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A Note on Energy Supply and Economic Growth: In Cases of Depletable Energy and Expendable Energy

By
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Abstract

This paper shows that the use of expendable energy does not induce endogenous economic growth any more than the use of depletable energy. This result comes mainly from two assumptions: (1) that knowledge and equipment for producing expendable energy are accumulated by investment, and (2) that labour moves smoothly between two sectors reacting to the difference in wages. Policy implications obtained from this analysis are: (1) that the use of expendable energy cannot attain endogenous growth since the decrease of marginal productivity of energy will appear as a constraint, and (2) that social policy is indispensable to attain steady state.

Key Words

Depletable energy; Expendable energy; Steady state

1. Introduction

The purpose of this paper is to examine some relationships between economic growth and the optimal inter-temporal use of energy, under certain conditions in a one-capital and two-consumption goods model.

Economic development in nations is now confronted with many problems. Of these, food demand, energy consumption and environmental pollution are considered particularly great constraints on sustainable development. To consider the effect of these three constraints on economic growth, an economic growth model and dynamic optimization are used. In the model of economic structure established in this paper, energy input has three effects, producing changes in: the level of industrial good output, agricultural goods output, and environmental pollution.

Here, two types of energy are considered. One is depletable energy, "whose adjustment speed is so slow that we can meaningfully model [it] as made available once and only once by nature" (Sweeney, 1993, p.759). This energy includes petroleum, natural gas, coal, uranium, oil shale and so on. The other is expendable energy, "whose adjustment speed is so fast that impacts on the resource in one time period have little or no effects in subsequent periods" (Sweeney, 1993, p.760). This energy includes solar radiation, hydropower, terrestrial heat and so on.[1]

Since the Industrial Revolution, our industrial activity has depended mainly on depletable energy, especially fossil fuel. It is, however, widely considered that the energy source should be diversified because depletable energy is in limited supply and also produces environmental pollution. Consequently, it is not capable of sustaining economic growth in the long term. Attention is focused on expendable energy.

Benefits of such energy use are that the potential supply is limitless and its use can reduce the impact of pollution. Negative aspects of expendable energy include the vast amount of research and investment needed to develop and harness it. It is widely assumed that if fossil fuels were replaced by expendable energy, the problem of physical resource constraints would disappear, pollution would be less, and the world could enjoy endless economic growth.

This paper clarifies the reality of the situation, using a model which, although simplified in its assumptions, suggests that expendable energy will not necessarily be any more likely to bring about endless growth than the use of fossil fuel.

This paper is organized into four parts. Section 2 considers the case of consuming depletable energy and shows that economic growth is restricted by both environmental and resource constraints. Section 3 considers the case of expendable energy, which is produced as a manufactured product, free from environmental and resource constraints. It is concluded that this energy also does not bring endogenous economic growth, when capital goods necessary to produce expendable energy are accumulated by investment. Section 4 discusses limitations of the model and some policy implications of the analysis.

2. Consumption of Depletable Energy under Constraints

The two-sector model used in this paper is based on Matsuyama (1992). The economy consists of two sectors: manufacturing and agriculture. Both sectors employ labour. Abstracting from the issue of population growth and population dynamics, the size of the population and the total labour supply is constant. The total labour supply is normalized to one in the following analysis. The output of the manufacturing sector at time t (time is continuous), X_{Mt}, and that of the agricultural sector, X_{At}, are given by

$$X_{Mt}=E_tF(n_t), \qquad F(0)=0,\ F'>0,\ F''<0, \tag{1}$$
$$X_{At}=G(1-n_t), \qquad G(0)=0,\ G'>0,\ G''<0, \tag{2}$$

where n_t is the fraction of labour employed in the manufacturing sector as of time t and E_t is the volume of energy consumed to produce manufactured goods. The agricultural sector employs one variable and indispensable factor of production, labour, while the manufacturing sector employs two factors, labour and energy. Both sectors operate under diminishing returns concerning labour.

Competition between the two sectors for labour leads to the equilibrium condition

[1]Non-energy resources can be classified similarly by using these two classifications. Sweeney (1993) introduces a further, third classification, renewable resources, which "adjust more rapidly so that they are self renewing within a time scale important for economic decisionmaking" (p.759). See Lopez (1994) for the analysis of renewable resource and the effect of economic growth and trade liberalization.

in the labour market,

$$G'(1-n_t)=q_tE_tF'(n_t), \tag{3}$$

where q_t is the relative price of the manufacturing goods.

