Discussion Papers In Economics And Business

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May 2010

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Can technological progress in renewable energy sustain an age of cheap energy?*

Hazuki Ishida†

Abstract: The fact that harnessing renewable energy depends heavily upon fossil fuels implies that a continuous rise in energy prices is inevitable without technological progress in saving fossil fuel use. Using a simple Hotelling model of optimal nonrenewable resource extraction, this paper explores the conditions under which the continuous price rise of renewable energy is restrained in the presence of technological progress in harnessing renewable energy. In these circumstances, the results show that the growth rate of technology in harnessing renewable energy has to be larger than the discount rate to sustain the age of cheap energy.

JEL: Q31; Q41; Q42

Keywords: renewable energy; fossil fuels; technological progress

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* I am grateful to Tsunehiro Otsuki for helpful comments and suggestions.

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1. Introduction

Many environmentalists seem to believe that technological improvements in the harnessing of wind/solar power can sustain our mass-consumption society. There is a simple belief underpinning this presumption: renewable energy can replace fossil fuels. However, the notion that we can replace our fossil fuel usage by wind/solar power is questionable. As Georgescu-Roegen (1971) pointed out, there is an intrinsic difference between fossil fuels and wind/solar energy in that we can extract the stock of fossil fuels at a rate to suit our current desires, whereas we cannot control the rate of energy flow from the sun. We dominate the former, while the latter dictates to us. Hence, it is quite misleading to believe that a mass-consumption society based on cheap energy can be sustained after the stock of fossil fuels is exhausted as the most significant problems for wind/solar energy are set by their intermittent nature. However, there are two ways to obtain stable energy from wind/solar power: backup through conventional coal-fired systems or energy storage. Clearly, the former requires coal-fired plants *in addition to* wind/solar power generation systems. Accordingly, the relationship between wind/solar power and fossil fuels is not substitutive, rather complementary.

To completely move away from a fossil fuel society, we have to develop reasonable measures to store very large quantities of wind/solar power. The most conventional way to store the energy is to pump water up into dams. Unfortunately, it is difficult to obtain a satisfactory number of sites well suited to the construction of many new dams with sufficient storage capacity (Trainer, 2007). Another traditional way to store renewable energy is to harvest and store biomass (solid or liquid). However, as the average energy production density of phytomass is very low (Smil, 2008), heavy dependence upon biomass energy to feed a mass-consumption society may lead to fierce competition over finite fertile lands for the production of food. Moreover, we note that conventional agriculture has only come about with huge inputs of fossil fuels (Patzek, 2008).

Other ways to store energy (hydrogen, compressed air, vanadium batteries, flywheels, etc.) have so far no prospects of supplying massive energy to our society without the help of coal-fired plants (Trainer, 2007). Again, as Ferguson (2008) pointed out, the whole project of producing a power-generating system and storage capacity cannot be implemented without fossil fuels. Above all, the more strongly we harness renewable energies, the more fossil fuels we have to use.

Thus far, some economists have discussed the optimal extraction path of natural resources by incorporating a backstop technology that substitutes unconventional resources for conventional nonrenewables (Dasgupta and Heal, 1979; Pearce and Turner, 1990; Hartwick and Olewiler, 1998; Tsur and Zemel, 2003). Although these findings are suggestive, it is not appropriate to use these models for investigating the economics of renewable energy whose use requires substantial backup by fossil fuels. Intuitively, in the absence of technological improvements in reducing fossil fuel use in harnessing renewable energy, the basic Hotelling's rule predicts that the price of renewable energy should continue to grow (Hotelling, 1931). This paper explores the conditions under which a continuous price rise of renewable energy is restrained in the presence of technological progress in harnessing renewable energy.

The remainder of the paper is organized as follows. Section 2 develops the model. Section 3 analyzes and discusses the main results. Section 4 concludes.

2. The model

Energy is a necessity in the economy. Although there are several forms of energy, not all forms are equally valuable. The second law of thermodynamics states that high-quality energy (such as motion and electricity) can be completely converted to heat, but not vice versa. Problematically, our mass-consumption society is based on the massive use of high-quality energy (especially electricity generated by fossil fuel combustion).

