Renewable Energy R&D:
Impacts of Energy and Environmental Policies
(Preliminary)

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Abstract

In this paper, we study the impacts of government energy and environmental policies on firm incentives to conduct R&D to (i) reduce costs of renewable energies such as biofuel, wind and solar, and (ii) increase the capacity of some renewable energies such as biofuel. We consider a range of policies including quantity mandates on biofuel use such as a minimum quantity requirement or a minimum blending requirement, taxes on nonrenewable energies or on environmental sensitive nonrenewable energies, subsidies on biofuel, wind and solar production, as well as direct subsidies on renewable R&D efforts. We find that there are a range of unintended consequences of these policies in a dynamic world. Taxes on nonrenewable energies discourage the development of cost reducing new technologies in solar, and may also discourage cost reducing and capacity enhancing innovations in biofuel. Subsidies to biofuel hurt the development of solar energy, but the impacts of solar subsidies on biofuel innovations depend on the kind of quantity restrictions in place. Under the minimum quantity mandate solar subsidies hurt biofuel innovations, while under the minimum blending requirement, solar subsidies might help biofuel innovations. Both kinds of quantity mandates hurt the development of cost reducing innovations in biofuel and solar.
Recent increases in oil prices have been a major concern among politicians, economists and the public in general. As a natural response to the high oil prices, governments and the oil extraction industry have called for increased efforts in exploration, sometimes in pristine environments such as Alaska’s Arctic National Wildlife Refuge (ANWR). Exploration and expanded drilling is not limited to conventional oil: with the high oil prices, Canada is increasing the extraction of its oil sands stock and potentially the US may start to extract its shale oil deposits in Colorado. In fact, the proven oil sands deposits in Alberta makes Canada the second largest oil producer after Saudi Arabia (Sexton (2006)). According to Bartis, LaTourrette, Dixon, Peterson and Cecchine (2005), the expected potentially recoverable oil shale resources in the US alone represent more than three times of the current proven oil reserve of Saudi Arabia.

A potential problem with the new exploration efforts is that new deposits are often found in environmentally fragile areas, and extraction of some resources can have serious environmental consequences. The major opposition to oil drilling in ANWR is the associated risk to the virgin environment. Oil sand extraction in Canada has already caused serious air and water pollution and is subject to intense debate about its overall environmental impacts (Sexton (2006)). Extracting oil from oil shale also has a number of potentially serious environmental impacts, including land use and ecological damages, air pollution and greenhouse gas emission (Bartis et al., 2005). Thus, extraction from these resources will be subject to environmental regulation that potentially raises the overall extraction costs.

Another response to high oil prices has been to promote the use and development of renewable energies, including biomass, wind, and solar energies. The US government has plans to increase automobile use of ethanol and biodiesel, and both the US and EU nations have proposed to raise the share of renewable energy in total energy use. For example, currently liquid biofuels such as ethanol and biodiesel constitute about 4% of total US fuel consumption, with the 2006 ethanol consumption at about 6 billion gallons, and the 2005 Energy Policy Act stipulates that gasoline producers blend 7.5 billion gallons of ethanol by 2012 (Rajagopal et al., 2007). The US also
provides a $0.51 per gallon subsidy to ethanol. Further, in his “Twenty in Ten” Plan, President Bush proposed a mandatory fuel standard requiring the use of 25 billion gallons of biofuels by 2017 (The White House (January 24, 2007)). Partly to fulfill EU’s pledge of cutting carbon emissions to 20% below 1990 levels by 2020, EU nations are discussing renewable energy targets, with several countries pledging to increase its share to 20% of total energy use, and to achieve 10% of transport fuel being derived from plants, all by the year 2020 (Hollinger, Parker, Bounds and Laitner (2008)). In addition, US and EU governments have plans to increase R&D expenditures and subsidies in renewable energies. For instance, in the US, the federal R&D spending on biofuels has been between $50 and $100 million per year between 1978 and 1998, and the Biomass Research and Development Program offers $12 million R&D support for bioenergy related research (Gielecki, Mayes and Prete (2001)).

For the most part, these renewable energies are considered as “backstop” resources: although currently they comprise a small share of total energy consumption, there is little doubt that their share will increase, possibly at a significant rate. There are, however, some critical differences among the renewable energies, especially between biofuel/wind and solar energies. First, solar energy remains much more costly than nonrenewable energies such as coal, oil and natural gas, but the costs of biofuel and wind energies have decreased sufficiently in recent years that they are becoming competitive with the nonrenewable energies. Second, and more importantly, the development of biofuel and wind energies are limited by their capacity constraints. Biofuel capacity is limited by land availability and increasing demand for food and feed. Although second generation biofuel (e.g., cellulosic ethanol) has the promise of significantly increasing the capacity, it is not yet competitive with other fuel sources. Even when it becomes competitive, its capacity is still limited by the availability of arable land. Wind power is the fastest growing energy source in the world, and its capacity in the US has increased dramatically in recent years, rising from 1600 megawatts in 1994 to more than 9200 MW in 2005 (Aabakken (2006)).

1This is due mainly to the significant decrease in its cost, from $0.40/kWh in early 1980s to about $0.04/kWh now, making it competitive with traditional forms of power generation in some areas (Bernstein, Griffin and Lempert 2001)).
prime wind sites are used up and less favorable sites will have to be used, increasing the siting cost. Further, these sites are usually located far away from consumption centers, leading to significant transportation costs and increased pressure on the electricity transmission grid. The cost is thus expected to increase sharply after a threshold, e.g., if wind energy replaces nonrenewable energies as the dominant energy source.

Undoubtedly, regulation of the environmentally sensitive nonrenewable resources and the development of renewable energies, the two major components of energy policies, will interact and affect each other’s effectiveness. Conventional wisdom holds that tighter environmental regulation of the extraction of nonrenewable energies will help the renewable energy sector grow. For instance, a popular rhetoric in the ANWR debate was that America’s energy solution lies in renewable energies rather than in further oil development. We show in this paper that this conventional wisdom is not entirely correct: in a dynamic world, the effects of environmental policies on renewable resource development depends on whether there are capacity limits to the renewable energies. If there are capacity limits to their supply, as in the case of biofuel, then the conventional wisdom might be correct. However, if the renewable energy is, as the literature usually assumes, a backstop technology without capacity limits (e.g., solar energies), the conventional wisdom might be incorrect: the environmental protection measures will make these renewable energies “less appealing” and thus reduce the R&D in this sector.

In this paper, we study the effects of government environmental and energy policies on firms’ incentives to conduct R&D in the renewable sector. We model four groups of energy resources: (i) conventional nonrenewable resources (CNR), e.g., oil, coal, and natural gas; (ii) environmentally sensitive (nonrenewable) resources (ESR), including nonrenewable unconventional oil such as oil sand, extra-heavy crude, and oil shale, nuclear, and oil from environmentally fragile areas such as ANWR; (iii) biomass (e.g., biofuels such as ethanol and biodiesel, and biopower such as cofiring switchgrass with fossil fuels) and wind energies (together referred to as BWE); and (iv) solar (2006)).
energies. CNR and ESR are nonrenewable with fixed stocks and BWE and solar are renewable. The costs of using these resources, including extraction, processing and transportation costs but excluding any scarcity rents, are increasing in the order of CNR, ESR/BWE and solar. (We study both cases when ESR is more or less costly than BWE.) There is a capacity constraint in the production of BWE, due to limited land availability and increasing demand for food and feed.

We study the effects of the following government policies: (i) energy policies including taxing nonrenewable energies (e.g., gasoline tax), subsidizing renewable energies, and mandatory requirements on the minimum quantity and/or proportion of renewable energies in the total energy mix; (ii) environmental policies including a carbon tax in general as well as pollution taxes in the ESR sector; (iii) conservation measures that reduce the energy demand, and (iv) subsidies to cost reducing and/or capacity expanding R&D in renewable energies.

Given the government policies and assuming that firms in the four energy sectors are competitive (we later allow CNR firms to have market power), we investigate the optimal decisions of firms that conduct R&D to reduce the production costs of the two renewable sectors and/or expand the production capacity of BWE (e.g., second generation biofuel). We allow for two kinds of innovations: sweeping innovations that lead to industry-wide cost reductions or capacity expansions and nonsweeping innovations that do not cause industry-wide effects. In essence, a nonsweeping innovation does not lead to price changes in the energy sectors and a sweeping innovation does.

We first solve for the (dynamic) competitive equilibrium in the energy sectors given R&D expenditures and government policies. In the equilibrium production pattern, CNR is used first, followed by ESR or BWE, and eventually followed by solar. Solar is used only when the nonrenewable resources are exhausted, while the capacity constraint in BWE implies that BWE will be used before the nonrenewable are exhausted. Given this pattern, we show the impacts of government policies on the incentives of the innovating firms to conduct R&D. The key observation is that the R&D incentives are directly related to the starting date of a renewable resource being used: since the marginal value of R&D is proportional to the discounted present value of the entire future stream
of saved costs or increased benefits from higher capacities, the incentive is higher if the resource is used earlier.

Our results show that there are prevalent unintended consequences of government policies. For instance, gasoline taxes and pollution taxes in ESR reduce R&D in the solar sector: by decreasing the consumption of nonrenewable energies, these taxes make these energies last longer, delaying the start of (full scale) use of solar energies and thus the marginal value of solar R&D. However, it is possible that these taxes may in fact encourage R&D in BWE. Since BWE starts to be used before the nonrenewable resources are exhausted, higher energy prices caused by these taxes make BWE more competitive and thus expedite the use of BWE.

We find that renewable energy policies may conflict with each other. BWE subsidies hurt R&D in solar by reducing the rate of extraction of nonrenewable energies. Policies that increase the capacity limit of BWE production have the unintended consequence of discouraging cost reducing R&D in BWE: increased BWE capacity suppresses the prices of nonrenewable resources, making BWE less competitive and delaying its start of widespread adoption. Further, price instruments such as taxes and subsidies have different consequences from quantity instruments such as the mandatory proportions of renewable energies in consumption.

The paper is organized as follows. After describing the basic model setup in Section 1 we characterize the competitive equilibrium of the energy market under the minimum quantity mandate in Section 2. Then in Section 3 we describe the two kinds of innovations, sweeping and nonsweeping. We study the effects of government policies on nonsweeping innovations under the minimum quantity mandate in Section 4 and under the minimum blending mandate in Section 5. Section 6 investigates the effects of policies on sweeping innovations and Section 7 concludes.

1 A Model of Different Energy Resources

We consider four kinds of energy resources, indexed by $i \in I \equiv \{c, e, b, s\}$: $i = c$ for conventional nonrenewable resources (CNR), e.g., oil, coal, and natural gas; $i = e$ for environmentally sensitive
(nonrenewable) resources (ESR), including nonrenewable unconventional oil such as oil sand, extra-heavy crude, and oil shale, nuclear, and oil from environmentally fragile areas such as ANWR; $i = b$ for biomass (e.g., biofuels such as ethanol and biodiesel, and biopower such as cofiring switchgrass with fossil fuels) and wind energies, referred to as BWE; and $i = s$ for solar energies. Let $c_i$ be the (constant) unit cost of using resource $i$, which includes extracting, processing and transportation costs. Thus, there is constant returns to scale in production and extraction and for nonrenewable resources, the cost of extraction is stock independent. We assume that there is a capacity constraint in the production of BWE, denoted by $\bar{q}_b$: $q_b \leq \bar{q}_b$.

