Renewable Energy and Greenhouse Gas Mitigation

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Abstract: The paper develops an exhaustible resource model with cumulative pollution and a backstop technology that exhibits increasing marginal costs of production. The model explores conditions under which it is optimal to have a protracted transition period where both an exhaustible and renewable energy resource are used simultaneously.

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Introduction

Reliance on fossil fuels as the primary source of energy in the world has raised two concerns. First, fossil fuels are exhaustible and so substitutes will eventually be needed to replace them. Second, their use has created the problem of greenhouse gas accumulation in the atmosphere. A transition to other energy sources will likely be necessary at some point in the future for both reasons. Current world reserves of fossil fuels are estimated to supply energy needs for at least another two hundred years, but mounting concern about climate change is fueling speculation that the transition may need to be undertaken long before the threat of exhaustion becomes palpable.

Renewable energy resources stand as the eventual substitute for fossil fuels in the long run. Renewable resources are often promoted as a means of mitigating the greenhouse gas problem because they are typically characterized by a lack of carbon emissions or the existence of sinks to offset carbon emissions. Assuming that a transition to renewable energy resources will be optimal at some point in the near or distant future, this paper examines whether the transition should occur in an immediate shift from one energy resource to another, or whether the transition should occur in a gradual fashion. The analysis seeks to understand the conditions that make it optimal to use both the exhaustible resource and the renewable resource simultaneously.

The literature has framed analyses of the transition from fossil fuels to a renewable energy source in terms of a transition from an exhaustible resource to a backstop technology. As in the Dasgupta and Heal (1974, 1994) framework, the backstop is assumed to be infinitely reproducible using a constant returns to scale technology although at a higher cost than the exhaustible resource. The assumption of a constant marginal cost of production of the backstop leads to the result that it is optimal to exhaust the fossil fuels before ever using the backstop technology. An instantaneous switch from the exhaustible resource to the backstop occurs at a discrete point in time.

Examination of the theoretical literature would lead a reader to conclude that simultaneous use of a low-cost exhaustible resource and a high-cost backstop is only optimal under special conditions. Tahvonen (1997) and Hoel and Kverndokk (1996) show that when a cumulative pollutant results from the use of the exhaustible resource then there may exist periods where it is optimal to use both resources simultaneously, but only when the rates of change for scarcity rent of the exhaustible resource and shadow value of the stock pollutant evolve in equal but opposite directions. Chakravorty and Krulce (1994) and Chakravorty, Roumasset and Tse (1997) show that when there are heterogeneous demands for energy resources it may be optimal to use multiple resources simultaneously; but within any particular sector of energy demand it is still optimal to switch instantaneously from one resource to another.

The results of these analyses hinge on the assigned cost structures of the two resources. In the studies mentioned, the exhaustible resource is assumed to have constant marginal costs of extraction (production) for any given level of cumulative extraction; the cost of extraction does not vary with current period level of extraction even though it may depend on the stock of the resource or on cumulative extraction. The backstop resource (technology), too, is assumed to have constant unit costs of production.

The assumption of constant marginal cost of producing the backstop resource is not entirely appropriate when discussing the problem of substitution of fossil fuels with a renewable energy resource. The production of energy using any renewable resource is likely to exhibit decreasing returns to scale and face an upward sloping marginal cost curve. Typically, the quality of inputs for renewable energy production vary from region to region, such as the intensity of sunshine for solar power or the availability of suitable sites for dams for hydro-power. As the quality of agricultural inputs (land, labor, climate) for the production of energy crops is heterogeneous, then the production of bioenergy will also exhibit increasing marginal cost of production. High quality (low cost) sites will be brought into production first and as demand increases, lower quality sites will be brought into production leading to rising marginal cost for renewable energy.

The paper presents a model with an exhaustible energy resource and a backstop with increasing marginal costs of production. It shows that it is generally optimal to have a gradual transition period in which both energy sources are used whenever either of the following conditions holds: (i) the marginal extraction cost of fossil fuels is increasing in current period extraction, or (ii) the marginal cost of production of the alternative energy source is increasing in the level of use. This result also holds in the presence of a cumulative pollutant. A graphical exposition is used to develop the intuition behind the results.

