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Energy Use and Division of Capital Stock in Endogenous R&D Model*

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This study constructs an endogenous R&D model in which energy and capital are employed to produce the intermediate goods, and the division of capital is assumed. Following the conventional endogenous R&D model, it incorporates energy use into the production of intermediate goods; meanwhile, capital is divided into two classes — one is invested in final goods sector directly, the other is allocated for the production of intermediate goods. With this modification, the study finds that the rising energy prices would spur the substitution of capital for intermediate goods in the final goods sector; such a substitution could alleviate the energy price shock. Contrasting with the existing literature, the present model finds that the growth rate of energy prices needs not to impede the rate of output growth. Rather the increasing energy price could spur innovations for energy technology, and then stimulate economic growth. It also finds that a tax aiming to energy conservation (e.g., a carbon tax) needs not to impede the economic growth; on the contrary, the tax could favor the economic growth if it is time-increasing and moderate. For the sake of energy conservation, the study suggests a policy that imposes a tax on energy use and subsidizes capital use.

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1. INTRODUCTION

Energy, or in a broader interpretation, natural resources have been added in the modern economic growth models. A Cobb-Douglas production function with resources, capital and labor as inputs was applied to produce final goods (Herfindahl and Kneese, 1974 and hereafter H-K model). The H-K model was extended by permitting the perfect substitution of physical capital for natural resources (Dasgupta and Heal, 1979 and hereafter D-H model). The D-H model shows that the substitution and technological progress overcome the problem of diminishing resources stock. However, these analyses have a drawback that they consider the technological progress as exogenous. In the 1990s, the endogenous R&D models address this concern by linking endogenous technological improvements with economic growth. Extending an endogenous R&D model (Romer, 1990), resources were introduced into the intermediate goods sector, but it is assumed that only resources are needed to produce intermediate goods (Aghion and Howitt, 1998). These models were modified further in such a way that both physical capital and energy are required for the production of intermediate goods (van Zon and Yetkiner, 2003). This study adopts the model by van Zon and Yetkiner (2003) and shows that the growth rate of energy prices stimulates the substitution of capital for energy in the intermediate goods sector.

Furthermore, this study modifies the endogenous R&D model (e.g., Romer, 1990) by introducing the idea of capital division (Davison, 1978). Even if most of the previous R&D models imply that the whole capital stock only presents in the intermediate goods sector, it is more realistic to suggest that capital goods might be used in both the production of intermediate goods and that of final goods. Therefore, the present model assumes that the total capital stock divides into two types of capital: one is used to exploit, extract raw energy, and then produce intermediate goods that provide composite energy services; the other is invested directly in final good production. With this modification, the present model finds that the rising energy prices spur the substitution of capital for intermediate goods in the final goods sector; such a substitution alleviates the energy price shock.

By linking energy use and the division of capital with an endogenous R&D model, this study aims to assert that the growth rate of energy prices may stimulate the rate of economic growth. The reason is that the rising energy prices spur the innovations and the substitution of capital for energy; if the partial output elasticity of energy is sufficient low, or the elasticity of substitution between consumption at any two points in time are sufficient large, the impact of energy price shock on economic growth is positive. Though the result contrasts with the existing studies focusing on energy prices and growth (e.g., van Zon and Yetkiner, 2003), it consists with the view of induced technological change (ITC).

The conventional view within the endogenous growth literature is that taxing interest income discourages economic growth and subsidizing investments promotes economic growth (e.g., Lucas, 1990; Rebelo, 1991; Jones *et al*., 1993; Barro and Sala-i-Martin, 1995; Stokey and Rebelo, 1995; Aghion and Howitt, 1998). This study gets the different result that some conditions have to be met to hold the common view. It also indicates that, a tax that aims to energy conservation (e.g., a carbon tax) needs not to impede the economic growth; on the contrary, the tax may favor the economic growth if it is time-increasing and moderate. The reason lies in that such a tax works as an implement that accelerates the growth rate of energy price; consequently, it spurs innovations and output in the long run.

An endogenous R&D growth model (e.g., Romer, 1990) links endogenous technological progress with economic growth. It presents a three-sector economy: the R&D sector uses human capital to create new designs; the monopolistic intermediate goods sector buys the new designs and then combines the designs and raw capital to produce intermediate goods, it recovers the cost of purchasing the blueprints by selling intermediate goods at a price that is higher than its constant cost of production. The final goods sector manufactures a composite output with labor and intermediate goods as inputs.

The conventional endogenous model considers R&D sector the "growth engine" and finds that economic growth depends on the growth of innovations. It also derives a negative relation between the growth rate of output and the interest rate. The reason lies in that human capital allocated for R&D are compensated by the present value of the profits of intermediate goods; if the interest rate goes up, the present value of profits decreases, hence less human capital is attracted by the R&D sector. The result implies that an increase in the price of factor is harmful to the growth of output. This model contributes to the literature greatly by connecting human capital, expanding varieties and endogenous technology to economic growth. However, it does not consider the act of energy.