Consider a representative firm in each of the four sectors. The CNR firm is endowed with a stock of $S_{c,0}$ and the ESR firm with $S_{e,0}$. We assume for now that the stocks are given but later will allow stock shocks due to sudden discovery of new reserves. Both firms face the possibility of a government tax $\tau_n$ on the use of nonrenewable resources, e.g., a gasoline tax, and the ESR firm faces an additional possibility of an environmental tax $\tau_e$, for instance, a tax imposed on sand oil for its environmental damages. Let $C_c = c_c + \tau_n$ and $C_e = c_e + \tau_n + \tau_e$ be the total costs after accounting for these taxes.

The BWE and solar firms can purchase innovations or undertake R&D themselves to reduce their costs $c_b$ and $c_s$ and the BWE firm can further purchase innovations or engage in R&D to expand its capacity $\bar{q}_b$. There have been many efforts in the literature to model R&D in backstop technologies, allowing discrete technological breakthroughs (e.g., Kamien and Schwartz (1978) and Hung and Quyen (1993)) as well as continuous reduction of extraction costs through R&D (e.g., Tsur and Zemel (2003)). In all of these models, R&D takes the form of accumulated investment, where the stock of knowledge brings about the breakthroughs or reduced costs. Implicitly, the R&D is assumed to be undertaken by a social planner or firms in the backstop sector. For our purpose, we sidestep the dynamic issues involved and assume instead that the firms in BWE and/or solar sectors or independent RND firms undertake a one time R&D investment now. In both cases, the innovating firm can license the new technology to other firms in the renewable sectors. The costs
and capacity of the adopters are functions of these R&D expenditures: \( c_b(k_b), \bar{q}_b(k_q) \), and \( c_s(k_s) \), with \( \partial c_i/\partial k_i < 0 \), \( \partial^2 c_i/\partial k_i^2 > 0 \) for \( i = b, s \), \( \partial \bar{q}_b/\partial k_q > 0 \), and \( \partial^2 \bar{q}_b/\partial k_q^2 < 0 \).

Governments routinely subsidize the renewable energy sector but the subsidy has taken different forms. In certain cases the government directly subsidizes the production of renewable energies (e.g., the US subsidy of ethanol and solar energies), while in other cases the government subsidizes the R&D in these sectors. Let the direct cost subsidies (or negative taxes) be \(-\tau_b\) and \(-\tau_s\). Then the net costs in BWE and solar production after adopting the new technologies are \( C_b = c_b(k_b) - \tau_b \) and \( C_s = c_s(k_s) - \tau_s \). Let the R&D subsidies be \(-\tau_{k_b}, -\tau_{k_q}\), and \(-\tau_{k_s}\). The net costs of R&D are \((1 - \tau_{k_b})k_b, (1 - \tau_{k_q})k_q\), and \((1 - \tau_{k_s})k_s\). The focus of this paper is on the effects of government tax policies on firms’ incentives to undertake the three kinds of R&Ds.

Governments have also adopted or planned quantity policies such as mandates on the minimum quantity or blend ratio of renewable energies. The linear cost functions in our model implies that the true backstop, solar energy, will be used only after all nonrenewable resources are exhausted. Such mandates, therefore, are relevant only for BWE; we represent the minimum quantity policy by \( q_b \geq \bar{q}_b \) and the minimum blend policy by \( q_b \geq \rho(q_c + q_e) \), with \( q_b < \bar{q}_b \) and \( \rho(q_c(t) + q_e(t)) < \bar{q}_b \) for all \( t \).

We assume for simplicity that resources from the four sectors are perfect substitutes. Let \( h(Q, \eta) \) be the inverse demand function, where \( Q = \sum_{i \in I} q_i \) is the total output from the four sectors and \( \eta \) is an exogenous demand parameter, the changes of which represent demand shocks. The demand function is given by \( Q = D(p, \eta) = h^{-1}(p, \eta) \) where \( p \) is the energy price.

\[ ^{2}\text{The analysis becomes much more complicated if we allow for continuous investment and R&D capital stocks. In particular, when the CNR firm has market power, it has incentive to choose extraction paths to influence the time path of the R&D expenditures. The analysis in itself may become analytically intractable; for instance, Powell and Oren (1989) used numerical methods to solve such a model.} \]

\[ ^{3}\text{These energies are in many cases imperfect substitutes, especially as transportation fuel. The relative advantages of different forms of energy vary spatially and across jurisdictions. For instance, in remote areas of developing countries without adequate infrastructure, solar and biomass energies may prove to be more efficient than electricity generated by nonrenewable resources. Chakravorty and Krulce (1994), Chakravorty, Roumasset and Tse (1997) and Chakravorty, Kruce and Roumasset (2005) provide more argument and modeling strategies for heterogeneous resources being imperfect substitutes.} \]
We assume that for all levels of taxes and R&D expenditures,
\[ C_c < C_b, C_e < C_s < h(q_b, \eta). \] (1)

That is, we limit the level of tax/subsidy that we consider and implicitly assume that the cost of renewable energies will exceed that of CNR even with R&D expenditures. This assumption approximates the current cost structure in energy use. CNR remains the cheapest energy and other energy sources have not yet been fully competitive with CNR. Solar energy is the most costly energy form among the four sectors, despite the technological progress in recent years. Between BWE and ESR, the cost advantage is not as clear: with the high oil prices, some forms of BWE and ESR, such as ethanol and Canadian oil sand, are starting to be competitive with CNR. However, ethanol’s competitiveness in the US arises partly from government subsidies, and there is a lack of sufficient environmental regulation on the pollution generated in extracting and processing oil sand.

We will consider both cases of \( C_b < C_e \) and \( C_b > C_e \). Finally, even though the BWE cost is lower than that of solar, the BWE sector cannot compete out the solar sector: due to its capacity limit, BWE production cannot satisfy the market demand all by itself even when energy price reaches \( C_s \).

Energy markets are typically characterized by the existence of market power in the CNR sector, particularly in oil. The renewable energy market is, on the other hand, much more competitive. We will consider two market structures: a competitive market in which firms in all four sectors are price takers, and an imperfectly competitive market in which the CNR firm is a Stackelberg leader and firms in the other three sectors are followers. From a long-run perspective, it is not clear \textit{a priori} which market structure represents a better approximation of the real world. In the medium term before outputs from the ESR, BWE and solar sectors capture sizable market share, it is likely that the market power of OPEC remains a dominant force in energy. However, in the long run, the

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\(^4\) Note that \( C_c \) and \( C_e \) are the total production costs and do not include the in situ values or scarcity rents of the two nonrenewable resources.

\(^5\) The International Energy Agency’s 2007 World Energy Outlook predicts that by 2030, OPEC countries will constitute over half of all world oil production: 60.6 mb/d versus the total world production of 116.3 mb/d. In contrast, in 2006, OPEC produced 35.8 in a total world production of 84.6 mb/d.
market power of OPEC will diminish as the market share of CNR output decreases.

2 Competitive Equilibrium of the Energy Market

In a competitive market, there are a number of price taking firms in each of the four sectors. For simplicity, we consider a representative firm in each sector and analyze the four representative firms’ behavior in three steps. In the first step, the firms choose the optimal output paths given government policies, after accounting for the renewable R&D expenditures. In the second step (Section 3), we calculate the benefits of R&D expenditures, given the competitive equilibrium in the energy market and the government policies, and thus find the firms’ optimal R&D expenditures. Finally (Sections 4 and 6), we analyze how the R&D expenditures respond to government policies and other shocks to the system (e.g., demand shocks).

Given the assumption of price taking behavior, the equilibrium production paths of the four competitive firms are equivalent to the optimal path of a single firm that is fully integrated into all of the four sectors. We thus study the optimization problem of such a fully integrated firm. Besides modeling convenience, this approach is also motivated by the observation that major international oil companies (IOCs) and national oil companies (NOCs) are often integrated into ESR and renewable energies.

We present the results when the government’s quantity policy mandates a minimum renewable usage: \( q_b \geq q_b \). As noted earlier, this is the kind of quantity policies adopted by the US. (We later show the results when the quantity policy mandates the minimum blend: \( q_b \geq \rho(q_c + q_e) \).) Then given a price trajectory \( p(t) \) for the energy output and costs \( C_i, i \in I \), which in turn depend

\[ \text{For instance, IOCs are the major players in extracting oil sands in Canada, and they are expected to be the major players if oil shale in the US is to be developed. (In early 1980s, Exxon poured a billion dollars into shale oil development in Colorado in response to high oil prices during the Second Oil Shock. This effort abruptly ended as the development cost skyrocketed and as oil price gradually decreased. (Yergin (1992)).) Shell plans to invest between $22 billion and $23 billion “to develop an energy portfolio including second-generation biofuels, wind energy and unconventional fuels” (McNulty (2007)). On the other hand, NOCs, a dominant force in the oil industry (controlling about 77% of world oil reserves, versus 10% controled by IOCs), have important national goals that go beyond simple profit maximization, including economic development and energy security (Baker Institute Policy Report (2007)). In other words, NOCs do not have to be integrated into other energy sectors to maximize the welfare of a nation from all energy sectors.} \]
on taxes $\tau = \{\tau_n, \tau_e, \tau_b, \tau_s, \tau_{kq}, \tau_{ks}\}$ and R&D expenditures $k = \{k_b, k_q, k_s\}$, the representative firm’s optimization problem is

$$J(\tau, k) = \max_{q_i, t \in T, S_c, S_e} \int_0^\infty e^{-rt} \left[ p(t) \sum_{i \in I} q_i(t) - C_c q_c(t) - C_e q_e(t) - C_b q_b(t) - C_s q_s(t) \right] dt$$

s.t. $\dot{S}_c(t) = -q_c(t); \dot{S}_e(t) = -q_e(t);$ 
$S_c(0) = S_{c,0}; S_e(0) = S_{e,0};$
$q_b \leq q_b(t) \leq \bar{q}_b; q_i \geq 0, i \in I;$ 
$S_b(t) \geq 0, S_e(t) \geq 0.$

The competitive equilibrium is determined by the firm’s optimal production choices $q_i(t)$ given $p(t)$, as well as the market clearing condition: $p(t) = h(\sum_i q_i(t), \eta)$.

The optimization problem in (2) is similar to one with multiple stocks and backstop resources (e.g., Heal (1976), Hartwick (1978), Kemp and Long (1980), and Holland (2003)). Different from the literature, in our model there are two backstop resources where one of them has a capacity as well as a minimum quantity constraint. In Appendix A we derive the solution to the optimization problem (2). Due to constant marginal extraction costs, the problem is linear in the output variables $q_i, i = c, e, b, s$. Thus the three resources without a capacity constraint, $i = c, e, s$, cannot be produced simultaneously, i.e., there should be a clear order of extraction among them. Let $\lambda_c$ and $\lambda_e$ be the current value shadow prices of stocks $S_c$ and $S_e$, which are constants (independent of time and stock sizes) due to the lack of stock effects in extraction costs. Then the effective marginal costs of resource $i$ at time $t, i = c, e$, which include the marginal production costs as well as the Hotelling rents or scarcity rents, are given by

$$P_c(t) = C_c + \lambda_c e^{rt}; \ P_e(t) = C_e + \lambda_e e^{rt}. \quad (3)$$

Linearity of the model in $q_c$ and $q_e$ implies that whenever resource $i$ is produced (i.e., $q_i > 0$), the market energy price must be $p(t) = P_i(t), i = c, e$. Further, whenever solar energy is produced, the price must be $p(t) = C_s$.

