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## Environment, energy and sustainable economic growth

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### Abstract

Sustainable energy utilization and environmental protection are important to sustainable economic growth. In this paper, we develop an endogenous economic growth model and discuss the optimal path of sustainable economic growth with the constraints of energy and environment. We find that sustainable economic growth can be achieved only when the relative contribution rate of environment protection investment to environmental quality is more than the relative contribution rate of combined input of energy and environment to production. The results indicate that long-run growth requires not only a continuous energy intensity decrease and technology progress in the fields of energy resources exploitation, exaction, refinement and utilization, but also an optimal structure adjustment from depending on nonrenewable energy to renewable energy.

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### 1. Introduction

The sustainable energy utilization and the environmental protection are very important to sustainable economy and society development. In the past twenty years, many several developing countries have made amazing achievements in economic development. However, as concomitance of rapid economic growth and industrialization advance, the energy shortage and the environmental degradation poses a grave threat to the progress of industrialization and civilization. How to get mutual benefits between the energy development and environmental protection has drawn a lot of attention in the past twenty years. Whether can economy pursues the optimal growing path under the dual restraints of the energy and environment is the focus of sustainable growth.

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Exhaustible resources, mainly including nonrenewable energy and mineral resource, were once the focus of research work concerned with economy growth in 1970's. Quite a number of research works introduced exhaustible resources into neoclassic growth model and discussed the consequent influences on economic growth. They introduced the exhaustible resources into the Cobb-Douglas production function and tried to seek the relationship between the exhaustion of the natural resources and the long term economic growth. It was found that optimal distribution of exhaustible resources will take the intergenerational equity of the total wealth in a society into account and the sustainable development should be measured by total capital stock. Although the introduction of exhaustible resources into neoclassic growth pattern confirmed their restraint mechanism in as well as impacts on economy growth, the inherent contradictions in the neoclassic growth pattern was still left unsolved. Given Hicks neutral technical progress, the long term economic growth depends on the marginal factor income increasing, while the theoretical premise of the neoclassic growth theory was the marginal factor income decreasing. So, the decreasing marginal income led to an increasing resource exhausting rate. If the regenerating rate of resources cannot exceed the exhausting rate, economy would come to the zero growth inevitably.

Since 1980s, some researchers developed new growth theory on the foundation of neoclassic pattern, which took the internal technique change as the core of economic growth and pay much attention to the knowledge overflow (P.M. Romer, 1986), human capital externality (R. E. Lucas, 1988), the new product introduction (G.M. Grossman, E. Helpman, 1991), learning by doing (Young and Allyn, 1991) and so on. By introduction of the knowledge and the specialized human capital, the new growth theory revealed that the human capital accumulation may cause an increasing marginal return as well as an increasing return to scale. Based on these theories, H. L Yang et al (2004) introduced energy into the Lucas endogenous growth model as a factor of production and discussed the function of the human capital accumulation in breaking out of the exhaustible energy reserve restraint. B. Yu et al (2006) introduced both energy exhaustion and environment protection into endogenous economic growth model and discussed the requirements of the sustainable growth. Omer and A Mustafa (2008) discussed several issues relating to renewable energies, environment and sustainable development from both current and future perspectives. Recently, some researchers attempt to use these models to anticipate the future of environment, energy and economy. For example, Z. G. Hu, J. H. Yuan and Z. Hu investigated the low-carbon development of China. According to their prediction of China's economic growth, energy reserves and emissions mitigation till 2030, China could save energy by more than 4 billion ton oil equivalences and reduce carbon dioxide emissions by nearly 17 billion tons during the coming 20 years. They also pointed out that China had to reconstruct its economy and depend much on technology progress in the future.

These research works succeeded in introducing the energy and the environment restraints into the economic growth. Nevertheless, most of them only considered the negative impacts of environment, i.e. pollution, and little attention had been paid to the positive environment quality which could make contribution to the economic growth. Also little literature investigated the ability of environmental protection investment in improving environment quality. In the following sectors, we will introduce the energy and the environment into the production function and discuss the double influences of energy and environment and the optimal path of economic growth under these restraints.