The Transition from an Exhaustible Resource to a Substitute

The perceived need to replace fossil fuels with renewable energy resources has inspired a discussion in the literature about the nature of the transition from an exhaustible resource to a costly, yet infinitely available, substitute. There has been some discussion about whether it is optimal to sustain a prolonged period where both the exhaustible and renewable resource are used simultaneously or if the transition should be sudden, using the resources in a sequential manner. This section surveys some of the recent work with models of optimal fossil fuel use in the presence of pollution when a backstop is present. In particular, the models presented by Hoel and Kverndokk (1996) and Tahvonen (1997) are employed to explore the conditions under which the optimal transition between resources is gradual.

Consider the problem of a social planner who must determine the optimal levels of resource use, choosing between an exhaustible resource and a backstop. The planner maximizes social welfare, which is measured as the sum of producer and consumers surplus. Define $q(t)$ and $s(t)$ as the quantities of the exhaustible resource and the backstop used in each period, *t*; and $Q(t)$ as the total quantity of the exhaustible resource available at time *t* where $Q(0) = \overline{Q}$. The cost of producing a unit of *q* is *c*, and the cost of producing a unit of *s* is *b*, where $c < b$.

Inverse demand is represented by $p(q+s)$, which is continuous and downward sloping; i.e. $p'(x) < 0$. A choke price for energy exists and is bounded away from infinity; $p(0) < \infty$. The demand curve for energy is assumed constant through time; there are no exogenous shifts in demand due to changes in population or technological change.

The social planner's problem is thus[1]:

$$\max_{q,s} \int_t^{\infty} e^{-rt} \left\{ \int_0^{q+s} p(x)dx - cq - bs \right\} dt \qquad \textbf{(1)}$$

Subject to the exhaustibility constraints: $\dot{Q} = -q$ and $\int_0^{\infty} q(t)dt \le \overline{Q}$. The current value Hamiltonian for the basic problem is written:

$$H = \int_0^{q+s} p(x)dx - cq - bs - fq \qquad \textbf{(2)}$$

The first order conditions necessary for a maximum are as follows:

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[1] For ease of exposition, the time argument is suppressed for most of the discussion in the paper. Derivatives of functions that have a single argument will be denoted by a prime, i.e. $f'(x) \equiv df(x)/dx$. Derivatives of functions with multiple arguments will be denoted by the function subscripted by the differentiating variable, i.e. $g_y(w,y) \equiv \partial g(w,y)/\partial y$. Derivatives with respect to time will be represented as, $\dot{x} \equiv \partial x/\partial t$. The sign on the

$$\begin{aligned} &p(q+s)-c-f \leq 0; \\ &q \geq 0; \\ &q\left[p(q+s)-c-f\right]=0 \end{aligned} \tag{3}$$

$$\begin{aligned} &p(q+s)-b \leq 0; \\ &b \geq 0; \\ &b\left[p(q+s)-b\right]=0 \end{aligned} \tag{4}$$

$$\dot{Q}=-q \tag{5}$$

$$\dot{f}=rf \tag{6}$$

$$\lim_{t\to\infty} e^{-rt} f(t)Q(t)=0 \tag{7}$$

It is evident by examining conditions (3) and (4) that a gradual transition from an exhaustible resource to the backstop, by way of a prolonged period of simultaneous use of the two resources is infeasible as it requires the following condition to hold:

$$b=c+f \tag{8}$$

Condition (6) is the standard Hotelling (1931) result that requires the scarcity rent of the resource (f) to increase monotonically through time at the social discount rate. As the scarcity rent at no time remains constant, condition (8) cannot hold for any period of finite time. Thus the resources are optimally used in a sequential order; the low cost exhaustible resource is used exclusively until the social cost of using the resource reaches the cost of using the backstop. The result here is comparable to that found in Dasgupta and Heal (1974, 1994.)

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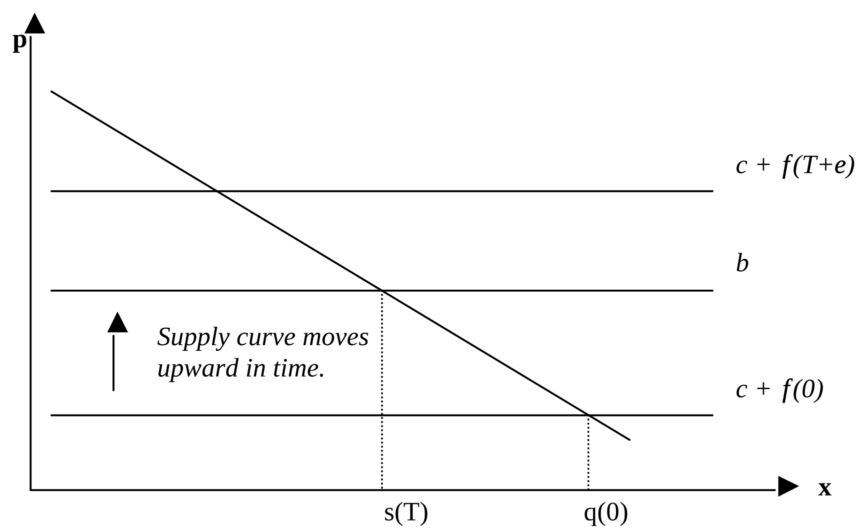
co-state variables have been selected so that they can be easily interpreted as the scarcity rent (f) and the so-called carbon tax (l).