The minimum quantity and capacity constraints in producing BWE imply that $q_b(t) = \bar{q}_b$ when $p(t) < C_b$, and $q_b(t) = \bar{q}_b$ when $p(t) \geq C_b$. Let $T_b = \min\{t \geq 0 : q_b(t) \geq \bar{q}\}$ be the earliest time
at which BWE production hits full capacity, and let $T_i$, $i = c, e, s$, be the time at which resource $i$ starts to be produced. Proposition 1 proved in Appendix A characterizes the optimal production pattern.

**Proposition 1** In the optimal solution to (2), $T_c = 0$ and $T_i > 0$, $i = b, e, s$: at the beginning, both CNR and BWE are produced, with $q_b(t) = q_b$. Further,

(i). If $T_b < T_e$, i.e., if BWE starts to be produced at full capacity before the start of ESR production, then

(a) For $t \in [0, T_b)$, $q_c(t) > 0$, $q_b(t) = q_b$, $q_j = 0$, $j = e, s$, and $p(t) = P_c(t)$: only CNR and BWE are produced, and CNR’s effective marginal cost determines the energy price;

(b) For $t \in [T_b, T_e)$, $q_e(t) > 0$, $q_b(t) = \bar{q}_b$, $q_c(t) = q_s(t) = 0$, and $p(t) = P_c(t)$: now BWE is produced at its full capacity;

(c) For $t \in [T_e, T_s)$, $S_c(t) = 0$, $q_e(t) > 0$, $q_b(t) = \bar{q}_b$, $q_c(t) = q_s(t) = 0$, and $p(t) = P_c(t)$: CNR has been exhausted and now ESR and BWE are produced. BWE produces at full capacity and the energy price is given by ESR’s effective marginal cost.

(d) For $t \geq T_s$, $S_c(t) = S_e(t) = 0$, $q_b(t) = \bar{q}_b$, $q_s(t) > 0$, $q_c(t) = q_e(t) = 0$, and $p(t) = C_s$: both CNR and ESR have been exhausted and only BWE and solar are produced.

(ii). If $T_e < T_b$, i.e., if ESR starts to be produced before the production of BWE hits full capacity, then

(a) For $t \in [0, T_e)$, $q_c(t) > 0$, $q_b(t) = \bar{q}_b$, $q_j = 0$, $j = e, s$, and $p(t) = P_c(t)$;

(b) For $t \in [T_e, T_b)$, $S_c(t) = 0$, $q_e(t) > 0$, $q_b(t) = \bar{q}_b$, $q_j = 0$, $j = c, s$, and $p(t) = P_c(t)$;

(c) For $t \in [T_b, T_s)$, $S_c(t) = 0$, $q_e(t) > 0$, $q_b(t) = \bar{q}_b$, $q_c(t) = q_s(t) = 0$, and $p(t) = P_c(t)$;

(d) For $t \geq T_s$, $S_c(t) = S_e(t) = 0$, $q_b(t) = \bar{q}_b$, $q_s(t) > 0$, $q_c(t) = q_e(t) = 0$, and $p(t) = C_s$.

Figure 1 presents the two possible production patterns. If $C_b < C_e + \lambda_e e^{T_e}$, BWE is produced at full capacity before ESR starts to be produced. Note that this may occur even if $C_b > C_e$.
since ESR is nonrenewable and has a limited supply, its scarcity rent may render it noncompetitive against the renewable BWE even if ESR has a lower production cost. ESR becomes competitive only when the energy price is sufficiently high (when $t > T_e$): in this case, ESR is produced even though its effective marginal cost is higher than $C_b$ due to the capacity constraint of BWE. On the other hand, $T_b > T_e$ if $C_b > C_e + \lambda_e e^{rT_e}$, or when the cost of BWE is sufficiently high. In summary,

**Remark 1** A sufficient condition for BWE to be produced at full capacity before ESR starts to be produced is $C_b < C_e$.

The production patterns in Figure 1 are similar to one in which there are only three resources, CNR, ESR, and solar. The existence of the renewable BWE does not affect the production pattern due to its capacity constraint. Of course, it does affect the levels of production as well as the energy price. Due to the linear production cost, the production of BWE “jumps up” at $T_b$: the minimum quantity constraint binds for $t < T_b$, and at $t = T_b$, $q_b$ jumps up to $\bar{q}_b$.

The production patterns identified in Proposition 1, together with the market clearing condition, lead to a set of conditions that determine the optimal solutions in a closed form, including the levels of costate variables $\lambda_c$ and $\lambda_e$ as well as switch times $T_i$, $i \in I$.

**Corollary 1** (i) If $T_b < T_e$, the optimal solutions to (2) are fully characterized by

\[
\begin{align*}
C_c + \lambda_c e^{rT_b} &= C_b \\
C_c + \lambda_c e^{rT_e} &= C_e + \lambda_e e^{rT_e} \\
C_e + \lambda_e e^{rT_s} &= C_s
\end{align*}
\]

\[
\begin{align*}
\int_0^{T_b} \left[ D(C_c + \lambda_c e^{rt}, \eta) - q_b \right] dt + \int_{T_b}^{T_e} \left[ D(C_c + \lambda_c e^{rt}, \eta) - \bar{q}_b \right] dt &= S_{c,0} \\
\int_{T_e}^{T_s} \left[ D(C_e + \lambda_e e^{rt}, \eta) - \bar{q}_b \right] dt &= S_{e,0}
\end{align*}
\]
(a) Case (i): $T_b < T_c$

(b) Case (ii): $T_b > T_c$

Figure 1: Possible Optimal Production Patterns
(i) If $T_b > T_e$, the optimal solutions to (2) are fully characterized by

\[
C_c + \lambda_c e^{rT_e} = C_e + \lambda_e e^{rT_e} \\
C_e + \lambda_e e^{rT_b} = C_b \\
C_e + \lambda_e e^{rT_s} = C_s
\]

\[
\int_0^{T_e} \left[ D(C_c + \lambda_c e^{rt}, \eta) - q_b \right] dt = S_{c,0} \\
\int_{T_b}^{T_e} \left[ D(C_e + \lambda_e e^{rt}, \eta) - q_b \right] dt + \int_{T_b}^{T_s} \left[ D(C_e + \lambda_e e^{rt}, \eta) - \bar{q}_b \right] dt = S_{c,0}
\]

The Corollary is proved in Appendix A. In each case, the first three equations describe the starting conditions for a particular kind of resource to be produced (at full capacity for BWE), and the last two equations are for CNR and ESR to be exhausted. The five equations then fully determine the five optimization variables: $\lambda_c$, $\lambda_e$, and $T_i$, $i = b, e, s$.

3 R&D and Investment in Renewable Energies

In this paper, we study two kinds of innovations resulting from R&D in renewable energies: cost reducing and capacity enhancing innovations. So far innovations in renewable energies have resulted in significant cost reductions, especially for wind and solar energies. Research activities lowering the cost of producing second generation ethanol can potentially drastically raise the ethanol capacity. Firms can further invest in new equipment and facilities to reduce cost and raise capacity. The nature of investment is the same as R&D in the context of our model: they both result in lower cost or higher capacity. We thus do not distinguish between R&D and investment, and refer both activities as R&D for simplicity.

The literature of R&D in backstop technology with perfectly competitive backstop supply typically assumes that it is the government that conducts R&D; the R&D level is chosen to maximize the social welfare rather than profits of individual firms (see, for example, Kamien and Schwartz (1978), Hung and Quyen (1993), and Tsur and Zemel (2003)). We focus instead on private incentives to innovate while allowing government subsidies to the private R&D efforts.
A major consideration in our analysis is whether innovations in renewable energies are significant enough to affect the energy price, which in turn will affect the production path of nonrenewable energies. One might argue that such innovations will unlikely have any price effect in the world energy market given the relatively small market share of renewable energies. However, in the long run such innovations might lead to price effects through two channels: eventually the market share of renewable energies will increase (and exceed that of nonrenewable energies), and anticipating this, firms in CNR and ESR sectors adjust their production paths, leading to price changes now.

We call innovations that lead to industry-wide cost reductions or capacity expansions sweeping innovations, and those without industry-wide effects nonsweeping innovations. It is straightforward to imagine an innovation that is sweeping: this happens when the innovation significantly reduces production costs or raises production capacities and when it is widely adopted. There can also be many reasons for an innovation to be nonsweeping. For example, it might be adopted by only some of the firms in renewable sectors; Kamien and Tauman (1986) shows that an R&D firm may optimally choose to license the innovation to one firm only, even though potentially it can license the innovation to the entire competitive industry. A firm in the renewable sector may resort to secrecy rather than seeking patent protection for its innovation, preventing widespread adoption and any industry-wide effects. In Appendix A, we argue that for cost reducing innovations, the concept of sweeping innovation is closely related to that of drastic innovations (Arrow (1962)): a cost reducing innovation is sweeping if it is drastic and nonsweeping if nondrastic.

Consider a firm that engages in cost reducing R&D in the BWE sector: it can either be an independent R&D firm or a BWE firm that also conducts R&D. Suppose the firm invests $k_b$ in R&D and thus reduces the production cost from $c_b(0)$ to $c_b(k_b)$. If the innovation is nonsweeping, there is no industry-wide effect and the innovation does not change the energy price or the production.

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7 According to Rajagopal, Sexton, Roland-Holst and Zilberman (2007b), the entire worldwide ethanol production resulted in 1.5% increase in world fuel supply (adjusted for energy equivalence) and 3% fuel price decrease in 2006.
8 Levin et al. (1987) finds that firms consider secrecy as being a more effective mechanism of appropriation than patent for process innovations. Based on a more recent survey, Cohen, Nelson and Walsh (2000) finds that secrecy is considered as being a more effective appropriation mechanism than patent and lead time by US manufacturing firms for both product and process innovations.
levels. Let $\beta_b \in (0, 1]$ be the market share of the innovation, measuring the proportion of BWE firms adopting the new technology. Suppose the innovating firm captures all the benefits from the innovation. Then its present value profit is

$$\pi_n^n(T_b, k_b) = \beta_b \left[ \int_0^{T_b} e^{-rt} (c_b(0) - c_b(k_b)) q_b dt + \int_{T_b}^{\infty} e^{-rt} (c_b(0) - c_b(k_b)) \bar{q}_b dt \right] - (1 - \tau_{k_b}) k_b, \quad (6)$$

where superscript $n$ stands for nonsweeping. Note that the time at which BWE starts to produce at full capacity, $T_b$, is not affected by the innovation and is given exogenously by the equilibrium conditions in Corollary 1.