## **2. The Model**

### *2.1. Energy, environment and output*

Quite different from the neoclassical growth theory, we construct a model in which economic growth will not depend on the energy reserve heavily due to deceased marginal return of capital. In our work, we introduce accumulated human resource into production function. We assume that labor force is constant,

i.e. no population growth and that outputs will not only depend on capital and human resources, but also energy and environment. The product per capita is defined as

$$Y = F(K, hV, n, R) = AK^\alpha n^\beta S^\gamma (M - Mv)^\zeta \quad (1)$$

where  $K$  is capital stock,  $n$  is energy input and  $S$  is environment input.  $M - Mv$  can be seen as effective labor input including human capital. Provided constant return to scale, we have  $\alpha + \beta + \gamma + \zeta = 1$ . For simplicity, we assume a constant accumulation rate of skill, so we have

$$\dot{M} = vWM \quad (2)$$

where  $W$  denotes human capital accumulation rate,  $B$  denotes knowledge and technology held by a representative unit labor.  $1 - v$  of one unit time will be spent on production and  $v$  will be spent on human capital accumulation.

## 2.2. Investment

We divide investment into two parts, one is directed to accumulation in capital stock and the other is used to improve environmental quality. Thus, we have

$$\dot{K} = Y - C - E \quad (3)$$

where  $C$  is consumption and  $E$  is environmental investment. For convenience, we assume that asset depreciate rate is zero.

It is reasonable to anticipate that an increase in capital stock will lead to an increase in environmental investment. For simplicity, we define this positive effect as

$$E = pK \quad (4)$$

where  $p$  describes the proportion of environmental investment in capital stock. Thus we have

$$\dot{K} = Y - C - pK \quad (5)$$

## 2.3. Environmental constraint

In order to bring environmental constraint into endogenous growth model, we assume that there are dual effects on the environment quality, one is brought by self-cleaning process and the other is resulted to by human activities. Thus we define the environmental constraint equation as

$$\dot{S} = a_0 p^{a_1} M^{a_2} K^{a_3} Y + \theta S = ZY + \theta S \quad (6)$$

Where  $ZY$  denotes the current environmental deterioration, and  $a^0 < 0$  means that environment quality will deteriorate with output increase.  $p^{a_1} M^{a_2} K^{a_3}$  can be seen as the combination of two parts, one is that environmental investment makes contribution to environmental quality and the other is that the technology advances will enforce pollution control. We define that  $a_1, a_2, a_3 \in (-1, 0)$ , which implies that the environmental investment and technology progress can reduce pollution brought by production and energy consumption. This equation implies that environment quality may improve because environment investment and technology will not only reduce the pollution brought by production, but also enhance the positive effects of environmental investment by improving efficiency.  $\theta \in (0, 1)$  is the measurement of the environment self-cleaning capacity.  $S \geq S_{\min}$  indicates that environment quality has a minimum value, i.e. the lower bound of environment capacity for sustainable economic growth.

## 2.4. Energy constraint

Generally, energy stock includes two different types of resources, one is renewable and the other is nonrenewable. Renewable energy resource stock can regenerate at certain ratio. Nonrenewable energy resources can also grow to the extent of that the advances in exploration and production technology makes more and more reserves be found. Suppose that combined growth rate of energy resources is constant (i.e. not taking energy consumption into account), we have

$$\dot{R} = (\phi + \rho)R - n \quad (7)$$

where  $R$  is the energy stock per capita,  $\phi + \rho$  is the growth rate and  $n$  is the energy input in the production.

### 2.5. Consumers

We adopt a utility function of constant substitute elasticity

$$U(C) = \frac{C^{1-\sigma} - 1}{1 - \sigma} \quad (8)$$

where  $\sigma \in (0,1)$  is substitution elasticity.

A representative consumer chooses to maximize his utility by

$$\max \int_0^{\infty} U(C)e^{-\rho t} dt \quad (9)$$

where  $\rho$  is discount rate.