Let E_t denote high-quality energy consumption at t and $U(E_t)$ a strictly concave utility function. It would be inappropriate to define utility as a function of energy if there was a strong decoupling between energy use and consumption of goods. Although many studies have concerned the possibility of a decline in so-called *energy intensity*, most ignore the variation in energy quality. A few exceptional studies that take into account the difference in energy quality show that there is less decoupling between energy use and GDP (Cleveland et al., 1984, 2000). Once again, our economy is fueled by high-quality energy. This paper focuses on high-quality energy, which we hereafter simply refer to as energy.

Energy is obtained in two ways: either the conventional combustion of fossil fuels (q_t) or harnessing renewable energy (r_t). However, renewable energy is not itself stable and convenient to use, so harnessing renewable energy requires more or less inputs of low-entropy resources (namely fossil fuels).

The change rate in the stock of fossil fuels (R_t) at t is expressed by:

$$\dot{R}_t = -q_t - m_t\phi(r_t), \tag{1}$$

where a dot denotes the time derivative, and $\phi(\cdot)$ is the fossil fuel cost function of harnessing renewable energy without technological progress, assuming $\phi(0) = 0$ and $\phi(\infty) = \infty$. The m_t denotes exogenous technological progress taking the form:

$$m_t = e^{-\Gamma t}, \tag{2}$$

where Γ is a positive constant. As the most efficient energy sources tend to be developed first, it is reasonable to think that both the total cost and the marginal cost of harnessing renewable energy rises as more unconventional renewable energy is developed. Then, assume $\phi'(\cdot) > 0$, $\phi''(\cdot) > 0$, $\phi'(0) = 0$, and $\phi'(\infty) = \infty$. Then, the available energy at t is:

$$E_t = \alpha q_t + r_t, \tag{3}$$

where α is combustion efficiency (which is actually far less than Carnot efficiency). Given we have a long history of obtaining energy by fossil fuel combustion, α is assumed to be constant and will not increase any further.

Without any externalities, the competitive equilibrium equals the solution to the following social planner's problem:

$$max \int_0^\infty U(E_t)e^{-\rho t}dt, \tag{4}$$

subject to Eq.(1) and Eq.(3), and ρ is the discounting factor. The corresponding current value Hamiltonian is:

$$H = U(E_t) - \mu_t(q_t + m_t\phi(r_t)), \tag{5}$$

where μ_t is the shadow value of the stock of fossil fuels at t. The first-order conditions are:

$$\alpha U'(E_t) = \mu_t, \tag{6}$$

$$U'(E_t) = \mu_t m_t \phi'(r_t), \tag{7}$$

and

$$\frac{\dot{\mu}_t}{\mu_t} = \rho. \tag{8}$$

Using Eq.(6) and Eq.(8) together taking into account α is constant, we obtain:

$$\frac{\dot{U'}}{U'} = \rho. \tag{9}$$

In a competitive equilibrium, the marginal utility of energy equals the energy price. Hence, Eq.(9) shows that the energy price will rise at the discount rate.

On the other hand, taking the logarithm and time derivative of both sides of Eq.(7) yields:

$$\frac{\dot{U'}}{U'} = \frac{\dot{\mu}_t}{\mu_t} + \frac{\dot{m}_t}{m_t} + \frac{\dot{\phi'}}{\phi'}. \tag{10}$$

Combining Eq.(9) and (10) yields:

$$\frac{\dot{\phi'}}{\phi'} = -\frac{\dot{m}_t}{m_t} = \Gamma. \tag{11}$$

Eq.(9) implies that energy consumption monotonically declines, while Eq.(11) implies that the harnessing of renewable energy monotonically rises. From Eq.(3), the extraction of fossil fuels for conventional combustion is:

$$q_t = \frac{1}{\alpha}(E_t - r_t). \tag{12}$$

Hence, q_t will eventually fall to zero [1]. Then, let T_P denote the time at which the right-hand side of Eq.(12) is equal to zero. As the value of q_t cannot be negative, $q_t = 0$ and $E_t = r_t$ for all $t > T_P$. Note that the first-order condition Eq.(6) is not available after $t = T_P$. Therefore, the time path of energy consumption for $t > T_P$ is determined by Eq.(7) and Eq.(8).