Suppose instead the innovation is sweeping and for simplicity is adopted by all BWE firms; e.g., the firm licenses the innovation to all BWE firms, charging a license fee of $l$. Suppose further that the firm bargains with the BWE firms as a group and can only appropriate part $\alpha_b \in (0, 1)$ of the cost saving benefit $c_b(0) - c_b(k_b)$. We assume for simplicity that $\alpha_b$ is independent of $k_b$, the scale of the innovation. Then the cost of BWE firms, including the licence fee $l$, becomes $c_b(k_b) + l = \alpha_b c_b(0) + (1 - \alpha_b) c_b(k_b)$, a weighted average of the original and new costs. As long as $\alpha_b < 1$, the innovation leads to industry-wide cost reduction, affecting the energy price and production patterns.

The R&D firm’s profit from licensing the innovation is

$$\pi_w^w(k_b; \alpha_b) = \alpha_b \left[ \int_0^{T_b(k_b)} e^{-rt} (c_b(0) - c_b(k_b)) q_b dt + \int_{T_b(k_b)}^{\infty} e^{-rt} (c_b(0) - c_b(k_b)) \bar{q}_b dt \right] - (1 - \tau_{k_b}) k_b, \quad (7)$$

where superscript $w$ stands for sweeping. In (7), $k_b$ affects $T_b$ through its effect on the industry-wide production cost $C_b$.

---

9 For instance, if a BWE firm makes the innovation, it adopts the innovation by itself and thus earns all the cost reduction benefits. If an independent R&D firm makes the innovation and chooses to license the innovation to a single BWE firm, through its bargain power (one versus many BWE firms), it is able to appropriate all the cost reduction benefits. In both cases, $\beta_b$ equals one divided by the number of (identical) BWE firms.

10 If we assume that the R&D firm is a monopolist (e.g., fully protected by a patent of infinite periods) and charges a monopoly price, then the price is likely to depend on $k_b$. The analysis becomes intractable without adding further qualitative insights.

11 If the R&D firm captures all the cost reduction benefits so that $\alpha_b = 1$, the new technology, even though widely adopted, does not lead to industry-wide cost reduction because of the license fee. The innovation then becomes nonsweeping with a market share of $\beta_b = 1$. 

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The first order conditions of (6) and (7) are

\[
\frac{\beta_b}{r} \left[ (1 - e^{-rT_b})q_b + e^{-rT_b}\bar{q}_b \right] \left[ -c'_b(k_b) \right] = 1 - \tau_{k_b}, \tag{8}
\]

\[
\alpha_b \left[ \frac{1}{r} (1 - e^{-rT_b})q_b + e^{-rT_b}(\bar{q}_b - q_b) \right] \left[ -c'_b(k_b) \right] = 1 - \tau_{k_b}, \tag{9}
\]

where in (9), we used the condition \( \frac{\partial T_b}{\partial k_b} = \frac{\partial T_b}{\partial C_b} \frac{\partial C_b}{\partial k_b} \) and the fact that \( \frac{\partial C_b}{\partial k_b} = (1 - \alpha_b) c'_b(k_b) \). Note that when \( \alpha_b = \beta_b = 1 \), (9) and (8) coincide.

In (9), the left hand side measures the marginal benefit of \( k_b \), which equals the decrease in the cost \( -c'_b \) multiplied by the profit share of the R&D firm \( \beta_b \), as well as total discounted BWE outputs, the term in the square brackets. When the innovation is sweeping, there is an additional effect in the marginal benefit of \( k_b \), represented by the second term in the first set of square brackets on the left hand side of (9). The innovation, by reducing the industry wide BWE cost \( C_b \), affects the production pattern of the entire energy sector. In particular, it affects \( T_b \), the time at which BWE starts full capacity production. Later we will show that \( \frac{\partial T_b}{\partial C_b} > 0 \). Thus, by reducing the BWE cost, the sweeping innovation also speeds up the full scale use of BWE. Since the innovating firm captures more rent when the BWE sector produces more, the earlier full capacity BWE production further increases the rent accrued to the innovating firm. Thus, the innovating firm with a sweeping innovation has more incentive to license the technology to all BWE firms due to the added production pattern effect.

Taking a similar approach, we know that for the solar sector, a firm that invests \( k_s \) to reduce the production cost from \( c_s(0) \) to \( c_s(k_s) \) earns the following profits:

\[
\pi^n_s(T_s, k_s) = \beta_s \int_{T_s}^{\infty} e^{-rt} (c_s(0) - c_s(k_s)) (D(C_s(0), \eta) - \bar{q}_b)dt - (1 - \tau_{k_s})k_s, \tag{10}
\]

\[
\pi^w_s(k_s) = \alpha_s \int_{T_s}^{\infty} e^{-rt} (c_s(0) - c_s(k_s)) (D(C_s(k_s), \eta) - \bar{q}_b)dt - (1 - \tau_{k_s})k_s, \tag{11}
\]

where \( C_s(0) = c_s(0) - \tau_s \) equals the production cost (including license fee and government subsidy) under a nonsweeping innovation, \( C_s(k_s) = \alpha_s c_s(0) + (1 - \alpha_s) c_s(k_s) - \tau_s \) is that under a sweeping innovation, \( \beta_s \) is the market share of the nonsweeping innovation, and \( \alpha_s \) is the share of the cost
reduction benefit the R&D firm appropriates for the sweeping innovation. We have assumed again that the market share of the sweeping innovation is one.

The first order conditions are given by

$$\beta_s(D(C_s(0), \eta) - \bar{q}_b)e^{-\gamma T_s} \frac{1}{r} \left[-c_s'(k_s)\right] = 1 - \tau_{k_s}, \quad (12)$$

$$\alpha_s(D(C_s(k_s), \eta) - \bar{q}_b)e^{-\gamma T_s} \left[\frac{1}{r} + (1 - \alpha_s)(c_s(0) - c_s(k_s)) \left(\frac{\partial T_s}{\partial C_s} + \frac{\epsilon_r'(k_s)}{rC_s'(k_s)}\right)\right] \left[-c_s'(k_s)\right] = 1 - \tau_{k_s}, \quad (13)$$

where \(\epsilon_r' = -D'(C_s(k_s), \eta)C_s/(D(C_s(k_s), \eta) - \bar{q}_b)\) is the (absolute value of the) residual demand elasticity facing the solar sector, net of the demand supplied by the BWE sector. Again, (12) and (13) are identical when \(\alpha_s = \beta_s = 1\). From (12), we see that for a nonsweeping innovation, the marginal benefit of \(k_s\) derives from the resulting cost reduction. In (13), R&D in the sweeping innovation has two additional effects, through its influence on \(T_s\), the time at which solar energy starts to be used, and on the (residual) demand facing the solar sector because \(p = C_s\): industry-wide cost changes bring forth equal changes in energy prices, affecting the demand for solar energy. It is obvious that \(\epsilon_r' > 0\) and later we will show that \(\partial T_s/\partial C_s > 0\). Thus, similar to the case of \(k_b\), the additional effects for sweeping innovation are positive due to the effects of the innovation on the dynamic energy use patterns. An innovating firm with a sweeping innovation has incentive to license it to as many solar firms as possible.

A firm that invests \(k_{\bar{q}}\) to increase the production capacity \(\bar{q}_{\bar{q}}\) earns the following profits, for nonsweeping and sweeping innovations:

$$\pi_n^q(T_b, T_e, T_s, k_{\bar{q}}) = \beta_{\bar{q}} \int_{T_b}^{\infty} e^{-r t} (p(t) - C_b)(\bar{q}_b(k_{\bar{q}}) - \bar{q}_b(0))dt - (1 - \tau_{k_{\bar{q}}})k_{\bar{q}}, \quad (14)$$

$$\pi_n^q(k_{\bar{q}}) = \alpha_{\bar{q}} \int_{T_b(k_{\bar{q}})}^{\infty} e^{-r t} (p(t; k_{\bar{q}}) - C_b)(\bar{q}_b(k_{\bar{q}}) - \bar{q}_b(0))dt - (1 - \tau_{k_{\bar{q}}})k_{\bar{q}}, \quad (15)$$

where \(\beta_{\bar{q}}\) is the market share of the nonsweeping innovation, \(\alpha_{\bar{q}}\) is the proportion of the BWE profits due to the sweeping innovation appropriated by the innovating firm, \(C_b = c_b - \tau_b\) is the
production cost of BWE firms, and energy price \( p(t) \) under nonsweeping innovation is given by

\[
p(t) = \begin{cases} 
  C_c + \lambda_c e^{rt} & T_b \leq t \leq \max\{T_b, T_e\} \\
  C_e + \lambda_e e^{rt} & \max\{T_b, T_e\} \leq t \leq T_s \\
  C_s & t \geq T_s
\end{cases}
\]  

(16)

For the sweeping innovation, price \( p(t; k_{\bar{q}}) \) is similar except that the \( \lambda \)'s and the \( T \)'s are affected by \( k_{\bar{q}} \) through their dependence on \( \bar{q}_b \) in Corollary 1.

The first order conditions of (14) and (15) are given by

\[
\beta_{\bar{q}} \left[ \int_{T_b}^{\infty} e^{-rt} (p(t) - C_b) dt \right] \bar{q}'_b(k_{\bar{q}}) = 1 - \tau_{k_{\bar{q}}},
\]

(17)

\[
\alpha_{\bar{q}} \left[ \int_{T_b}^{\infty} e^{-rt} (p(t) - C_b) (1 + \epsilon_{\bar{q}}(t, k_{\bar{q}})) dt \right] \bar{q}'_b(k_{\bar{q}}) = 1 - \tau_{k_{\bar{q}}},
\]

(18)

where

\[
\epsilon_{\bar{q}}(t, k_{\bar{q}}) = \frac{\partial(p(t; k_{\bar{q}}) - C_b)}{\partial(\bar{q}_b(k_{\bar{q}}) - \bar{q}_b(0))} \frac{(\bar{q}_b(k_{\bar{q}}) - \bar{q}_b(0))}{(p(t; k_{\bar{q}}) - C_b)}
\]

measures the elasticity of the profit margin with respect to the added capacity in the BWE sector.

As we show in the next section, a higher \( \bar{q}_b \) reduces the values of both CNR and ESR, thus reducing price \( p(t) \) for all \( t \). Consequently, \( \epsilon_{\bar{q}}(t, k_{\bar{q}}) \) is negative. Thus, when the capacity raising innovation is sweeping, the innovating firm has less incentive to license it to many BWE firms due to the price (or production pattern) effects.

We next study the effects of government environmental and energy policies \( q_b \) and \( \tau \) and economic parameters such as the demand shock \( \eta \) on firms’ incentives to conduct R&D. We study the nonsweeping (Section 4) and sweeping innovations (Section 6) separately.