All consumers in this economy share identical preferences and the aggregate preference function is given by

$$W=\int_0^{\infty}U(C_{At},C_{Mt},P_t)e^{-\rho t}dt,\quad U_{C_{At}}>0,\ U_{C_{At}C_{At}}<0,\ \lim_{C_{At}\to 0}U_{C_{At}}=\infty,$$
$$U_{C_{Mt}}>0,\ U_{C_{Mt}C_{Mt}}<0,\ \lim_{C_{Mt}\to 0}U_{C_{Mt}}=\infty,$$
$$U_{P_t}<0,\ U_{P_tP_t}<0,\ \lim_{P_t\to 0}U_{P_t}=0,$$
$$U_{C_{At}C_{Mt}}=U_{C_{Mt}P_t}=U_{P_tC_{At}}=0,$$

or, more specifically:

$$W=\int_0^{\infty}(\beta\log C_{At}+\log C_{Mt}-P_t^2)e^{-\rho t}dt,\qquad \beta,\ \rho>0,$$

where ρ is the discount rate and constant, C_{At} and C_{Mt} reflect aggregate consumption of agricultural goods and of manufactured goods, respectively, and P_t is pollution in this economy as a stock variable, as at time t.

P_t has a character of pure public goods (bads) and it decreases the welfare of all consumers equally. It is assumed that consumers make decisions about the volume of each good's consumption by considering only the income constraints and benefits from consuming each good, and not considering environmental damage that is brought about by producing manufactured goods for consumption. In other words, consumers do not take the external effect of the demand for consumption goods to the environment into consideration when they decide the volume of consumption, or P_t seems purely external for individual consumers.[2]

Therefore, from this equation, aggregate demand for the two consumption goods in this economy can be seen to satisfy:

$$C_{At}=\beta q_tC_{Mt}. \tag{4}$$

In this section, $C_{Mt}=X_{Mt}$ and $C_{At}=X_{At}$, which combined with equations (1)−(4), yields:

$$\frac{F'(n_t)}{\beta F(n_t)}=\frac{G'(1-n_t)}{G(1-n_t)}. \tag{5}$$

Thus, the employment share of each sector is constant over time. In this model, more energy consumption brings more manufacturing production, while agricultural production stays constant.

Now, two kinds of constraint on energy consumption are introduced: environmental constraints and resource constraints. When energy is used to produce goods, a flow of pollution is also produced as a by-product; this devastates the environment and reduces the standard of living in the economy. Consequently, the consumption of energy cannot increase limitlessly. This is called an environmental constraint. Resource constraint, on the other hand, assumes that the estimated amount of energy in deposit is finite. The consumption of energy therefore has a limit.

[2]It is also assumed in the following that consumers do not have perfect-foresight.

In this paper, these two constraints are expressed as follows. First, for the environmental constraint, the flow of pollution at time t, $\dot{P}_t$, is generated proportionally by consuming energy, aE_t $(a>0)$. Let the pollution stock be subject to exponential decay at the rate of $b>0$, then $\dot{P}_t/P_t=-b$. Combining these factors,

$$\dot{P}_t=aE_t-bP_t.$$

Second, for the resource constraint, let us assume for simplicity that the stock of energy is not increased. The change of energy stock S_t is, therefore, due only to the additional drain on the energy deposit, or

$$\dot{S}_t=-E_t.$$

The socially optimal level of energy use would then be determined by

$$\begin{aligned}\max_{E_t} W &= \int_0^{\infty}(\beta\log X_{At}+\log X_{Mt}-P_t^2)e^{-\rho t}dt,\\ \text{s.t.}\ \dot{P}_t&=aE_t-bP_t,\\ \dot{S}_t&=-E_t,\\ P_0&=\bar{P}_0,\\ S_0&=\bar{S}_0,\end{aligned}$$

where P_0 is the initial level of environmental pollution and S_0 is that of energy stock, where both are given and constant.

The first-order necessary conditions are

$$\begin{aligned}&E_t^{-1}+a\lambda_{Pt}-\lambda_{St}=0,\\ &\dot{\lambda}_{Pt}=2P_t+(b+\rho)\lambda_{Pt},\\ &\dot{\lambda}_{St}=\rho\lambda_{St},\\ &\dot{P}_t=aE_t-bP_t,\\ &\dot{S}_t=-E_t,\\ &P_0=\bar{P}_0;\ \lim_{t\to\infty}e^{-\rho t}\lambda_{Pt}P_t=0,\\ &S_0=\bar{S}_0;\ \lim_{t\to\infty}e^{-\rho t}\lambda_{St}S_t=0,\end{aligned}$$