$$\frac{\dot{\phi}'}{\phi'} - \frac{\dot{U}'}{U'} = \Gamma - \rho \tag{13}$$

From the definition of $U(\cdot)$ and $\phi(\cdot)$,

$$sign\left[\frac{\dot{r}}{r}\right] = sign\left[\frac{\dot{\phi}'}{\phi'}\right] = -sign\left[\frac{\dot{U}'}{U'}.\right] \tag{14}$$

Using Eq.(13) and Eq.(14) together, we can evaluate the direction of change in the energy price for $t > T_P$:

$$sign\left[\frac{\dot{U}'}{U'}\right] = -sign\left[\Gamma - \rho\right]. \tag{15}$$

3. The age of cheap energy again?

From Eq.(9), the price of energy continues to rise at the discount rate during $0 < t < T_P$ regardless of the growth rate of technology. This result is not surprising as the marginal production of energy in equilibrium is determined by the lowest efficiency in the use of fossil fuels, which is never below combustion efficiency.

On the other hand, after $t = T_P$, from Eq.(15) the following proposition holds:

[1] Assume that $q_0 > 0$ ($E_0 > r_0$), namely, part of energy is generated by the combustion of fossil fuels at the initial time.

Proposition 1. *If $\Gamma > \rho$, the energy price will begin to decline at T_P.*

After T_P, the extraction level of fossil fuels is too small to be used to generate energy from conventional combustion systems. This means that the technological progress in harnessing renewable energy affects the energy price differently from period $0 < t < T_P$. Note that the technological progress may not necessarily lead to a decline in the energy price unless the growth rate is beyond a certain value.

What about the effect of technological progress on the time when the price of energy will go into continuous decline? T_P is determined endogenously by the model parameters, which include the technological growth rate. To go further, let us formulate the utility function as:

$$U(E) = E^{\beta}, \tag{16}$$

where β is a positive constant and less than unity. We also need to specialize the function $\phi(\cdot)$. To simplify the analysis, suppose that the marginal energy cost of harnessing renewable energy, $\phi'(\cdot)$, is proportional to the level of harnessing:

$$\phi'(r) = 2Kr, \tag{17}$$

where K is a positive constant. As $\phi(0) = 0$ is already assumed, $\phi(\cdot)$ should be:

$$\phi(r) = Kr^2. \tag{18}$$

Using Eq.(6) and Eq.(16), the time path of energy consumption during $0 < t < T_P$ is obtained as:

$$E_t = E_0 e^{-\frac{\rho}{1-\beta}t}. \tag{19}$$

Using Eq.(11) and Eq.(18) yields:

$$r_t = r_0 e^{\Gamma t}, \tag{20}$$

where r_0 is determined by the first-order conditions:

$$\phi'(r_0) = \frac{1}{\alpha}. \tag{21}$$

Inserting Eq.(19) and Eq.(18) into Eq.(12) yields:

$$q_t = \frac{1}{\alpha}\left(E_0 e^{-\frac{\rho}{1-\beta}t} - r_0 e^{\Gamma t}.\right). \tag{22}$$

Given $q_{T_P} = 0$, the following equation is obtained:

$$E_0 e^{-\frac{\rho}{1-\beta}T_P} = r_0 e^{\Gamma T_P}. \tag{23}$$

Taking the natural logarithm of both sides of Eq.(23) and rearranging terms yields:

$$T_P = \frac{\ln \frac{E_0}{r_0}}{\Gamma + \frac{\rho}{1-\beta}}. \tag{24}$$

Given that E_0 is constant, the derivative of T_P with respect to Γ is:

$$\frac{dT_P}{d\Gamma} = -\frac{\ln \frac{E_0}{r_0}}{\left(\Gamma + \frac{\rho}{1-\beta}\right)^2}. \tag{25}$$

Eq.(25) implies that although an increase in Γ leads to decrease in T_P, marginal (absolute) value of T_P decreases with each additional increase in Γ [2].