4 Nonsweeping Innovations: Effects of Government Policies

The optimality conditions on R&D efforts \( k_b, k_s \) and \( k_{\bar{q}} \) are given in (8), (12) and (17) respectively. We see from these conditions that policy interventions and market shocks affect the optimal R&D efforts through influencing (i) the production patterns, in particular, the switch times, \( T_i, i \in I \),

\[19\]
and (ii) the price patterns, in particular the levels of $\lambda_c$ and $\lambda_e$. For example, the marginal benefit of cost reducing R&D $k_b$ depends on $T_b$, the time at which the BWE sector starts to produce at full capacity. This is intuitive since cost reducing R&D in the BWE sector reaps more benefit when $q_b$ rises. If a policy intervention delays $T_b$, it will reduce the benefit of $k_b$ and thus reduce firms’ incentive to conduct cost reducing R&D in the BWE sector. Similarly, since the benefit of R&D in solar, $k_s$, depends on $T_s$, policies that delay the start of solar production will reduce R&D efforts in this sector. The marginal benefit of capacity expanding R&D depends on the entire production and price paths, and the policy impacts are more complicated.

The following Lemma, derived from Corollary I and proved in Appendix A, describes how the production and price patterns and values of the CNR and ESR resources change in response to policy intervention and market shocks. It will be useful in characterizing the impacts on R&D incentives.

**Lemma 1**  
(i) $\frac{\partial T_b}{\partial C_c} > 0$, $\frac{\partial T_e}{\partial C_c} > 0$, $\frac{\partial \lambda_c}{\partial C_c} < 0$, and $\frac{\partial \lambda_e}{\partial C_c} < 0$. The effects of $C_c$ on $T_b$ depends on the magnitudes of $T_b$. In particular, there exists $\hat{T}_b \in (0, T_e)$ such that $\frac{\partial T_b}{\partial C_c} < 0$ if $T_b < \hat{T}_b$ and $\frac{\partial T_b}{\partial C_c} > 0$ if $T_b > \hat{T}_b$.

(ii) $\frac{\partial T_b}{\partial C_e} > 0$, $\frac{\partial T_e}{\partial C_e} > 0$, $\frac{\partial \lambda_c}{\partial C_e} > 0$, and $\frac{\partial \lambda_e}{\partial C_e} < 0$. The effect of $C_e$ on $T_b$ depends on the relative magnitudes of $T_b$ and $T_e$: $\frac{\partial T_b}{\partial C_e} < 0$ if $T_b < T_e$, and $\frac{\partial T_b}{\partial C_e}$ has ambiguous sign if $T_b > T_e$.

(iii) $\frac{\partial T_b}{\partial k_b} > 0$, $\frac{\partial T_b}{\partial k_b} < 0$, $\frac{\partial \lambda_c}{\partial k_b} > 0$, and $\frac{\partial \lambda_e}{\partial k_b} > 0$. Further, $\frac{\partial T_e}{\partial k_b} < 0$ if $T_b < T_e$ and $\frac{\partial T_e}{\partial k_b} > 0$ if $T_b > T_e$.

(iv) The signs of other parameters’ effects are independent of the relative magnitudes of $T_b$ and $T_e$. 

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In particular,

\[
\begin{align*}
\frac{\partial T_b}{\partial C_s} &< 0, \quad \frac{\partial T_s}{\partial C_s} > 0, \quad \frac{\partial T_e}{\partial C_s} > 0, \quad \frac{\partial \lambda_c}{\partial C_s} > 0, \quad \frac{\partial \lambda_e}{\partial C_s} > 0; \\
\frac{\partial T_b}{\partial q_b} &> 0, \quad \frac{\partial T_s}{\partial q_b} > 0, \quad \frac{\partial T_e}{\partial q_b} < 0, \quad \frac{\partial \lambda_c}{\partial q_b} < 0, \quad \frac{\partial \lambda_e}{\partial q_b} < 0; \\
\frac{\partial T_b}{\partial \eta} &< 0, \quad \frac{\partial T_s}{\partial \eta} < 0, \quad \frac{\partial T_e}{\partial \eta} > 0, \quad \frac{\partial \lambda_c}{\partial \eta} > 0, \quad \frac{\partial \lambda_e}{\partial \eta} > 0; \\
\frac{\partial T_b}{\partial S_{c,0}} &> 0, \quad \frac{\partial T_s}{\partial S_{c,0}} > 0, \quad \frac{\partial T_e}{\partial S_{c,0}} > 0, \quad \frac{\partial \lambda_c}{\partial S_{c,0}} < 0, \quad \frac{\partial \lambda_e}{\partial S_{c,0}} < 0; \\
\frac{\partial T_b}{\partial S_{e,0}} &> 0, \quad \frac{\partial T_s}{\partial S_{e,0}} > 0, \quad \frac{\partial T_e}{\partial S_{e,0}} < 0, \quad \frac{\partial \lambda_c}{\partial S_{e,0}} < 0, \quad \frac{\partial \lambda_e}{\partial S_{e,0}} < 0.
\end{align*}
\]  

(19)

The results in Lemma 1 are intuitive. As the cost of using CNR increases, its rent \( \lambda_c \) decreases although the resource price \( p(t) = P_c(t) \) increases initially. Consequently, it takes a longer time for CNR to be exhausted, so that both \( T_e \) and \( T_s \) increases. Since ESR is used at a later date, its present value \( \lambda_e \) decreases. Finally, time \( \hat{T}_b \) is such that \( P_c(t) \) is higher as \( C_c \) increases when \( t < \hat{T}_b \) and lower when \( t < \hat{T}_b \). Since BWE starts full capacity production when \( P_c(t) = C_b \), we know \( T_b \) decreases if and only if \( T_b < \hat{T}_b \).

As the cost of using ESR increases, ESR becomes less valuable: \( \lambda_e \) decreases. CNR is used before ESR, and as the future substitute becomes less appealing, CNR becomes more valuable: \( \lambda_c \) increases. This implies that \( P_c(t) \) increases and \( q_c(t) \) decreases, so that it takes a longer time for CNR to be exhausted: both \( T_e \) and \( T_s \) increase. Again, the effects of \( T_b \) depends on the magnitudes of the parameters.

As BWE becomes more costly, the start date of its full capacity production is delayed. The two nonrenewable resources CNR and ESR become more valuable, i.e., \( \lambda_c \) and \( \lambda_e \) increases, raising the prices of the resources and thus reducing energy demand. However, the reduced energy demand does not imply reduced extraction of both nonrenewable resources. Since the full capacity use of BWE is delayed, more nonrenewable resources are extracted, so that in aggregate, the renewable resources are exhausted at an earlier date and thus \( T_s \) decreases. More specifically, if \( T_b < T_e \), i.e., if full capacity production of BWE occurs earlier than ESR, a higher BWE cost expedites the start
of ESR: $\partial T_e / \partial C_b < 0$. Since ESR is used only after CNR is exhausted, this result implies that overall, the full scale use of BWE is sufficiently delayed so that CNR is exhausted earlier, even though the total demand for energy decreases due to the higher energy price.

If the solar energy becomes more costly, again the nonrenewable resources become more valuable, consistent with the conventional wisdom that nonrenewable resources are more valuable when the backstop technology becomes more expensive. It also takes a longer time for each nonrenewable resource to be exhausted. Since the energy price is higher when $t < T_s$, full capacity production of BWE starts at an earlier date.

As intuition suggests, a higher production capacity of BWE makes both nonrenewable resources less valuable, pushing down the energy price. The lower price of nonrenewable resources reduce the competitiveness of BWE so that BWE starts the full capacity production at a later date. Although the energy demand is higher due to the lower price, increased BWE capacity means that it takes a longer time for both nonrenewable resources to be exhausted: $T_s$ increases. Similar results hold for the minimum quantity restriction $q_b$. When $q_b$ is higher, more BWE has to be used, reducing $\lambda_c$ and $\lambda_e$, the values of the nonrenewables. Consequently, the energy prices decrease, delaying the exhaustion of the nonrenewable stocks.

When energy demand rises due to exogenous shocks, both nonrenewable resources become more valuable, raising their prices. Consequently BWE is used earlier. A higher demand also implies that the nonrenewables are exhausted at an earlier date, so that solar is used sooner. Finally, both renewable resources start to be used at later dates when the two nonrenewable stocks increase.

Based on Lemma 1 and (8), (12) and (17), we obtain the impacts on R&D incentives of various government policies.

**Proposition 2** (i) If the government raises the minimum BWE quantity mandate $q_b$, both $T_b$ and $T_s$ increase and both $\lambda_c$ and $\lambda_e$ decrease, reducing energy price $p(t)$ for $t < T_s$. Further,

- The R&D incentive in solar energy, $k_s$, decreases;

- The R&D incentive in raising the BWE capacity, $k_{q_b}$, decreases;
The impact of a higher $q_b$ on the R&D incentive in BWE, $k_b$, depends on the magnitude of the BWE cost $C_b$. If $C_b$ and thus $T_b$ are sufficiently low and $\bar{q}_b - q_b$ is relatively large, $k_b$ decreases. Otherwise, $k_b$ will increase.

(ii) If the government raises the nonrenewable tax $\tau_n$ and/or the pollution tax $\tau_e$ on ESR extraction, $T_s$ increases, $\lambda_e$ decreases, and $T_b$ decreases if $C_b$ is low and increases if $C_b$ is high. Price $p(t)$ increases for low $t$ but decreases for high $t$, with the two price paths crossing at point $t^*$ at a price level denoted by $C_b^* \equiv p(t^*) = p'(t^*)$. Further,

- The R&D incentive in solar, $k_s$, decreases;
- The R&D incentive in BWE, $k_b$, depends on the magnitude of $C_b$. It increases when $C_b < C_b^*$ and decreases when $C_b > C_b^*$.
- The R&D incentive in BWE capacity, $k_{\bar{q}}$, decreases when $C_b > C_b^*$, and may increase or decrease when $C_b < C_b^*$.

(iii) If the government raises the subsidy $\tau_b$ on BWE, $T_b$ decreases, $T_s$ increases, both $\lambda_c$ and $\lambda_e$ decrease, and thus price $p(t)$ decreases for all $t < T_s$.

- The cost reducing R&D incentive in BWE, $k_b$, increases;
- The R&D incentive in solar, $k_s$, decreases,
- The impact on the capacity enhancing R&D in BWE, $k_{\bar{q}}$, is ambiguous.

(iv) If the government raises the subsidy $\tau_s$ on solar, $T_b$ increases, $T_s$ decreases, both $\lambda_c$ and $\lambda_e$ decrease, and thus price $p(t)$ decreases for all $t < T_s$.

- The R&D incentives in BWE, $k_b$ and $k_{\bar{q}}$, decrease;
- the R&D incentive in solar, $k_s$ increases.

(v) All R&D incentives, $k_b$, $k_{\bar{q}}$ and $k_s$, increase as there are positive demand shocks, i.e., as $\eta$ rises.

(vi) All R&D incentives, $k_b$, $k_{\bar{q}}$ and $k_s$, decrease as there are positive stock shocks, i.e., as $S_{c,0}$
(vii) The R&D subsidies always raise the R&D incentives: \( k_i \) is increasing in \( \tau_{ki} \), \( i = b, s, \bar{q} \).

When the government imposes a higher minimum renewable energy use mandate, energy price \( p(t) \) decreases, delaying both switch times \( T_b \) and \( T_s \). Since innovation in the solar sector reaps benefits only after solar starts to be used, a higher \( T_s \) reduces the marginal benefit of \( k_s \), thereby reducing the R&D incentives in solar energy. For the capacity increasing innovation in BWE, it derives benefits from the full capacity production of BWE, with unit net profit of \( p(t) - C_b \). Thus, a higher \( q_b \) reduces the benefit through both delaying the full capacity production and reducing price \( p(t) \).