where λ_P and λ_S are the current value co-state variables measuring the shadow value of P and S, respectively.[3] The dynamics of the system can be represented by the following two derived differential equations:

$$\dot{E}_t=[2aP_t+(b+\rho)(e^{\rho t}\lambda_{S0}-E_t^{-1})]E_t^2, \tag{6-1}$$

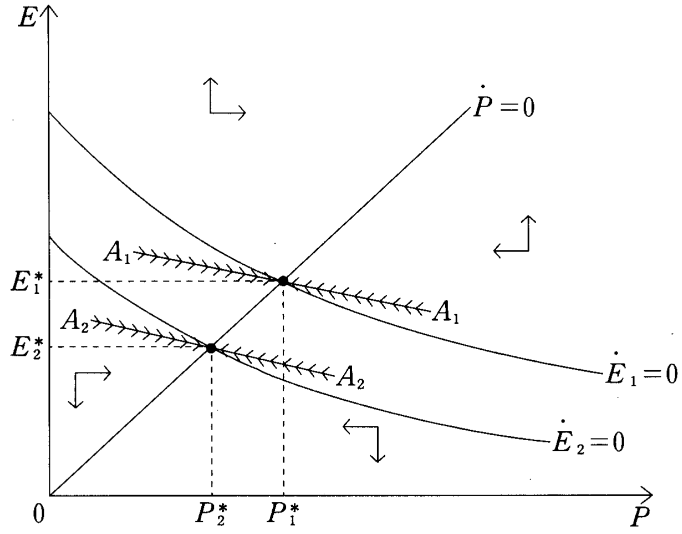
$$\dot{P}_t=aE_t-bP_t, \tag{6-2}$$

note that $\lambda_{St}=e^{\rho t}\lambda_{S0}$.

From (6-1) and (6-2), the slopes of the $\dot{E}_t=0$ and $\dot{P}=0$ schedules are obtained. These are shown in Figure 1. This figure also shows, with the arrows, the motion of the system in the neighbourhood of the steady state in the figure. This is the saddle point, thus requiring some adjustment process. P_1^* and E_1^* are steady states of environmental pollution and energy use, respectively, at time 1. In order to put the economy on an adjustment process shown as line A_1A_1 government should make energy consumption policy changes, if it has an ability to apply the socially optimal policy.

[3]Though energy price is not considered explicitly, the following analysis holds if relative market price of energy is equal to λ_S.

Figure 1. Phase diagram: depletable energy



With the passage of time, however, $e^{\rho t}\lambda_{S0}$ in (6-1) increases, which makes the $\dot{E}_t=0$ line shift downward. At time 2, for example, steady states of pollution and energy shift to P_2^* and E_2^*, and the new adjustment schedule becomes A_2A_2. Because of the movement of the adjustment schedule in each period, it is not sufficient to adjust the volume of energy consumption at one initial time in order to maintain this economy. Government must continually aim to put the economy on a new temporal adjustment schedule to converge the economy towards the steady state. Thus, the role of government for achieving economic stability becomes important when compared with the case where steady state and the adjustment process are fixed. However, this policy implication arises mainly from the assumption that consumers do not take the external effect of demand for consumption goods to environment into consideration, while government can follow the socially optimal policy. The use of energy decreases with time, and so does manufacturing production. This result comes naturally from the fixed energy stock assumption.

This analysis also says that, even if resource constraint does not exist and energy is inexhaustible, the volume of energy consumption is restricted by environmental constraints. In the case of there being no resource constraint, equation (6-1) is modified to

$$\dot{E}_t=[2aP_t-(b+\rho)E_t^{-1}]E_t^2. \qquad (6\text{-}1')$$

There is no $e^{\rho t}\lambda_{S0}$ in (6-1'). Thus, the slope of the $\dot{E}_t=0$ schedule is constant over time. Other characters of the $\dot{E}_t=0$ schedule stay valid. This means that, even if a resource constraint does not exist, there are steady states of environmental pollution and energy use, as well as adjustment process. Government's role is still needed to put the economy on an adjustment process at an initial time.

3. Expendable Energy as a Manufactured Product

Consumption of depletable energy is confronted with two constraints; resource constraint and environmental constraint. To surmount these constraints, supporters of expendable energy are now engaged in research and development for producing and harnessing it as an alternative to depletable energy. This section considers the relationship between production and consumption of this expendable energy and economic growth. It is assumed that using expendable energy produces no environmental pollution as a polar case, since if the use of this energy also brings environmental damage, environmental constraints operate, and the volume of expendable energy consumption is capped. This conclusion is the same as that given in the previous section.

