\frac{1}{\theta}\right],$$

where $\theta=(c_s-c_f)/\left[\left(h^{-1}(c_s)-\overline{q}_b\right)h'\left(h^{-1}(c_s)\right)\right]$. Therefore $\partial\mu/\partial c_s<0$ and $\partial T_i/\partial c_s>0$, $i=\{1,2\}$ if and only if

$$F(\theta)=-(1+\theta)\ln\left(1+\frac{1}{\theta}\right)+1+\frac{1}{\theta}<0.$$

Note that $\theta<-1$. We derive the sign of $F(\theta)$ by characterizing its curvature. First we have

$$F'(\theta)=-\ln\left(1+\frac{1}{\theta}\right)+\frac{1}{\theta}-\frac{1}{\theta^2}\text{ and }F''(\theta)=\frac{1}{\theta(\theta+1)}+\frac{2-\theta}{\theta^3}.$$

It can be verified that $F''(\theta)>0$ if and only if $\theta\in(-2,-1)$. Moreover, $F'(\theta^*)=0$ has a unique solution, $\theta^*=-1.4624$, which is in the convex range of $F(\theta)$ and thus minimizes $F(\theta)$. Therefore, $F(\theta)$ decreases in $\theta\in(-\infty,\theta^*)$ first and then increases in $\theta\in(\theta^*,-1)$. Now if we can show $\lim_{\theta\to-\infty}F(\theta)\le 0$ and $\lim_{\theta\to-1}F(\theta)\le 0$, we have $F(\theta)<0$ for all $\theta<-1$. By L'Hoptial rule

$$\lim_{\theta\to-\infty}F(\theta)=\lim_{\theta\to-\infty}\left[-\frac{\ln\left(1+\frac{1}{\theta}\right)}{\frac{1}{1+\theta}}+1+\frac{1}{\theta}\right]=\lim_{\theta\to-\infty}\left[-\frac{\frac{1}{\theta(\theta+1)}}{\frac{1}{(1+\theta)^2}}+1+\frac{1}{\theta}\right]=0$$

Similarly, $\lim_{\theta\to-1}F(\theta)=0$. Therefore, $F(\theta)<0$ for all $\theta\in(-\infty,-1)$, which proves $\partial\mu/\partial c_s<0$ and $\partial T_i/\partial c_s>0$, $i=\{1,2\}$.

$\partial T_3/\partial c_s>0$ is obtained by the fact that the new price path after policy implementation between T_2 and T_3 cannot cross the original one. If the two price paths cross with each other at some time $\widetilde{t}\in[T_2,T_3]$, then the two corresponding marginal revenues for the monopolist are same at $\widetilde{t}$. Further, the optimal solutions require the marginal revenue to be equal to the augmented marginal cost for all $t\in[T_2,T_3]$. That implies at time $\widetilde{t}$, the shadow value of fossil fuels before policy implementation is the same as that after policy implementation, which contradicts with the fact that $\partial\mu/\partial c_s<0$.

Finally, $\partial T/\partial c_s>0$ can be easily derived from (19) and $\partial\mu/\partial c_s<0$. ■

Proof of Propositioin 6. Following the same exercise of comparative dynamic analysis in Proposition 5, we have

$$\Omega \times \frac{\partial w}{\partial c_{b,h}} = \begin{pmatrix} -\frac{T_2 - T_1}{h'\left(h^{-1}\left(c_{b,h}\right)\right)} \\ -\frac{\partial MR(T_1)}{\partial c_{b,h}} \\ 0 \\ 0 \\ -\frac{\mu\left(e^{rT_2} - e^{rT_1}\right)}{h'\left(h^{-1}\left(c_{b,h}\right)\right)} \end{pmatrix} \tag{30}$$

where

$$\frac{\partial MR(T_1)}{\partial c_{b,h}} = h''\left(h^{-1}\left(c_{b,h}\right)\right)\frac{h^{-1}\left(c_{b,h}\right) - \overline{q}_{b,l}}{h'\left(h^{-1}\left(c_{b,h}\right)\right)} + 2 > 0.$$