The impacts on the R&D incentive in reducing the cost of BWE, \( k_b \), are more complicated. This kind of R&D generates benefits from reducing the costs of producing BWE. Since the policy delays \( T_b \) and more BWE is produced after \( T_b \), the benefit from \( k_b \) decreases when \( q_b \) rises. On the other hand, the policy, by directly raising the amount of BWE produced before \( T_b \), increases the benefit from \( k_b \). The net impact on \( k_b \) depends on the relative magnitude of the two effects. If the cost of BWE is sufficiently low, the switch time \( T_b \) will be low, and the benefit from the higher BWE use before \( T_b \) is relatively smaller. In this case, the effect from a delayed \( T_b \) dominates and the optimal \( k_b \) decreases. Specifically, from (8), we obtain

\[
\frac{\partial k_b}{\partial q_b} = \frac{1 - e^{-rT_b} \left[ 1 + r(\bar{q}_b - q_b) \frac{\partial T_b}{\partial q_b} \right]}{(1 - e^{-rT_b})q_b + e^{-rT_b}\bar{q}_b}.
\]

In summary,

**Remark 2** The minimum BWE use mandate hurts cost reducing R&D incentives in solar and capacity enhancing R&D incentives in BWE, and may also reduce the cost reducing R&D incentive in BWE.

When the government imposes a nonrenewable tax \( \tau_n \) or a pollution tax on ESR \( \tau_e \), costs \( C_n \) and/or \( C_e \) increase, leading to slower extraction rates and thus delaying the start of solar energy \( T_s \). Consequently, the R&D incentive in solar, \( k_s \), decreases. The full capacity start date of BWE, \( T_b \),
may either decrease or increase, as shown in Figure 2. \( T_b \) decreases as the taxes increase if \( C_b < C_b^* \) and increases if \( C_b > C_b^* \). (The bold curves indicate the prices after the taxes are imposed.) The R&D incentive \( k_b \) increases when \( C_b < C_b^* \) or when \( T_b \) decreases, but decreases otherwise. Note that when \( C_b > C_b^* \), the taxes raise \( T_b \) but reduce price \( p(t) \) for \( t > T_b \). From (17), \( k_q \) decreases. However, when \( C_b < C_b^* \), the taxes reduce \( T_b \), but the future price \( p(t), t > T_b \), first increase and then decrease. The effect on \( k_q \) is thus ambiguous.

**Remark 3** The nonrenewable tax and/or the pollution tax on ESR hurts the R&D incentives in solar. They also hurt cost reducing and capacity enhancing R&D in BWE when the BWE cost is high. They help cost reducing R&D in BWE only when the BWE cost is sufficiently low.

Thus, energy and environmental policies that restrict the use of nonrenewable energies might in fact hurt the development of the competing alternatives, namely the renewable energies. In other words, although the nonrenewables and renewables are substitutes at a point of time (or statically), they might be complements dynamically. Thus, efforts at protecting ANWR may indeed hurt the
development of solar, and will help the development of BWE only when the cost of BWE is so low that the static substitution effect dominates the dynamic complementation effect.

The BWE subsidy \( \tau_b \) helps the cost reducing BWE R&D, as intuition suggests. However, by reducing the energy prices throughout time, the subsidy also delays the start of solar energy being used, thereby decreasing the solar R&D \( k_s \). The price decrease also implies that the subsidy might hurt the capacity enhancing R&D in BWE, especially when \( T_b \) is low (or cost \( C_b \) is low). On the other hand, solar subsidy \( \tau_s \), by reducing the energy prices throughout time, delays the full capacity production of BWE. The lower price and the delayed \( T_b \) imply that both cost reducing and capacity enhancing R&D incentives in BWE decrease.

**Remark 4** The BWE subsidy hurts solar R&D and may also hurt the capacity enhancing BWE R&D. The solar subsidy hurts both cost reducing and capacity enhancing R&D in BWE.

Although it seems intuitive that, between two competing renewable resources, the subsidy to one hurts the development of the other, we should note that Remark 4 is obtained in a setup where BWE and solar do not compete directly with each other. Either the two energies are not used together (when \( t < T_s \)), or when they are simultaneously used (i.e., leaving rooms for competition), the BWE is produced at a fixed level \( \bar{q}_b \). The “competition” result in Remark 4 is entirely due to the *dynamic* interaction of the two energies: a subsidy to one renewable energy affects the development of the other indirectly through influencing the production paths of the two nonrenewable energies.

### 5 Minimum Blend Mandates

In this section, we present the results when the quantity restriction takes the form \( q_b \geq \rho(q_c + q_e) \). As noted earlier, this is the kind of quantity policies adopted or proposed by some EU nations. We follow the same procedure as the baseline case to derive the impacts of the government policies on the R&D incentives. Given the government policies and firms’ R&D decisions, the optimization decisions of the four sectors are characterized by (2) with \( q_b \geq q_b \) replaced by \( q_b(t) \geq \rho(q_c(t) + q_e(t)) \).
We assume that \( q_c(0) + q_e(0) < \bar{q}_b \) so that \( q_c(t) + q_e(t) < \bar{q}_b \) for all \( t \geq 0 \) (since \( q_c(t) + q_e(t) \) is decreasing in time along the optimal path).

Given the linear production cost of BWE, we know the constraint \( q_b(t) \geq \rho(q_c(t) + q_e(t)) \) is binding when \( t < T_b \), where again \( T_b \) is the time at which BWE is produced at full scale, and the constraint is slack when \( t \geq T_b \). By the same reasoning as in Section 2, energy price \( p(t) \) equals \( P_c(t) \) or \( P_e(t) \) when \( t > T_b \), depending on which of the two nonrenewables is being produced simultaneously with BWE. When \( t < T_b \), price \( p(t) \) is greater than \( P_c(t) \) or \( P_e(t) \) to justify the proportional production of BWE. We will show that in this case, the price is given by the constrained effective marginal cost

\[
\hat{P}_i(t) = \frac{C_i + \rho C_b}{1 + \rho} + \frac{1}{1 + \rho} \lambda_i e^{rt}, \quad i = c, e, \tag{20}
\]

when resource \( i \) is produced with BWE. Path \( \hat{P}_c(t) \) lies above \( \hat{P}_e(t) \) when \( t \) is low and below \( \hat{P}_e(t) \) when \( t \) is high, and the two paths cross at the same time at which paths \( P_c(t) \) and \( P_e(t) \) cross, as illustrated in Figure 3. (It is important to note that \( \lambda_c \) and \( \lambda_e \) in this Section are different from those in Section 2 although we still use the same notations.)

Similar to Proposition 1, we obtain the following energy use and price patterns.

**Proposition 3** Along the optimal energy use path, \( T_c = 0 \) and \( T_i > 0, i = b, e, s \): at the beginning, both CNR and BWE are produced with \( q_b(t) = \rho q_c(t) \). Further,

(i). If \( T_b < T_c \), i.e., if BWE starts to be produced at full capacity before the start of ESR production, then

(a) For \( t \in [0, T_b) \), \( q_c(t) > 0, q_b(t) = \rho q_c(t), q_j = 0, j = e, s, \) and \( p(t) = \hat{P}_c(t) \): only CNR and BWE are produced, and CNR’s constrained effective marginal cost determines the energy price;
(b) For \( t \in [T_b, T_c) \), \( q_c(t) > 0, q_b(t) = \bar{q}_b, q_e(t) = q_s(t) = 0, \) and \( p(t) = P_c(t) \): now BWE is produced at its full capacity and the energy price is given by CNR’s effective marginal cost;

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(c) For $t \in [T_e, T_s)$, $S_c(t) = 0$, $q_e(t) > 0$, $q_0(t) = \bar{q}_b$, $q_c(t) = q_s(t) = 0$, and $p(t) = P_e(t)$: CNR has been exhausted and now ESR and BWE are produced. BWE produces at full capacity and the energy price is given by ESR’s effective marginal cost.

(d) For $t \geq T_s$, $S_c(t) = S_e(t) = 0$, $q_b(t) = \bar{q}_b$, $q_s(t) > 0$, $q_c(t) = q_e(t) = 0$, and $p(t) = C_s$: both CNR and ESR have been exhausted and only BWE and solar are produced.

(ii). If $T_e < T_b$, i.e., if ESR starts to be produced before the production of BWE hits full capacity, then

(a) For $t \in [0, T_e)$, $q_c(t) > 0$, $q_b(t) = \rho q_c(t)$, $q_j = 0$, $j = e, s$, and $p(t) = \hat{P}_c(t)$;

(b) For $t \in [T_e, T_b)$, $S_c(t) = 0$, $q_e(t) > 0$, $q_b(t) = \rho q_e(t)$, $q_j = 0$, $j = c, s$, and $p(t) = \hat{P}_e(t)$;

(c) For $t \in [T_b, T_s)$, $S_c(t) = 0$, $q_e(t) > 0$, $q_b(t) = \bar{q}_b$, $q_c(t) = q_s(t) = 0$, and $p(t) = P_e(t)$;

(d) For $t \geq T_s$, $S_c(t) = S_e(t) = 0$, $q_b(t) = \bar{q}_b$, $q_s(t) > 0$, $q_c(t) = q_e(t) = 0$, and $p(t) = C_s$.

Figure 3 illustrates the production patterns. The patterns are similar to those under the minimum quantity mandate for BWE, except for the level of energy prices before the full capacity BWE production. Consequently the mathematical relations describing the pattern are also similar to those in Corollary 1.

**Corollary 2** (i) If $T_e < T_b$, the optimal production patterns are fully characterized by

$$C_c + \lambda_c e^{r T_b} = C_b$$

$$C_c + \lambda_c e^{r T_e} = C_c + \lambda_e e^{r T_e}$$

$$C_e + \lambda_e e^{r T_s} = C_s$$

$$\frac{1}{1 + \rho} \int_0^{T_b} \left[ D(\hat{P}_c(t), \eta) \right] dt + \int_{T_b}^{T_e} \left[ D(C_c + \lambda_c e^{r t}, \eta) - \bar{q}_b \right] dt = S_{c,0}$$

$$\int_{T_e}^{T_s} \left[ D(C_e + \lambda_e e^{r t}, \eta) - \bar{q}_b \right] dt = S_{e,0}$$

(21)
Figure 3: Possible Optimal Production Patterns Under Blend Requirements

(a) Case (i): $T_b < T_e$

(b) Case (ii): $T_b > T_e$
(i) If $T_b > T_e$, the optimal production patterns are fully characterized by

\[
C_c + \lambda_c e^{r T_e} = C_e + \lambda_e e^{r T_e}
\]

\[
C_c + \lambda_c e^{r T_b} = C_b
\]

\[
C_e + \lambda_e e^{r T_b} = C_s
\]

(22)

\[
\frac{1}{1 + \rho} \int_0^{T_e} \left[ D(\hat{P}_c(t), \eta) \right] dt = S_{c,0}
\]

\[
\frac{1}{1 + \rho} \int_0^{T_b} \left[ D(\hat{P}_s(t), \eta) \right] dt + \int_{T_b}^{T_s} \left[ D(C_e + \lambda_e e^{r t}, \eta) - \bar{q}_b \right] dt = S_{e,0}
\]

Based on the Corollary, we obtain a set of comparative dynamics results that are similar to those in Lemma 1. The effects of $\rho$ are similar to those of $q_b$, although the derivation is much more complicated. Another complication relates to the effects of a higher $C_b$: it raises $\hat{P}_c(t)$ and/or $\hat{P}_e(t)$ through two effects: by raising the values of the two resources $\lambda_c$ and $\lambda_e$, and by increasing the “base” price level $(C_i + \rho C_b)/(1 + \rho)$, $i = c, e$.