### 2.6. Optimization

Treating  $C$ ,  $v$ ,  $p$  and  $n$  as control variables and  $K$ ,  $M$ ,  $S$  and  $R$  as state variables, we apply the optimal control theory and write Hamilton function as

$$H = U(C) + \lambda_1(Y - C - pK) + \lambda_2 v M + \lambda_3(ZY + \theta S) + \lambda_4(\phi R + \rho R - n) \quad (10)$$

According to maximization conditions, we have

$$-\frac{\partial H}{\partial v} = 0 \Rightarrow \lambda_1 \frac{\partial Y}{\partial v} + \lambda_2 M + \lambda_3 Z \frac{\partial Y}{\partial v} = 0 \quad (11)$$

$$\frac{\partial H}{\partial p} = 0 \Rightarrow -\lambda_1 K + \lambda_3 \frac{\partial Z}{\partial p} Y = 0 \quad (12)$$

$$\frac{\partial H}{\partial n} = 0 \Rightarrow \lambda_1 \frac{\partial Y}{\partial n} + \lambda_3 Z \frac{\partial Y}{\partial n} - \lambda_4 = 0 \quad (13)$$

State equations are (2), (3), (6) and (7). Dynamic equations are

$$\dot{\lambda}_1 = \rho \lambda_1 - \lambda_1 \frac{\partial Y}{\partial K} + \lambda_1 p - \lambda_3 \left( Y \frac{\partial Z}{\partial K} + Z \frac{\partial Y}{\partial K} \right) \quad (14)$$

$$\kappa_2 = \rho\lambda_2 - \lambda_1 \frac{\partial Y}{\partial M} - \lambda_2 v W - \lambda_3 \left( Y \frac{\partial Z}{\partial M} + Z \frac{\partial Y}{\partial M} \right) \quad (15)$$

$$\kappa_3 = \rho\lambda_3 - \lambda_1 \frac{\partial Y}{\partial S} - \lambda_3 Z \frac{\partial Y}{\partial S} - \lambda_3 \theta \quad (16)$$

$$\kappa_4 = \rho\lambda_4 - \lambda_4 \phi - \lambda_4 \rho \quad (17)$$

Where  $Z = a_0 D^{a_1} M^{a_2} K^{a_3}$

We define  $g_x$  as the long run growth rate of variable  $x$ , e.g.  $g_y$  is the long run growth rate of gross production. Provided long run capital output ratio constant, we conclude that

$$g_K = g_Y = g_C = \frac{Wv\zeta + Wv\gamma a_2 + \beta\phi}{\sigma\beta + \zeta - \gamma a_3} \quad (18)$$

$$g_R = g_n = \phi \frac{1 - \gamma - \alpha - \gamma a_3}{\sigma\beta + \zeta - \gamma a_3} + Wv \frac{\zeta - \sigma\zeta + \gamma a_2 - \gamma\sigma a_2}{\sigma\beta + \zeta - \gamma a_3} \quad (19)$$

$$g_S = \frac{Wva_2(\gamma + \zeta + \sigma\beta) + (\phi\beta + Wv\zeta)(1 + a_3)}{\sigma\beta + \zeta - \gamma a_3} \quad (20)$$

### 3. Economic Growth, Energy Exhaustion And Environmental Protection

#### 3.1. Sustainable economic growth

Sustainable economic growth requires three conditions at least according to our model. The first one is a positive economic growth rate, i.e.  $g_y > 0$ , the second is that environment cannot deteriorate with economic scale expansion, i.e.  $g_s > 0$  and the third is that energy resource growing can keep up with energy demand extension, which implies that  $g_R$  is not less than  $g_n$ . When taking into account that renewable energy will replace nonrenewable energy gradually, it is reasonable to infer that  $\square \geq 0$ . Therefore we have

$$Wva_2(\gamma + \zeta + \sigma\beta) + (\phi\beta + Wv\zeta)(1 + a_3) \leq 0 \quad (21)$$

For simplicity, we assume that the combined contribution rate of environmental investment, capital stock and technology to environment protection is constant, i.e.  $1 + a_1 + a_2 + a_3 = 0$ . It can be concluded that the condition of sustainable economic growth is

$$\frac{-a_1}{-a_2} \geq \frac{\beta + \gamma}{\zeta} \quad (22)$$

The above equation implies that sustainable economic growth can be achieved only when the relative contribution rate of environmental protection technology to environment quality is more than the relative contribution rate of combined input of energy and environment to production. It also means that the technology will take a more important role in the manufacture sector than in environmental protection. Therefore, there are three keys in maintaining sustainable economic growth, the first one is to increase environmental investment scale and efficiency so as to improve the performance of environmental

investment in environmental protection, the second is to stimulate human capital accumulation and make more technology progress, and the third one is to improve energy efficiency and speed up renewable energy development.