Applying Cramer rule, we have

$$\begin{aligned}
\frac{\partial \mu}{\partial c_{b,h}} &= -r^3\mu^3 e^{r(T_1+T_2+T_3)}\frac{\mu\left(e^{rT_2} - e^{rT_1}\right) + B\frac{\partial MR(T_2)}{\partial q_f(T_2)}\left[\left(1 - e^{r(T_1-T_2)}\right)/r + T_1 - T_2\right]}{h'\left(h^{-1}\left(c_{b,h}\right)\right) \times \det(\Omega)} \\
\frac{\partial T_2}{\partial c_{b,h}} &= -r^2\mu^2 e^{r(T_1+T_2+T_3)}\frac{\frac{\partial MR(T_2)}{\partial q_f(T_2)}\left[\begin{array}{c} \frac{\left(1-e^{r(T_1-T_2)}\right)\left(h^{-1}(c_s) - \overline{q}_b - rA\mu\right)}{r} \\ +B\left(T_2 - T_1\right) \end{array}\right] - \mu\left(e^{rT_2} - e^{rT_1}\right)}{h'\left(h^{-1}\left(c_{b,h}\right)\right) \times \det(\Omega)} \\
\frac{\partial T_3}{\partial c_{b,h}} &= \frac{\partial T}{\partial c_{b,h}} = -\frac{\partial \mu}{\partial c_{b,h}}/\left(r\mu\right) \\
\frac{\partial q_f\left(T_2\right)}{\partial c_{b,h}} &= -r^2\mu^2 e^{r(T_1+T_2+T_3)}\frac{\mu\left(e^{rT_2} - e^{rT_1}\right)}{h'\left(h^{-1}\left(c_{b,h}\right)\right)}\left[h^{-1}\left(c_s\right) - \overline{q}_b + B - r\mu A\right]/\det(\Omega).
\end{aligned}$$

It is easy to check that $\partial T_2/\partial c_{b,h} > 0$ and $\partial q_f\left(T_2\right)/\partial c_{b,h} < 0$, and it remains to verify $\partial\mu/\partial c_{b,h} < 0$. Denote $G = 1 - e^{r(T_1-T_2)} + r\left(T_1 - T_2\right)$. To show $\partial\mu/\partial c_{b,h} < 0$, it is enough to show $G < 0$. By some arrangement, we have $G(z) = 1 - z + \ln z$, where $z = e^{r(T_1-T_2)}$. Since $T_1 < T_2$, $0 < z < 1$. Moreover, we have $\lim_{z\to 0} G(z) = -\infty$, $\lim_{z\to 1} G(z) = 0$ and $G'(z) = 1/z - 1 > 0$. Therefore $G(z) > 0$ for all $z \in (0,1)$, establishing $\partial\mu/\partial c_{b,h} < 0$. $\partial T_1/\partial c_{b,h} > 0$ follows the similar argument to that in the proof of Proposition 5: the new price path after policy implementation between 0 and T_1 cannot cross the one before policy implementation. ■

Proof of Proposition 7. From (14) and (19), we know that $T - T_3$ is given by

$$T - T_3 = \frac{1}{r}\ln\left(\frac{c_s - c_f}{h'\left(h^{-1}\left(c_s\right)\right)\left(h^{-1}\left(c_s\right) - \overline{q}_b\right) + c_s - c_f}\right). \tag{31}$$

From (18), we know that the remaining fossil fuel stock at T_3 is given by

$$X_{T_3} = \frac{h^{-1}(c_s) - \overline{q}_b}{r} \ln\left(\frac{c_s - c_f}{h'\left(h^{-1}(c_s)\right)\left(h^{-1}(c_s) - \overline{q}_b\right) + c_s - c_f}\right), \tag{32}$$

which is independent of the initial stock X_0. It is straightforward to show that $\partial X_{T_3}/\partial \overline{q}_b < 0$ and $\partial (T - T_3)/\partial \overline{q}_b < 0$.

1) We first show $\partial \mu / \partial \overline{q}_{b,l} < 0$ by contradiction. Suppose $\partial \mu / \partial \overline{q}_{b,l} \geq 0$, then from (15), (17) and (32), we can easily show that $\partial q_f(t)/\partial \overline{q}_{b,l} < 0$ for any $t \in [0, T_1] \cup [T_2, T_3]$, and $\partial X(T_3)/\partial \overline{q}_{b,l} < 0$, which implies that as $\overline{q}_{b,l}$ rises, the total amount of fossil fuel extraction out of period $[T_1, T_2]$ decreases. In addition, we also know that the fossil fuel extraction during the period $[T_1, T_2]$ equals $h^{-1}(c_b) - \overline{q}_{b,l}$ and evidently is decreasing in $\overline{q}_{b,l}$. Hence to satisfy the resource exhaustion condition for fossil fuels, we must have $\partial (T_2 - T_1)/\partial \overline{q}_{b,l} > 0$, which is not true as will be shown below.

We move on to drive the effect of $\overline{q}_{b,l}$ on $(T_2 - T_1)$. First since we already know the effect of $\overline{q}_{b,l}$ on μ, we can take μ as a function of $\overline{q}_{b,l}$ which is exogenously given, and thus $\{T_1, T_2, q_f(T_2)\}$ can be solved by the three equations (16), (21) and (22). Then by applying implicit function theorem, we have

$$\begin{pmatrix} -r\mu e^{rT_1} & 0 & 0 \\ 0 & -r\mu e^{rT_2} & \frac{\partial MR(T_2)}{\partial q_f(T_2)} \\ 0 & r\mu e^{rT_2} B & 0 \end{pmatrix} \begin{pmatrix} \frac{\partial T_1}{\partial \overline{q}_{b,l}} \\ \frac{\partial T_2}{\partial \overline{q}_{b,l}} \\ \frac{\partial q_f(T_2)}{\partial \overline{q}_{b,l}} \end{pmatrix} = H \tag{33}$$