In this case, the impacts of government policies are similar to those in Proposition 2, Remark 2 (with $q_b$ replaced by $\rho$) and Remark 3. However, part of the results in Remark 4 changes: solar subsidy $\tau_s$ may help the cost reducing R&D incentive in BWE, especially when $T_b$ is high or $C_b$ is high. A higher $\tau_s$ reduces energy price $p(t)$, resulting in a higher demand for energy. The mandatory blending requirement implies that BWE production also increases, raising the value of cost reducing R&D. This effect dominates the negative impact through delaying $T_b$ when $T_b$ is high.

6 Sweeping Innovations

To study the impacts of government policies on sweeping innovations, we return to the baseline case of a minimum BWE use mandate $q_b \geq q_b^*$. The R&D decisions are given in (9), (13) and (18). As we discussed following these equations, the marginal benefit of a sweeping innovation includes an additional term compared with that of a nonsweeping innovation, and in this section, we study how the additional benefit is affected by government policies.

We are able to obtain analytical results only for the cost reducing R&D in BWE and solar;
the additional effects for a sweeping innovation in BWE capacity depend on an elasticity measure whose time profile is impossible to characterize analytically. We measure the additional benefits of sweeping innovations in two ways, with analytical results obtained only for some of these measures. Let the additional absolute benefits of \( k_b \) and \( k_s \) for sweeping innovations be denoted as \( v^w_b \) and \( v^w_s \) (cf. (9) and (13)):

\[
v^w_b = e^{-rT_b} (\bar{q}_b - q_b) (1 - \alpha_b) (c_b(0) - c_b(k_b)) \frac{\partial T_b}{\partial C_b}
\]

\[
v^w_s = (D(C_s(k_s), \eta) - \bar{q}_b) e^{-rT_s} (1 - \alpha_s) (c_s(0) - c_s(k_s)) \left( \frac{\partial T_s}{\partial C_s} + \frac{\epsilon_s'(k_s)}{rC_s(k_s)} \right)
\]

In addition to the “absolute” benefits, we also consider “proportional” benefits: the additional benefits of sweeping innovations as a proportion of the benefits of nonsweeping innovations. In the case of BWE, we study the proportional benefits only when \( q_b = 0 \). Let the additional proportional benefits of \( k_b \) and \( k_s \) for sweeping innovations be denoted as \( v^p_b \) and \( v^p_s \) (cf. (9) and (13)):

\[
v^p_b = \frac{\alpha_b}{\beta_b} \left[ 1 + r (1 - \alpha_b) (c_b(0) - c_b(k_b)) \frac{\partial T_b}{\partial C_b} \right]
\]

\[
v^p_s = \frac{\alpha_s}{\beta_s} \frac{D(C_s(k_s), \eta) - \bar{q}_b}{D(C_s(0), \eta) - \bar{q}_b} \left[ 1 + r (1 - \alpha_s) (c_s(0) - c_s(k_s)) \left( \frac{\partial T_s}{\partial C_s} + \frac{\epsilon_s'(k_s)}{rC_s(k_s)} \right) \right]
\]

Then we know

**Proposition 4**  
(i) Both additional absolute benefits \( v^w_b \) and \( v^w_s \) are decreasing in the minimum BWE mandate \( q_b \).

(ii) When the government raises the nonrenewable tax \( \tau_n \) and/or pollution tax \( \tau_e \), both additional proportional benefits \( v^p_b \) and \( v^p_s \) increase.

(iii) When the government raises the subsidy to BWE, \( \tau_b \), the additional absolute benefit for BWE, \( v^w_b \), increases, but that for solar, \( v^w_s \), decreases.

(iv) When the government raises the subsidy to solar, \( \tau_s \), the additional absolute benefit for BWE, \( v^w_b \), decreases, and that for solar, \( v^w_s \), increases.

(v) Positive demand shocks (a higher \( \eta \)) raise both absolute benefits \( v^w_b \) and \( v^w_s \).

(vi) Positive stock shocks (higher \( S_{c,0} \) and/or \( S_{e,0} \)) reduce both benefits \( v^w_b \) and \( v^w_s \).
Comparing Proposition 2(i) and Proposition 4(i), we see that the minimum quantity mandate hurts the sweeping innovations in BWE and solar (and likely more than it hurts nonsweeping innovations). To see the intuition of (i), recall that as discussed in Proposition 2, $T_b$ and $T_s$ rise when $q_s$ increases. This tends to reduce $v^w_b$ and $v^w_s$. The term $(\bar{q}_b - q_b)$ also decreases, further reducing $v^w_b$. Finally, we can show that $\partial T_b/\partial C_b$ is independent of $q_b$, and the change in $\partial T_s/\partial C_s$ when $q_s$ changes is of second order importance compared with the first two effects (and is thus dominated by the two first negative first order effects).

To understand the intuition of the last observation, note that the first order effects of $\partial T_s/\partial C_s$ is captured by the slope of the price path $p(t)$ as $t$ approaches $T_s$: when $C_s$ decreases, the change in $T_s$ is inversely related to the slope of $p(t)$ at $t = T_s^-$. However, the slope of $p(t) = C_e + \lambda_e e^{rt}$ at $t = T_s$, $\Delta p(T_s)$, equals $r\lambda_e e^{rT_s}$. Then

$$d\Delta p(T_s) = r e^{rT_s} d\lambda_e + r^2 \lambda_e e^{rT_s} dT_s = r (dC_s - dC_e), \quad (23)$$

where the second equality follows from the second equation in (26) in the Appendix. Immediately we see that the slope is not affected by $q_b$.

Similar to (24), we can obtain the change in the slope of $p(t)$ at $t = T_b$:

$$d\Delta p(T_b) = \begin{cases} 
    r(dC_b - dC_e) & \text{if } T_b < T_e \\
    r(dC_b - dC_e) & \text{if } T_b > T_e
\end{cases} \quad (24)$$

When $T_b < T_e$, $p(t) = c_e + \lambda_e e^{rt}$ for $t < T_b$, and we obtain (24) from this and the first equality in (26). When $T_b > T_e$, $p(t) = c_e + \lambda_e e^{rt}$ when $t$ approaches $T_b$, and we get (24) from this and the observation that $d\lambda_e = -r\lambda_e dT_b - e^{-rT_b} dC_e + e^{-rT_b} dC_b$, obtained from the second equation in (5).

When the nonrenewable tax $\tau_n$ increases, the slope of the price path at $T_b$ decreases (from (24)). Consequently $\partial T_b/\partial C_b$ increases, so is the proportional benefit $v^p_b$. Similarly, from (23), we know the slope of $p(t)$ at $T_s$ also decreases, raising $\partial T_s/\partial C_s$ and thus $v^p_s$. The same reasoning applies when $\tau_e$ increases. Comparing with Proposition 2(ii), Proposition 4(ii) implies that $\tau_n$ and/or $\tau_e$ are likely to hurt sweeping innovations in BWE and solar less than nonsweeping innovations, weakening...
the results obtained in Proposition 2(ii).

As \( \tau_b \) rises, \( T_b \) decreases so that \( e^{-rT_b} \) rises. Further, since \( C_b \) decreases, we know the slope of \( p(t) \) at \( T_b \), \( d\Delta p(T_b) \), decreases and thus \( \partial T_b / \partial C_b \) increases. Consequently, \( v^w_b \) increases. For solar, we know \( T_b \) increases as \( \tau_b \) rises, and there is no first order change in \( \partial T_s / \partial C_s \). Thus, \( v^w_s \) decreases. The same reasoning applies to the case when \( \tau_s \) rises. Comparing with Proposition 2(iii) and (iv), we see that the impacts of these policies on R&D incentives obtained for nonsweeping innovations are enhanced for sweeping innovations.

Again, similar to the case of nonsweeping innovations, nonrenewable and pollution taxes might further reduce the R&D incentives for sweeping innovations: the additional proportional benefits decrease for both BWE and solar. We also observe the dynamic competition between the two renewable energies: a higher subsidy to one also reduces the additional benefit of a sweeping innovation in the other sector. In summary,

**Remark 5** (i) The negative effects of \( \tau_n \) and \( \tau_e \) on nonsweeping cost reducing innovations in BWE and solar are (partly) alleviated when the innovations are sweeping; (ii) The effects of other policies on nonsweeping innovations \( k_b \) and \( k_s \) are further enhanced when the innovations are sweeping.

7 Conclusions

In this paper, we study the impacts of government energy and environmental policies on firm incentives to conduct R&D to (i) reduce costs of renewable energies such as biofuel, wind and solar, and (ii) increase the capacity of some renewable energies such as biofuel. We emphasize that the different energy forms compete only dynamically in our model: due to the linear costs, there is a clear order of use of the energy forms, from CNR to ESR and finally to solar, so that at any moment of time they are not used simultaneously. Even when there is no minimum quantity restrictions on BWE, the capacity constraint of BWE production implies that it might compete directly with other energy forms: at a moment of time, it might be used simultaneously with CNR
or ESR, and eventually with solar. Thus, the policy impacts we obtain in this paper are derived from the dynamic interactions of the different energy forms, rather than from assuming that they are simultaneously utilized and thus compete with each other in a static world.

We find that there are a range of unintended consequences of these policies in the dynamic world. Taxes on nonrenewable energies discourages the development of cost reducing new technologies in solar, and may also discourage cost reducing and capacity enhancing innovations in BWE if the BWE cost is relatively high. Subsidies to BWE such as the current subsidy to biofuel in the US hurt the development of solar energy, but the impacts of solar subsidies on BWE innovations depend on the kind of quantity restrictions in place. When the government adopts a minimum quantity mandate (as the case in US), solar subsidies hurt BWE innovations. But when the quantity restriction takes the form of a minimum blend of BWE in total energies, solar subsidies might indeed help the development of BWE innovations. Both kinds of quantity mandates hurt the development of cost reducing innovations in solar and capacity enhancing innovations in BWE. Most of these results are further enhanced for sweeping innovations.