In terms of environment, the improvement of environmental investment scale and efficiency will give rise to environment capital stock. Moreover, the increase of environmental investment contribution rate can reduce the adverse impacts of production on environment sharply. For this reason, economic growth will not lead to continuous deterioration of environment if the decline rate is less than self-cleaning rate.

As far as energy is concerned, the progress of exploration technology and utilization efficiency will increase the aggregate growth rate of nonrenewable energy resources, which will promote energy growth sustainably. With the continuous structure change from depending on nonrenewable energy resources to more renewable energy resources, economic growth will get away from the restraint of exhaustible energy resources. More importantly, human capital investment has increasing returns of scale both internally and externally, which makes it possible that environmental investment contribution rate to environment quality will rise as well as aggregate regenerate rate of energy with technology progress and human capital accumulation. They are keys of sustainable growth of energy system, eco environment system and economy.

### 3.2. Energy exhaustion and environmental protection

Sustainable growth of energy and economy require that the energy resource stock cannot be exhausted completely, which implies that stock growth rate  $g_R$  is positive. From (18) and (19), we can conclude that

$$\phi > (\sigma - 1)g_Y \quad (23)$$

Satisfying the above equation, the energy resource stock will increase and economy can grow in the long run on the basis of sustainable use of energy. The equation also implies that both sustainable energy utilization and economic growth require a comparatively large aggregate regenerate rate of energy, i.e.  $\square + \rho$ . So, long run growth will not only demand continuous decrease of energy intensity and technology progress in the field of exploitation, exaction, refinement and utilization, but also require a structure adjustment from depending on nonrenewable energy to renewable energy.

We also find that economic growth rate convergence requires that the proportion of environmental investment in total investment i.e.  $p$  remains constant and there is a relatively high contribution rate of investment to environment improvement. With the growth of economy scale and capital stock, it is necessary to ensure the scale of environmental investment to grow simultaneously and the investment efficiency to be improved. We can decide on parameter  $p$  by

$$p = \frac{a_1\sigma\beta\phi + a_1\psi v\sigma\zeta + a_1a_2\psi v\sigma\gamma}{(\alpha + a_3 - a_1)(\sigma\beta + \zeta - \gamma a_3)} + \frac{\alpha a_1 Y_0 - \rho a_1 K_0}{K_0(\alpha + a_3 - a_1)} \quad (24)$$

It is easy to explain this relation between the scale and the efficiency of environmental investment. Higher investment efficiency will attract more financial support than lower one and less financial support will certainly slow down the technology progress, which can impair the environment investment efficiency.

## 4. Conclusions

In this paper, we develop an endogenous economic growth model with dual constraints of energy and environment. We find that with the restraints of energy and environment, economy growth can hardly be

sustained without human capital accumulation, environmental protection investment or energy structure adjustment. Firstly, sustainable economic growth need an uninterrupted supply of energy, which can hardly been guaranteed with the limited reserve of exhaustible energy resources. Without technology progress, exploitation, refinement and utilization of exhaustible energy are not efficient enough to ensure energy structure change accomplished before we run out of fossil fuels. Secondly, environment investment is so important that the enlargement of economy scale will break the limit of environmental carry capacity sooner or later because self-regenerate rate of environment can hardly outpace the damage rate by economic growth without environmental recovery which is usually financial supported by government. Thirdly, change from depending on conventional fossil fuels to renewable energy is necessary because any technology advance cannot stop these energy resources from exhaustion eventually and negative effects to environment is often irreversible, or at least difficult to be eliminated or even mitigated.

We also find that sustainable economic growth can be achieved only when the relative contribution rate of environment protection investment to environmental quality is more than the relative contribution rate of combined input of energy and environment to production. It implies that technology progress is not as important in environment recovery as it does in economic growth. Although there is no evidence, it can be reasonably inferred that technology advance in industrial emission control will bring more benefits to environment than it does in ecosystem restoration. Since so much environment deterioration is irreversible, financial support and scientific research should be directed to prevention rather than repairmen.

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