Two types of the production of expendable energy are considered. The first one is that the knowledge and equipment for producing expendable energy, which is called energy capital, is accumulated as a by-product of manufactured output, as follows:[4]

$$\dot{E}_t = \delta X_{Mt}, \qquad \delta > 0.$$

If the production of expendable energy has this kind of character, and this effect is purely external to individual firms, the equilibrium condition of the labour and goods markets in the previous section, equation (5), stays effective. Thus, the employment share of each sector is constant over time. This model suggests that manufacturing production continues to increase because of the availability of an increasing energy supply with the passage of time, while agricultural production stays constant. Supposedly, through such endogenous growth, this economy can keep on growing forever - a very rosy scenario for the future - even though such a definition of energy capital is not realistic, judging from the effort made mainly in developed countries to utilize expendable energy.

The second type of energy capital to be considered is that accumulated by investment. Forster (1980) considers the case where it is possible to install any amount of energy capital at the start of a plan at some cost. Here, optimal capital accumulation is taken into account. The source of investment comes from the sector producing manufactured output, which is produced but not consumed in any one period. The accumulation of this investment, which becomes energy capital, is as follows:[5]

$$\dot{K}_t = I_t = X_{Mt} - C_{Mt},$$

and energy is produced proportionally by this capital:

$$E_t = \sigma K_t, \qquad \sigma > 0.$$

This case does not bring about endogenous growth; there is a steady state concerning the volume of consumption and the level of capital stock. This results from the decrease in the marginal productivity of energy of the manufacturing sector, which is brought about by the movement of labour from the manufacturing to the agricultural

[4]For simplicity, it is assumed that knowledge and equipment of producing and harnessing expendable energy do not depreciate.

[5]It is also assumed that energy capital never depreciates.

sector, due to the accumulation of energy capital.

Hence, the equilibrium condition of the goods market in the previous section, equation (4), becomes

$$C_{At} = \beta q_t (X_{Mt} - I_t). \tag{7}$$

Combining equations (1), (2), (3) and (7) yields

$$\varphi(n_t) = \beta I_t / E_t, \tag{8}$$

where $\varphi(n) = \beta F(n) - F'(n)G(1-n)/G'(1-n)$, whereby $\varphi(1) = \beta F(1)$, $\varphi(0) < 0$, and $\varphi' > 0$. Equation (8) has a unique solution in $(0, 1)$. Each sector employs labour so as to satisfy this condition. Since the right-hand side is decreasing in terms of E_t, this solution can be written as

$$n_t = \omega(E_t), \qquad \text{with } \omega'(E) < 0.$$

Thus, the employment share of manufacturing is related negatively to the level of energy supply E_t, or the level of energy capital K_t. An increase in energy supply or energy capital immediately increases manufacturing output, decreases its price, and then releases labour to the agricultural sector, thus increasing its output, and *vice versa*.

The socially optimal level of energy investment can then be determined as follows:

$$\max_{C_{Mt}} W = \int_0^{\infty} (\beta \log C_{At} + \log C_{Mt}) e^{-\rho t} dt,$$
$$\text{s.t. } \dot{K}_t = \sigma K_t F(n_t) - C_{Mt},$$
$$K_0 = \overline{K}_0.$$

The first-order necessary conditions are

$$C_{Mt}^{-1} = \lambda_{Kt},$$
$$\dot{\lambda}_{Kt} = -\frac{\beta\sigma}{C_{At}} \frac{dX_{At}}{dE_t} + \left(\rho - \sigma \frac{dX_{Mt}}{dE_t}\right)\lambda_{Kt},$$
$$\dot{K}_t = \sigma K_t F(n_t) - C_{Mt},$$
$$K_0 = \overline{K}_0;\ \lim_{t\to\infty} e^{-\rho t}\lambda_{Kt} K_t = 0,$$