Our results provide a clear message for government policy making: energy and environmental policies as well as different forms of energy policies should be evaluated simultaneously in a broad framework. Although this seems a rather innocuous conclusion, our paper shows how policies chosen with one objective might undermine the objectives of other policies. For instance, in the debate on the protection of ANWR, a central tenet is that protecting ANWR from development will help encourage the growth of renewable energies. We find that the opposite is true in a dynamic framework. Although biofuel and solar, both renewable energies, are typically considered as substitutes and competing with each other, we find that when there is a minimum blend mandate on biofuel, they could become partly complements in a dynamic world: solar subsidy can in fact improve the R&D efforts in BWE. Further, even policies with the same objective might undermine each other’s effectiveness: quantity mandates in BWE use hurts capacity enhancing R&D incentives and may also hurt the cost reducing R&D efforts in BWE.
All four energy forms are used today, although in different quantities in different parts of the world. Solar energy, assumed to be the most expensive and the true backstop in our model, is the profitable choice in some parts of the world, e.g., at places with sufficient sunshine and without the necessary infrastructure for electric power generation and transmission. Further, both CNR such as coal and oil and ESR such as sand oil are extracted today. There are a number of reasons for the simultaneous extraction, including convex extraction costs and the uneven geographic distributions of these resources. To a certain extent, the four energy forms are imperfect substitutes and each has its comparative advantage for certain uses, in different regions, and possibly at different time of the year. Our paper abstracts from this fact and as a result represents only the “large picture” of the energy sector. Thus, an appropriate interpretation of the time at which solar starts to be used in our model is that it represents the time of the full scale adoption of solar, the time when solar becomes the dominant energy form. In reality solar is used before that time, but the proportion of it in overall energy use is sufficiently small so that our model provides a good approximation to the real world situation.

There are different ways in which our model can be extended. Perhaps the most important extension is to introduce imperfect competition into the energy sector. In a model where the CNR sector has market power and engage in a Cournot competition with the other sectors, we find that the main results of our paper still hold. In the other extreme, the CNR sector might behave as a Stackelberg leader adopting closed loop strategies: the resulting model is too complicated for us to obtain analytical solutions.

A Model Details

Optimal order of extraction

We first derive the optimal solution to (2). Forming the present value Hamiltonian,

\[
H(t) = \left[ p(t) \sum_i q_i(t) - C_c q_c(t) - C_e q_e(t) - C_b q_b(t) - C_s q_s(t) \right] e^{-r t} - \lambda_c(t) q_c(t) - \lambda_e(t) q_e(t),
\]
we obtain the following necessary conditions:

\[
q_c \begin{cases}
  = 0 & \text{if } p(t) - C_c - \lambda_e e^{rt} < 0, \\
  \geq 0 & \text{if } p(t) - C_c - \lambda_e e^{rt} = 0
\end{cases},
q_e \begin{cases}
  = 0 & \text{if } p(t) - C_e - \lambda_e e^{rt} < 0, \\
  \geq 0 & \text{if } p(t) - C_e - \lambda_e e^{rt} = 0
\end{cases},
q_b \begin{cases}
  = q_b & \text{if } p(t) - C_b < 0, \\
  \in [q_b, \bar{q}_b] & \text{if } p(t) - C_b = 0, \\
  = \bar{q}_b & \text{if } p(t) - C_b > 0
\end{cases},
q_s \begin{cases}
  = 0 & \text{if } p(t) - C_s < 0, \\
  \geq 0 & \text{if } p(t) - C_s = 0
\end{cases},
\lambda_c = 0, \quad \lambda_e = 0, \quad \int_0^\infty q_c(t)dt = S_{c,0}, \quad \int_0^\infty q_e(t)dt = S_{e,0}.
\]

These conditions together with the market clearing condition lead to Proposition 1.

**Proof of Proposition 1.** We prove the Proposition in several steps.

**Step 1:** we show that $C_c + \lambda_c < C_e + \lambda_e < C_s$. This observation follows from the necessary conditions in (25) as well as the assumption in (1). To see this, note that if the first inequality is not satisfied, resource CNR will not be extracted, violating the resource exhaustion condition. For instance, if $C_c + \lambda_c \geq C_e + \lambda_e$, then $\lambda_c > \lambda_e$ (because $C_c < C_e$) and thus $P_c(t) > P_e(t)$ for all $t > 0$ (where the effective marginal costs $P_c$ and $P_e$ are given in (3)). Then from (25), we know $q_c(t) = 0$ for all $t$ because whenever $q_c(t) > 0$, $p(t) = P_c(t) > P_e(t)$, violating the condition that $p(t) \leq P_e(t)$.

**Step 2:** we show that $\lambda_c > \lambda_e$. If $\lambda_c \leq \lambda_e$, $C_c < C_e$ implies that $P_c(t) < P_e(t)$ for all $t$. Then ESR will never be extracted, violating the resource exhaustion condition.

**Step 3:** from Steps 1 and 2, we know $P_c(t)$ and $P_e(t)$ cross only once at $T_e$: $P_c(t) < P_e(t)$ for $t < T_e$ and $P_c(t) > P_e(t)$ for $t > T_e$. Also, $P_e(t)$ and $C_s$ cross only once, at $T_s$: $P_e(t) < C_s$ for $t < T_s$ and $P_e(t) > C_s$ for $t > T_s$. Thus, CNR is extracted for $t < T_e$ and is exhausted at $T_e$, and ESR starts to be extracted at $T_e$ and is exhausted at $T_s$. The price $p(t) = P_c(t)$ for $t < T_e$, $p(t) = P_e(t)$ for $t \in [T_e, T_s)$, and $p(t) = C_s$ for $t \geq T_s$.

**Step 4:** the first order condition on $q_b$ in (25) implies that $T_b$, the time when BWE is produced at full capacity, occurs when $p(t) = C_b$. From the results in Step 3, we know $T_b < T_s$ but it can either be higher or lower than $T_e$. Since $p(t)$ is strictly increasing for $t < T_s$, we know $q_b(t) = q_b$. 36
for \( t < T_b \), and \( q_b(t) = \bar{q}_b \) for \( t \geq T_b \). The two cases in the Proposition then follow naturally.

**Relationship between (non)sweeping and (non)drastic innovations**

Consider an R&D firm that has invented a cost reducing technology that can be used in BWE or solar production. Suppose the market structure in the R&D industry is such that the firm has monopoly power in the new technology. Given the (derived) demand for the new technology in the renewable energy sectors, the R&D firm prefers to charge a monopoly price to license the new technology. However, if the new technology does not reduce the production cost \( c_b \) or \( c_s \) significantly, then the monopoly price can be so high that the production cost of the BWE or solar firms who have purchased the new technology, including the license fee, exceeds the production cost using the original technology. In this case, the R&D firm can only license the new technology at a price below the monopoly price level: the price is set so that the cost in BWE or solar under the new technology (including the license fee) equals that under the original technology. Arrow (1962) called this type of innovation *non-drastic*, but it is also nonsweeping according to our definition: the pricing of the new technology is constrained by the original technology, and consequently the marginal cost \( c_b \) or \( c_s \), including both the (reduced) production cost and license fee, is unchanged after the new technology is adopted.

On the other hand, a drastic innovation significantly reduces the production cost \( c_b \) or \( c_s \), so that the production cost and the license fee (at the monopoly price level) under the new technology is lower than that under the original technology even when the new technology is licensed at the monopoly price. The new cost (including both the production cost and the license fee) thus decreases after the new technology is adopted. The innovation is thus sweeping according to our definition.

**Proof of Lemma**

We prove the Lemma for two cases, when \( T_b < T_e \) and when \( T_e \geq T_b \).

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12 If there are multiple R&D firms working on similar kinds of technologies, the monopoly profit of each new technology will be diluted but our analysis and the qualitative features of our results still hold.

13 See Moschini and Lapan (1997) for an analysis of drastic and nondrastic innovations where R&D results in a new and more efficient input to be used in the production in a competitive industry (agriculture).
Case 1: \( T_b < T_e \). The set of equations in (4) in Corollary 1 completely describes the optimal extraction pattern, where the variables to be determined are \( \lambda_c, \lambda_e, T_b, T_e, \) and \( T_s \). Applying the implicit function theorem to the first and third equations in (4), we obtain

\[
d\lambda_c = -r\lambda_c dT_b + e^{-rT_b} dC_b - e^{-rT_b} dC_c,
\]

\[
d\lambda_e = -r\lambda_e dT_s + e^{-rT_s} dC_s - e^{-rT_s} dC_e.
\]

(26)

Applying the implicit function theorem to the three remaining equations in (4) and substituting in (26), we get

\[
\begin{bmatrix}
-A e r \lambda_c + \bar{q}_b - q_b & q_e (T_e) & 0 \\
-r \lambda_c & r (\lambda_c - \lambda_e) & r \lambda_e \\
0 & -q_e (T_e) & -A e r \lambda_c + q_s (T_s)
\end{bmatrix}
\begin{bmatrix}
dT_b \\
dT_e \\
dT_s
\end{bmatrix}
= \begin{bmatrix}
-A e^{-rT_b} - B_c \\
A e^{-rT_b - e^{-rT_e}} dC_c \\
0
\end{bmatrix}
\begin{bmatrix}
0 \\
e^{-rT_b} dC_c \\
e^{-rT_s} dC_s
\end{bmatrix}
+ \begin{bmatrix}
e^{-rT_e - e^{-rT_s}} dC_e \\
e^{-rT_b} dC_b \\
e^{-rT_s} dC_s
\end{bmatrix}
\begin{bmatrix}
1 \\
0 \\
0
\end{bmatrix}
+ \begin{bmatrix}
0 \\
0 \\
-\gamma_c
\end{bmatrix}
d\gamma + \begin{bmatrix}
T_e - T_b \\
0 \\
T_s - T_e
\end{bmatrix}
d\eta + \begin{bmatrix}
T_b \\
0 \\
0
\end{bmatrix}
d\bar{q}_b + \begin{bmatrix}
0 \\
0 \\
0
\end{bmatrix}
dq_b,
\]

(27)

where

\[
A_c = \int_0^{T_e} D' (C_c + \lambda_c e^{r t}, \eta) e^{r t} dt,
B_c = \int_0^{T_e} D' (C_c + \lambda_c e^{r t}, \eta) dt,
\gamma_c = \int_0^{T_e} D (C_c + \lambda_c e^{r t}, \eta) dt
\]

\[
A_e = \int_0^{T_e} D' (C_e + \lambda_c e^{r t}, \eta) e^{r t} dt,
B_e = \int_0^{T_e} D' (C_e + \lambda_c e^{r t}, \eta) dt,
\gamma_e = \int_0^{T_e} D (C_e + \lambda_c e^{r t}, \eta) dt.
\]

In addition, there are several useful facts that will be relied on in proving the Lemma: \( \lambda_c > \lambda_e \) (from Step 2 in the Proof of Proposition 1), \( A_c < B_c, e^{-rT_e} A_c > B_c, e^{-rT_e} A_c < B_e, \) and \( e^{-rT_e} A_e > B_e \).

The Lemma is then obtained from applying Cramer’s rule to (27) to obtain the effects of the exogenous parameters on the times \( T_b, T_e, \) and \( T_s, \) and subsequently on values \( \lambda_c \) and \( \lambda_e \) using (26) and the following relationship (obtained from totally differentiating the second equation in (4) and
substituting in (26):

\[ d\lambda_c = d\lambda_e - r(\lambda_c - \lambda_e)dT_e + e^{-rT_e}dC_e - e^{-rT_e}dC_c \]

In the Lemma, \( T_b \) satisfies the condition that \( A_c e^{-rT_b} > B_c \). The details are available from the author upon request.

Case 2: \( T_b > T_e \). The procedure is the same as Case 1, but the derivation is more complicated for some cases. Detailed derivation is available from the author upon request.

References