Figure 1 illustrates the intuition behind the Dasgupta and Heal result. The figure comprises the demand curve, $p(x)$, the supply curve for the exhaustible resource at time *t=0*, $c + f(0)$, the supply curve for the exhaustible resource at time $t = T + e$ and the supply curve for the backstop, *b*. At time zero, the backstop is too costly to use, so the exhaustible resource is used at the level *q(0)* where the supply curve intersects the demand curve. The scarcity rent increases, eventually reaching a point *t=T* when the two supply curves lie on top of each other, $c + f(T) = b$. For an infinitesimal period of time the two resources have equal social costs, yet the scarcity rent never remains constant and continues to rise. The supply curve for the exhaustible resource continues to rise and at time $T + e$ the relative positions of the supply curves are reverse of the initial time period. It is optimal to switch instantaneously to the backstop at time *T* to a level $s(T)$ and use the backstop exclusively for the remainder of the planning horizon.

Figure 1. Transition from an exhaustible resource to a backstop with constant marginal costs.



Now consider the case presented by Hoel and Kverndokk (1996) where the cost of using the exhaustible resource increases with cumulative extraction. In this formulation $Q(t)$ represents the total amount extracted from time 0 to time *t*, $Q(t) = \int_0^t q(t)dt$, where $Q(0) = 0$ and $\dot{Q} = q$. The marginal cost of using the exhaustible resource is now represented by $c(Q) > 0$, where $c'(Q) > 0$. Note that in this formulation, no fixed geologically available amount of the exhaustible resource $(\overline{Q})$ is exogenously specified. Exhaustibility of the resource is now defined in purely economic terms. The amount of economically recoverable resource is finite because the marginal cost of extracting the resource is always increasing and the choke price for energy is bounded away from infinity. As a result, the resource is extracted only to the point when it is no longer economical to do so.

The Hamiltonian now becomes,

$$H = \int_0^{q+s} p(x)dx - c(Q)q - bs - fq. \qquad \textbf{(9)}$$

Combining first order conditions leads to the condition for simultaneous use of the two resources:

$$b = c(Q) + f \qquad \textbf{(10)}$$

The equation of motion for scarcity rent, $\dot{f} = -c'(Q)q + rf$, is solved to find:

$$f(t) = \int_t^{\infty} e^{-r(t-t)} c'(Q(t))q(t)dt \qquad \textbf{(11)}$$

Alternatively, the equation of motion for the scarcity rent can be arranged and written as follows:

$$\frac{d}{dt}[c(Q)+f]=rf$$

Condition (11) implies that the scarcity rent of the resource is always positive whenever the resource is being used. This implies that the effective marginal cost of using the resource, marginal extraction plus the scarcity rent, is monotonically increasing over time. As the cost of using the backstop is constant over time, the equality in (10) cannot hold for a finite period of time when both *q* and *s* are strictly positive. Thus even when costs of extraction are increasing in the level of cumulative extraction, simultaneous use of the resource with a backstop is not optimal for an extended period of time. The graphical depiction of the situation with extraction costs increasing in cumulative extraction is qualitatively the same as that shown in Figure 1.