where

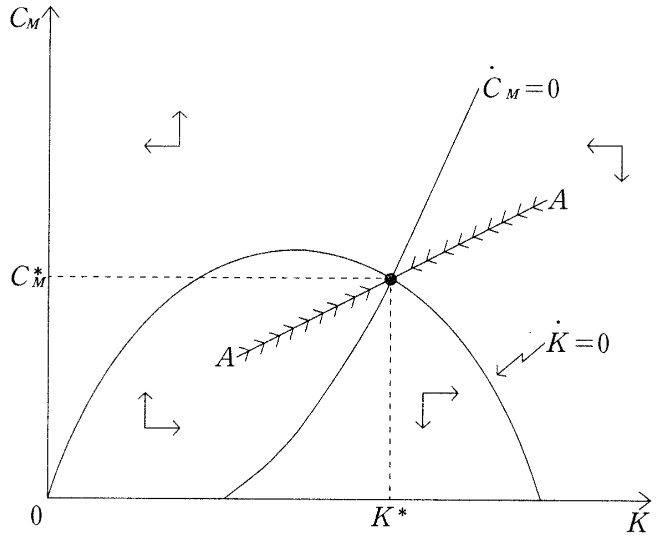
$$\frac{dX_{Mt}}{dE_t} = \frac{\partial X_{Mt}}{\partial E_t} + \frac{\partial X_{Mt}}{\partial n_t}\frac{dn_t}{dE_t} = F(n_t) + E_t F'(n_t)\omega'(E_t),$$
$$\frac{dX_{At}}{dE_t} = \frac{\partial X_{At}}{\partial n_t}\frac{dn_t}{dE_t} = -G'(1-n_t)\omega'(E_t) > 0.$$

The dynamics of the system can be represented by the following two differential equations.

$$\dot{C}_{Mt} = \left(\sigma\beta \frac{C_{Mt}}{C_{At}} \frac{dX_{At}}{dE_t} + \sigma \frac{dX_{Mt}}{dE_t} - \rho\right) C_{Mt},$$
$$\dot{K}_t = \sigma K_t F(n_t) - C_{Mt}.$$

From these two differential equations, the slopes of the $\dot{C}_M = 0$ and $\dot{K} = 0$ schedules are obtained, as shown in Figure 2. The $\dot{C}_M = 0$ line exists in the region where K satisfies the condition $\rho - \sigma dX_M / dE > 0$, meaning that the marginal productivity of the energy

Figure 2. Phase diagram: expendable energy



capital stock in the manufacturing sector is lower than the time discount rate. This situation occurs for considerably high values of K.

K^* and C_M^* represent steady states of the energy capital stock and the consumption of manufacturing output, respectively. This satisfies the condition $\rho=\sigma F(n_t)$, meaning that the average productivity of the energy capital stock in the manufacturing sector is equal to the time discount rate. In addition, the arrows in Figure 2 represent the movement of the system in the neighbourhood of the steady state. This is again the saddle point. The required adjustment process is shown as line AA in the figure. Government should implement a policy that changes the consumption of manufacturing goods once at an initial time in order to put the economy on an adjustment process. Stocks of energy capital and the current consumption of manufacturing goods are then gradually adjusted along line AA. This figure shows that, in the case where energy capital is invested to produce expendable energy, economic growth is limited, and sustainable growth will not be achieved.

4. Concluding Remarks

This paper presents the case where the use of expendable energy, (for example, radiation, hydropower and terrestrial heat,) does not bring about endless economic growth any more than the use of depletable energy, (petroleum, natural gas, coal and so on).

This counter-commonsense result is based mainly upon two assumptions. One is that the knowledge and equipment for producing expendable energy are accumulated by investment. This assumption seems reasonable because producing and harnessing expendable energy require huge amounts of research and development investment, together with massive capital facilities. Even if solar energy, for example, receives much attention, there are problems in designing efficient methods of collecting and storing solar energy. Wind and wave energy have similar weak points. Large amounts of investment have been required for research into and construction of nuclear power plants, in order to enable nuclear energy to supply electrical power safely.

The other assumption is that labour moves smoothly between the two sectors, reacting to the difference of wages. This induces the movement of labour from the manufacturing to the agricultural sector and a decrease in the marginal productivity of energy in the manufacturing sector, due to the accumulation of the energy capital stock. In order to reconstruct this model in a more realistic way, it is useful to introduce another labour sector; the research and development sector. Such a modification may alter the result of this paper. If a decrease of manufacturing goods prices pushes labour to move to the research and development sector, the possibility arises that the marginal productivity of energy in the manufacturing sector does not decrease, and the economy can attain endogenous growth.

Some policy implications can be deduced from this analysis. First, nations may avoid food shortages and environmental degradation as constraints on their sustainable development if expendable energy is put to practical use. The use of this energy cannot, however, attain endogenous growth, because the decrease of marginal productivity of energy will then appear as a new constraint on economic development. Other factors, such as technical progress, human capital accumulation, are necessary to maintain the process of endogenous economic development. Secondly, this model shows that social policy is indispensable in putting an economy on the adjustment schedule and in attaining its steady state. In particular, if there is a resource constraint on energy consumption, government continues adjusting policy on energy consumption in order to hold the economy stable. This policy implication, however, depends on the asymmetric assumption that consumers do not know the economic structure in which they are living, while government knows it perfectly.

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