For $t > T_P$, $q_t = 0$ and,

$$E_t = r_t = r_{T_p} e^{\frac{\Gamma-\rho}{2-\beta}(t-T_p)}, \tag{26}$$

[2]Strictly speaking, both E_0 and T_P are determined endogenously from Eq.(23) and the

where

$$r_{T_P} = r_0 e^{\Gamma T_P}. \tag{27}$$

Note that, even if $\Gamma > \rho$, T_P is just the starting point of the price decline of energy, namely, the price of energy is at its peak. When will the energy price equal the initial price? Let T_S denote the time at which the energy price will be equal to the initial price. Using Eq.(19), Eq.(23) and Eq.(26) yields the following equation:

$$\frac{T_S}{T_P} = \left(1 + \left(1 + \frac{1}{1-\beta}\right)\frac{\rho}{\Gamma - \rho}\right). \tag{28}$$

Eq.(28) shows that, for example, if $\Gamma = 2\rho$ then $\frac{T_S}{T_P} > 2$, namely, the duration of time before the energy price equals the initial level takes more than twice the time until the price hits a peak.

Unfortunately, it is difficult to observe quantitatively the long-term trend of technological progress. To aid approximation, we note, for example, that the cost of wind-generated electricity fell at an average rate of 8 percent per year from 1980 to 2005 [3]. However, the decline in the cost is projected to be slower from 2005 to 2020, say, 4 percent per year on average (Mathew, 2006).

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resource constraint:

$$\int_0^{T_P} (q_t + m_t\phi(r_t))dt + \int_{T_P}^{\infty} m_t\phi(r_t)dt = R_0,$$

where R_0 is the initial stock of fossil fuels. Although it is difficult to determine the sign of $\frac{dT_P}{d\Gamma}$ due to the complexity of the problem, the supposition that E_0 is constant would not lead to substantial error as the logarithmic conversion of E_0 in Eq.(24) mitigates the impact of change in E_0.

[3]As discussed above, the absence of decoupling between energy consumption and GDP implies that the cost of generating electricity is roughly proportional to fossil fuel use.

Similarly, although the cost of photovoltaic modules has fallen substantially in the last two decades, this downward trend now seems to have ceased (Trainer, 2007). Above all, it may be unlikely that the technological progress could bring about a continuous reduction in fossil fuel use at the same or greater rate as the magnitude of the discount rate. This problem will become obvious with the use of less ideal sites to install the power generating system.

4. Conclusion

It is inappropriate to suppose that the use of fossil fuels can be easily substituted for by the so-called backstop technology to harness renewable energy. In reality, backup by fossil fuels is indispensable to harnessing renewable energy to feed a mass-consumption society based on cheap energy. Therefore, if there is no technological progress in saving fossil fuel use, Hotelling's rule implies that the price of renewable energy should continue to rise as the stock of fossil fuels is close to exhaustion.

Even if continuous progress in the technology of harnessing renewable energy could be expected, there are three reasons why an optimistic view of technological progress may be undermined. First, to sustain an age of cheap energy, the growth rate of technology in harnessing renewable energy has to be larger than a certain level (= discount rate). Second, even if the rate of the technological progress is faster than the discount rate, the energy price will continue to rise until the conventional system of energy generation through the combustion of fossil fuels is obsolete. Third, although the rapid growth of the technology could theoretically shorten the duration of the continuous rise of the energy price, it is unlikely that the time when the energy price peaks, if at all, will come in the near future as fossil fuel combustion may remain the dominant source of primary energy generation for at least several decades (IEA, 2008).

Of course, this paper does not deny the possibility of a society without fossil fuels, as such is the case for all preindustrial small-sized societies. Instead, this paper is skeptical of a mass-consumption society based on a large amount of cheap energy without the assistance of fossil fuels.

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