Hoel and Kverndokk (1996) and Tahvonen (1997) suggest that the existence of a cumulative pollutant, such as the greenhouse gas resulting from fossil fuel use, may make it optimal to use both energy sources simultaneously. Suppose that the model above, equation (2), is modified to accommodate the accumulation of a pollutant, *G*, that results in damages, $D(G)>0$, where $D'(G)>0$ and $D''(G)>0$. Units of the fossil fuel and backstop are adjusted so that they are perfect substitutes, and that one unit of fossil fuel use results in one unit of the pollutant emitted.[2] Use of the backstop does not result in emission of the pollutant. Change in the stock of the pollutant is characterized by $\dot{G}=q-aG$. Accumulation of the pollutant occurs because the degradation rate is less than unity; $a<1$. The Hamiltonian may be written as:

$$H=\int_0^{q+s}p(x)dx-c(Q)q-bs-D(G)-fq-l\left[q-aG\right] \qquad \textbf{(12)}$$

[2] It can be argued that there are flow damages from the use of fossil fuels in the form of other air pollutants, oil spills, coal waste dumpage and health damages resulting from coal mining. (see Farzin (1996)) However, the issue of concern here is the damage resulting from *stock* of greenhouse gas that accumulates from the combustion of the fossil fuels.

The simultaneity condition now depends on the scarcity rent and the carbon tax as follows:

$$b = c(Q) + f + l \qquad \textbf{(13)}$$

Simultaneous use of the two resources depends crucially on the time path of the carbon tax (l). The equation of motion for the carbon tax, $\dot{l} = -D'(G) + l(r + a)$, can be solved to find:

$$l(t) = \int_t^\infty e^{-(r+a)(t-t)} D'(G(t))dt \qquad \textbf{(14)}$$

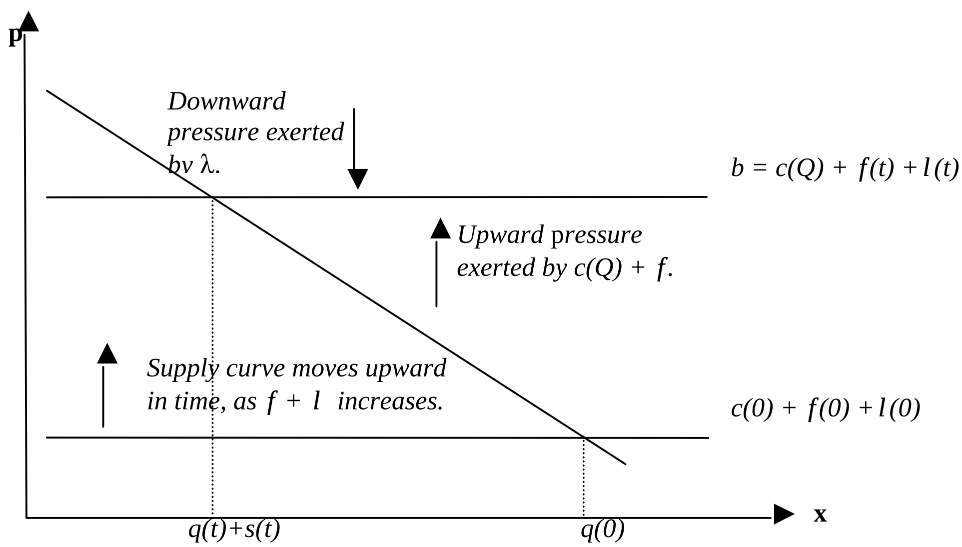
The carbon tax should equal the present value of the marginal damages of all future emissions resulting at point in time, *t*. The time path of the carbon tax depends on initial levels of greenhouse gas. When the initial level of the pollutant is high, the carbon tax should be monotonically decreasing in time; when the initial level is low, the carbon tax should exhibit an inverse-U shape over time [Hoel et al. (1996); Tahvonen (1997); Ulph and Ulph (1994).] It should be noted that the shape of the time path is dependent on the assumption in the models of the ability of the pollutant to degrade exponentially over time, as above. In contrast, Farzin and Tahvonen (1996) show that if at least some portion of the stock of carbon-gases never degrades over time, the carbon tax could be constant, monotonically increasing or even U-shaped over time.

Under the restriction of exponential decay of the pollutant, it is conceivably possible that condition (13) could hold for an extended period of time even when the effective marginal costs of using the resource is monotonically increasing over time. Consider the situation where the social cost of using fossil fuels (marginal extraction cost plus scarcity rent plus carbon tax) reaches the cost of using the backstop technology. If the use of fossil fuels becomes zero at this point, the stock of greenhouse gas in the atmosphere begins to fall and so the optimal carbon tax decreases. A decrease in the carbon tax causes the right hand side of condition (13) to decline in value, thereby causing the condition to hold as equality again. Fossil fuel use once again becomes socially optimal. A period of simultaneous use is possible so long as the effective marginal cost of using the resource and the carbon tax move in opposite but equal directions along the time path, i.e. $\frac{d}{dt}[c(Q)+f] = -\dot{l}$. During the entire period of simultaneous use, the carbon tax must be decreasing which requires that fossil fuel use be sufficiently low, $q < aG$, so that greenhouse gas levels degrade, $\dot{G} < 0$.