where

$$H = \begin{pmatrix} h'\left(h^{-1}(c_{b,h})\right) + e^{rT_1} \frac{\partial \mu}{\partial \overline{q}_{b,l}} \\ -h''\left(q_f(T_2) + \overline{q}_b\right) q_f(T_2) - h'\left(q_f(T_2) + \overline{q}_b\right) + e^{rT_2} \frac{\partial \mu}{\partial \overline{q}_{b,l}} \\ h\left(q_f(T_2) + \overline{q}_b\right) - c_{b,h} - Be^{rT_2} \frac{\partial \mu}{\partial \overline{q}_{b,l}} \end{pmatrix}.$$

Further, using Cramer rule, we can obtain

$$\frac{\partial (T_2 - T_1)}{\partial \overline{q}_{b,l}} = \frac{\left[h\left(q_f(T_2) + \overline{q}_b\right) - c_{b,h}\right] + h'\left(h^{-1}(c_{b,h})\right) e^{r(T_2 - T_1)} B}{r\mu e^{rT_2} B}.$$

The sign of $\partial (T_2 - T_1)/\partial \overline{q}_{b,l}$ is determined by the numerator, which is monotonically increasing in $T_2 - T_1$. Further if the demand function is linear and $T_2 - T_1 = 0$, the numerator of $\partial (T_2 - T_1)/\partial \overline{q}_{b,l}$ becomes $-\overline{q}_{b,h}$, which is strictly negative. Since $T_2 - T_1 > 0$ always holds, we must have $\partial (T_2 - T_1)/\partial \overline{q}_{b,l} < 0$ for any $T_1 \in (0, T_2)$, which violates the resource exhaustion condition mentioned above. Hence $\partial \mu / \partial \overline{q}_{b,l} > 0$ cannot be true, which completes the proof of $\partial \mu / \partial \overline{q}_{b,l} < 0$.

2) With $\partial\mu/\partial\overline{q}_{b,l} < 0$, the signs of $\partial T_1/\partial\overline{q}_{b,l}$, $\partial T_3/\partial\overline{q}_{b,l}$ and $\partial T/\partial\overline{q}_{b,l}$ can be easily derived from (21), (23) and (19). Using (33), we can derive the sign of $\partial T_2/\partial\overline{q}_{b,l}$:

$$\frac{\partial T_2}{\partial\overline{q}_{b,l}} = \frac{h\left(q_f\left(T_2\right) + \overline{q}_b\right) - c_{b,h} - Be^{rT_2}\frac{\partial\mu}{\partial\overline{q}_{b,l}}}{r\mu e^{rT_2}B} > 0.$$

3) To prove the statement we first show $\partial q_f\left(t\right)/\partial\overline{q}_{b,l} < 0$ at $t = 0$. Using (15) and (17) we have

$$\frac{\partial q_f\left(t\right)}{\partial\overline{q}_{b,l}} = -\frac{h'\left(q_f\left(t\right) + \overline{q}_{b,l}\right) - \frac{\partial\mu}{\partial\overline{q}_{b,l}}e^{rt}}{2h'\left(q_f\left(t\right) + \overline{q}_{b,l}\right)}.$$

Evidently given linear demand function, $\partial q_f\left(t\right)/\partial\overline{q}_{b,l}$ is monotonically increasing over time for $t \in [0, T_1] \cup [T_2, T_3]$. Suppose $\partial q_f\left(t\right)/\partial\overline{q}_{b,l} \geq 0$ at $t = 0$, then $\partial q_f\left(t\right)/\partial\overline{q}_{b,l} \geq 0$ for all $t \in [0, T_1] \cup [T_2, T_3]$. On the other hand, using (33), we can show that

$$\frac{\partial q_f\left(T_2\right)}{\partial\overline{q}_{b,l}} = -\frac{h^{-1}\left(c_{b,h}\right) - \overline{q}_{b,l}}{2\left[h^{-1}\left(c_{b,h}\right) - \overline{q}_{b,l} - q_f\left(T_2\right)\right]} < 0,$$

which contradicts with the fact that $\partial q_f\left(t\right)/\partial\overline{q}_{b,l} \geq 0$ for all $t \in [0, T_1] \cup [T_2, T_3]$. Hence we must have $\partial q_f\left(t\right)/\partial\overline{q}_{b,l} < 0$ at $t = 0$.

Finally given $\partial T_1/\partial\overline{q}_{b,l} < 0$ and $q_f\left(t\right)/\partial\overline{q}_{b,l} < 0$ at $t = 0$, we must have $q_f\left(t\right)/\partial\overline{q}_{b,l} < 0$ for all $t \in [0, T_1)$. Otherwise, the new fossil fuel supply path, as well as the energy price path, after policy implementation between $[0, T_1)$ would cross the one before policy implementation, which cannot be true as argued above. ■

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