Figure 2 illustrates the transition between resources in the presence of a cumulative pollutant. The demand curve intersects with the exhaustible resource supply curve at time *t=0* to determine the initial use of the resource, $q(0)$. Consider initial conditions are such that in early periods the carbon tax is increasing, thereby growing in tandem with the marginal extraction cost plus the scarcity rent. The marginal cost of using the resource and carbon tax exert positive pressure on the supply curve, driving up the social costs of the exhaustible resource as represented by moving the supply curve upward on the graph. At some later point in time, the carbon tax reaches a maximum and begins to fall, thereby exerting negative pressure on the supply curve. The effective marginal cost of the resource continues to rise, however, and counteracts the negative pressure exerted on the supply curve by a falling carbon tax. The two forces could for an extended period act against each other at sufficient rates to hold the supply curve at the same level as the supply curve for the backstop.

During this period, it is socially optimal to use both of the resources. Exhaustibility of the resource implies that there exists a level of cumulative extraction, $\overline{Q}$, where the marginal cost of using the resource equals the marginal cost of using the backstop, $b = c(\overline{Q})$. Further use of the exhaustible resource leads to an increase in the marginal cost of extraction and it is no longer economical to use the exhaustible resource. At this point, the transition to the backstop is complete.

Figure 2. Transition to backstop in the presence of pollution.



The model

The preceding results derive from models that assume constant marginal costs of production of both the fossil fuel and the backstop resource. But renewable energy technologies tend to exhibit decreasing returns to scale due to variations in the quality of renewable resources coupled with constraints on the quantity of high quality resources. For example, within the United States average daily solar energy varies from below 10 megajoules per square meter in upstate New York to greater than 25 megajoules per square meter in parts of the Southwest. As a result solar electricity production costs about 50% less in the Southwest than in New York [Kelly (1993)]. Just within the Southeastern region of the United States, median annual energy yields for switch grass, a standard energy crop, varies from 11 megajoules per square meter in Virginia to about 25 megajoules per square meter in Alabama [Graham et al. (1996); Turhollow (1994)]. Increases in yield for biomass allow for energy crops to be grown within a smaller radius of an electricity generating facility thereby decreasing transportation costs. In an analysis of the potential for biomass electricity production in the Southeast region, Larson and Marrison (1997) show that a 25% increase in biomass yields can result in a 12% decrease in the cost of generating electricity. These numbers indicate that the long run marginal cost function for producing energy using a renewable resource will be increasing in the quantity of energy produced.

This section presents a modification of the basic model used in the literature that incorporates increasing marginal costs of production of the backstop. I show that under this assumption an extended transition period is likely to be the rule rather than the exception. A graphical exposition of the reasoning is used to illustrate the intuition of the results.

Consider again the social planner's problem of choosing between an exhaustible resource and a backstop technology for the production of energy over an infinite horizon. For the moment, the existence of a cumulative pollutant is omitted from the model so that the only concern is the exhaustible nature of the fossil fuels. The basic model is altered by the inclusion of cost functions for both the exhaustible resource and the backstop. As in Hoel and Kverndokk, the marginal cost function of using the exhaustible resource, *q*, for the production of energy is denoted by $c(Q(t))$, where $c(\cdot)$ depends on cumulative extraction. The cost function includes the costs of extraction and costs of energy generation. Cumulative extraction from time 0 to time *t* is denoted by $Q(t) = \int_0^t q(t)dt$, where $Q(0) = 0$ and $\dot{Q} = q$. The cost of production of energy using the backstop technology is denoted by $b(s)$. Units on both *q* and *s* are selected so that one unit of each produces the same quantity of marketable energy. Both cost functions are strictly increasing and convex. Initially, both the total and marginal costs of producing energy using fossil fuels are less than using biomass; that is, $c(0)E < b(E)$ and $c(0) < b'(E)$, where *E* represents total energy produced.

The current value Hamiltonian for this problem is written as:

$$H = \int_0^{E=q+s} p(x)dx - c(Q)q - b(s) - fq \qquad \textbf{(15)}$$

The first order conditions for maximization are:

$$\begin{aligned} &p(q+s) - c(Q) - f \leq 0; \\ &q \geq 0; \\ &q\left[p(q+s) - c(Q) - f\right] = 0 \end{aligned} \qquad \textbf{(16)}$$

$$\begin{aligned} &p(q+s) - b'(s) \leq 0; \\ &s \geq 0; \\ &s\left[p(q+s) - b'(s)\right] = 0 \end{aligned} \qquad \textbf{(17)}$$

$$\dot{Q} = -q \tag{18}$$

$$\dot{f} = -c'(Q) + rf \tag{19}$$

$$\lim_{t\to\infty} e^{-rt} f(t)Q(t) = 0 \tag{20}$$

From conditions (16) and (17), one can derive the condition for simultaneous use of both the exhaustible resource and the backstop, where $q, s \geq 0$.

$$b'(s) = c(Q) + f \tag{21}$$

Equation (21) implies that it is possible to have a prolonged period of transition where the two forms of energy are both produced. To clarify, condition (21) can be written as two conditions:

$$\begin{aligned} p(q+s) &= b'(s) \\ p(q+s) &= c(Q) + f \end{aligned} \tag{22}$$

In the case where the alternative technology exhibits constant returns to scale $b'(s) = b$ and condition (22) implies that the price of energy remains constant during a period of simultaneous use. This is not possible when the marginal extraction cost plus the scarcity rent are rising through time and so an instantaneous switch from one resource to the other is optimal. However, when the alternative technology exhibits decreasing returns to scale the price for energy is no longer required to remain constant during a period of simultaneous use. Due to the downward sloping demand curve and the decreasing returns to scale nature of the alternative technology, a wide range of production levels for both q and s exist such that condition (22) holds.

Within this range, the alternative technology is competitive with the exhaustible resource for production of energy. The cost of using the exhaustible resource rises through time due to depletion effects so that eventually use of the alternative technology is less costly than the exhaustible resource to satisfy a portion of the demand for energy. Part of the demand is met by producing energy with the alternative technology at a level where marginal cost equals the marginal cost of using the exhaustible resource. The remainder of the demand is met by producing energy with the exhaustible resource. The producers of the alternative energy will earn rents during this period on the inframarginal units of energy that are produced at a cost below the market price of energy. The cost of the exhaustible resource continues to rise until it is no longer affordable to use and the alternative energy source supplants the exhaustible source as the primary provider of energy.

Suppose that initially the price of energy is below the minimum cost of producing electricity using the renewable resource, $p(E) < b'(0)$. Only the exhaustible resource is used at *t=0*, implying that $p(q) = c(Q_0) + f(0)$. As the marginal cost of the resource increases the effective supply curve for energy shifts upward. The price of energy rises and it is optimal to reduce the amount of the exhaustible resource used in each time period. Eventually the price of energy reaches the minimum marginal cost of producing energy using the backstop so that at a point $t = \underline{T}$, $p(q(\underline{T})) = b'(0)$.

Figure 3 depicts the time period where $t \in [0, \underline{T}]$, before the transition. In the figure, the supply and demand curves for energy are shown as thick lines. The supply curve consists solely of the marginal cost curve for the exhaustible resource. The backstop is too costly to use optimally during the period. At all points in the period, $p(E) < b'(s)$ and $E(t) = q(t)$. The supply curve for energy steadily moves upward and *q* steadily declines from $q(0)$ to $q(\underline{T})$.

The supply curve for the exhaustible resource continues to rise and so the optimal use of *q* continues to decline. The use of the renewable resource, *s*, continues to rise as it substitutes for the use of the exhaustible resource. At some point $t = \bar{T}$ the use of the exhaustible resource reaches zero, $q(\bar{T}) = 0$, the use of the backstop reaches a maximum of $s(\bar{T}) = \bar{s}$ and the price of energy also reaches a maximum at $p(\bar{s}) = b'(\bar{s})$. It is never optimal to use the exhaustible resource again at any point beyond $\bar{T}$ and exclusive use of the backstop at the maximum level is optimal for the remaining planning horizon, $t \in [\bar{T}, \infty)$. During the entire period where $t \in [\underline{T}, \bar{T}]$ optimal production of energy requires simultaneous use of the two resources.

Figure 4 depicts the time period where $t \in [\underline{T}, \bar{T}]$, the transition period. The supply curve for energy during this period is kinked as it consists of the cost curves for both of the resources. At any point *t* during this period, use of the backstop will equal $s(t)$ and use of the exhaustible resource will equal $E(t) - s(t)$. The cost curve for the exhaustible resource continues to move upward, use of the exhaustible resource declines, and use of the backstop increases. At the end of the period, use of the backstop reaches a maximum level $s(\bar{T})$ and q=0. Figure 5 depicts the time period where $t \in [\bar{T}, \infty)$, after the transition. At this point, the supply curve for energy consists solely of the backstop cost curve. Backstop use has reached a plateau and exhaustible resource use is zero.

A similar exposition follows when the exhaustible resource technology contributes to the accumulation of a stock pollutant. Consider the addition of a pollutant *G* to the model as before, the pollutant degrades exponentially, damages $D(G)$ are increasing and convex in the level of the pollutant, and the alternative technology does not contribute to the stock of pollution. In addition to the scarcity rent, there is a carbon tax so that condition (22) can be re-written as:

$$\begin{aligned} p(q+s) &= b'(s) \\ p(q+s) &= c(Q) + f + l \end{aligned} \qquad \textbf{(23)}$$

The addition of the pollution externality implies that the social cost of using the exhaustible resource will climb at a faster rate than it would without pollution, at least initially during periods when the carbon tax is rising. A period of simultaneous us occurs once the costs rise sufficiently so that condition (23) holds. Withagen (1994) shows that the existence of pollution extends the period of time when it is optimal to use the exhaustible resource, but it does not alter the total quantity of the exhaustible resource ultimately used over the planning horizon. Applying the logic here, the period of simultaneous use of the two resources is extended when there exists a stock pollution externality. As in the Hoel and Kverndokk model, if exhaustible resource declines sufficiently, the carbon tax begins to decrease. This makes it optimal to prolong the period of time when condition (23) holds, thereby extending the period of time when simultaneous use is optimal.

Figure 3. Supply and demand for energy before the transition period.

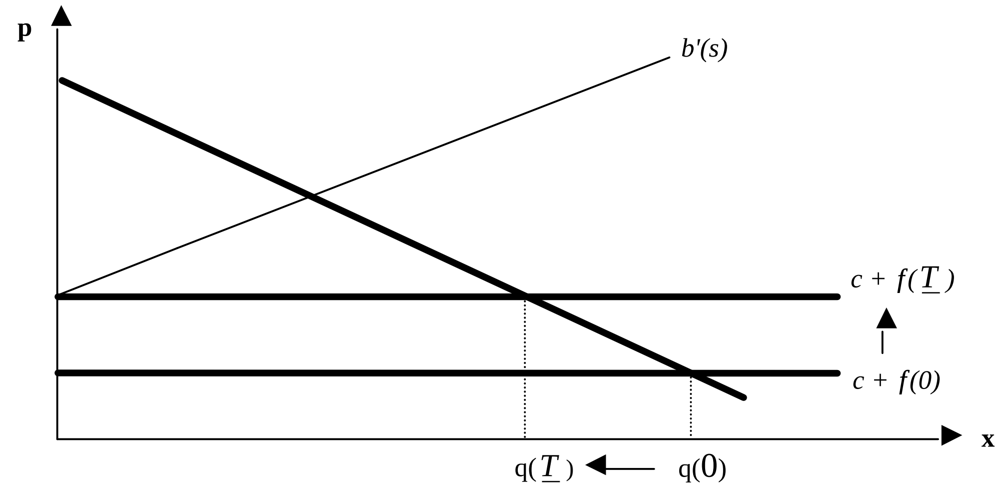


Figure 4. Supply and demand during the transition period.

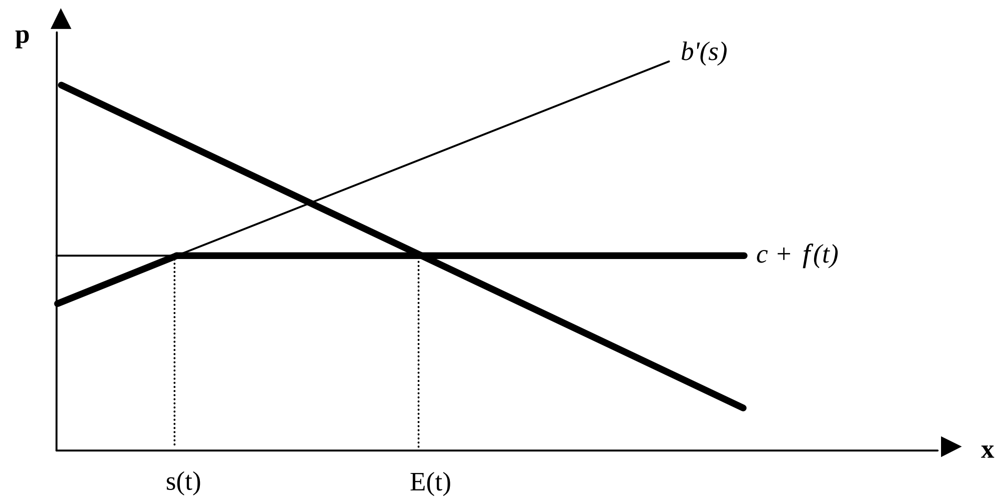
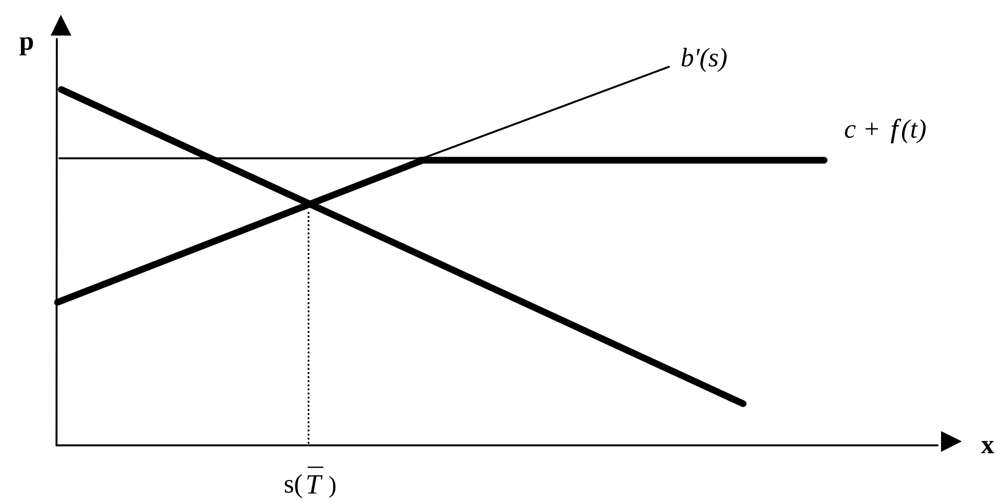


Figure 5. Supply and demand after the transition period.



Concluding Remarks

Traditionally, the literature has treated renewable energy resources as a constant returns to scale backstop technology. This has lead to the general result that the optimal transition from an exhaustible resource to a renewable resource must be instantaneous. Renewable energy resource technologies exhibit decreasing returns to scale, however, and the analysis here suggests that a transition from an exhaustible resource to a renewable resource should be undertaken gradually.

A prolonged transition period is likely to have significant benefits. A simultaneous switch from one resource to another could only be optimal if transition costs are assumed to be zero. Presumably, a switch from fossil fuels to another resource, like solar or biomass, will require the undertaking of costly activities such as investments in new types of physical capital, new types of labor skills, new methods of acquiring resources and new organizations for production. The ability to spread these costs over a period of time would lessen the social costs of the transition.

A gradual transition may also be desirable as a means of exploiting the effects of learning-by-doing. The efficiency of a new technology is likely to improve over time from the learning process that occurs with hands-on experience. At the onset of the transition period only a small portion of the energy would be produced using the new technology. Experience gained in the early stages of production could lead to significant improvements in the technology and lower capital and operating expenses. The industry could then make subsequent investments in the improved technology as production expands, thereby avoiding the hazard of over-investing significant amounts of capital in a technology that may soon become outmoded.

In addition, the effect of learning-by-doing may also lead to increases in productivity and quality of the product, which translates to improved reliability of energy supply. This effect is clearly demonstrated in Joskow and Rozanski's (1979) empirical analysis of reliability in the nuclear power generation industry. In early stages of transition, it is unlikely that a new technology would be able to attain the same level of reliability that consumers would expect from the established technology. An extended transition period would allow the industry to build a market for the new technology. Hands-on experience would lead to improvements in reliability that enhance the technology's reputation among consumers, thereby increasing demand for energy produced by the new technology. The gradual transition lessens the potential hardship of adapting to a new energy resource without imposing an inferior level of reliability on society.

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