This study modifies an endogenous R&D growth model by treating energy as an input for intermediate goods. With the presence of energy, the production of intermediate goods can be interpreted as using capital to extract, exploit raw energy, and then supplying composite energy services. The monopolistic status of the intermediate sector not only comes from the new technologies it applies, but also comes from the privilege of energy. Therefore, the change of energy prices has impacts on innovations and economic growth. The present model assumes the intermediate goods are manufactured by a Cobb-Douglas function, which permits the elasticity of substitution of raw energy and capital to be unity. Though this assumption contrasts with the traditional literature (Dasgupta and Heal, 1974), it is supported by the energy technologies the R&D sector carries out. If the energy price increases, the firms alleviate the price shock by substituting capital for raw energy.

Another shortcoming in the conventional endogenous R&D model is it implies that the whole capital stock only presents in the intermediate goods production. This suggestion is unlikely consistent with the facts that a portion of capital acts as an input for final goods directly. Hence the present paper introduces the idea of capital division (Davison, 1978). It assumes that a proportion of capital combines raw energy to provide intermediate goods; other is invested in the final goods sector directly, in the form of machinery, etc. With this modification, the present model suggests that if the energy prices keep increasing, capital substitutes for raw energy in the intermediate goods sector; meanwhile in the final good sector, capital substitutes for intermediate goods. Therefore, the impact of energy price shock is alleviated.

The structure of this study is as follows. Section 2 reviews existing literature relating to endogenous growth models and technological change. Section 3 presents a modified model by including energy in the production of the intermediate goods and introducing the idea of capital division. In section 4, this study suggests an energy conservation policy that imposes a time-increasing tax on energy consumption combining a constant capital subsidy rate, or a constant tax rate for energy use combining an increasing subsidy for capital use. The final section presents concluding remarks.

2. ENDOGENOUS GROWTH MODEL AND CAPITAL STOCK

The concern of sustainability in modern economic framework can be traced back to the early 20th century. One of the most important contributes is the Hotelling rule (Hotelling, 1931), which links the depletion of natural resources with the market mechanism. Some neoclassical economists pay a lot attention to the role of resources in sustainable development. Their main point of view is that the manufactured capital and 'natural capital' (resources) build up the capital stock, and they are perfect substitutes. In the model developed by Herfindahl and Kneese (1974 and H-K model hereafter), the environment provides the natural resources needed by the economy and sucks up residuals of production. The H-K model also introduces resources into the Cobb-Douglas aggregate production function, combining manufactured capital and labor to produce the final goods. The result it gets is that the limited supply of resources causes the economy to shrink, unless the technological progress to improve the productivity of manufactured capital and labor and then counteract the negative impact of resources.

The H-K model is extended by Dasgupta and Heal (1979 and D-H model hereafter) by permitting the substitution of manufactured capital for exhaustible resources. The work of Dasgupta and Heal sets up the common suggestion of neoclassical economics that the problem of diminishing exhaustible resources can be overcome by the technological progress and the substitution of manufactured capital for resources. This is also the common view of neoclassical economics on resources. Adopting a Cobb-Douglas production function with capital, resources and labor as inputs, the D-H model shows that if the output elasticity of capital is greater than that of resources, the substitution offsets the problem posed by the depletion of exhaustible resources. The condition is satisfied because the empirical evidences shows that the productivity of capital is as about four times large as that of resources (Solow, 1974b; Hartwick, 1977; Dasgupta and Heal, 1979). As pointed out by Victor (1991), even though the conclusion Dasgupta and Heal get is too optimistic to be realistic, "it is nevertheless important for all those interested in sustainable development to consider the role of substitution in alleviating the pressures of a diminishing resource base". A few studies that employ a CES production function suggest that the elasticity of substitution between energy and other factors is no more than unity (André and Smulders, 2004; Nakada, 2005; Bretschger and Smulders, 2006). But the empirical examinations state that the assumption of smooth substitution is not hard to realize, especially in the energy industries. With annual time series data for the Canadian metal mining industry for 1954 through 1974, it is shown that the elasticity of substitution between reproducible inputs (capital) and the natural resource, metallic ores are equal to unity (Halvorson and Smith, 1986). This study follows the suggestion of perfect substitution, and assumes the substitution is supported by the technologies carried out by the R&D sector. It suggests the intermediate goods are produced by a Cobb-Douglas function, which allows the elasticity of substitution between capital and energy to be unity.

Meanwhile, many neoclassical analyses contribute to the literature by researching the optimal depletion of exhaustible resources and/or the R&D

for so called “backstop technology” (e.g., solar power, nuclear energy), which provides unlimited resources at a constant cost and supports the economic sustainability (Stiglitz, 1974; Dasgupta and Heal, 1974; Solow, 1974a; Davidson, 1978). For example, a portion of capital is invested for the R&D to obtain a “resource-independent” technology and the R&D activities cease at the time when the new technology presents (Davidson, 1978). But a more important contribution of Davidson’s work is the idea of capital division it suggests.

These neoclassical resource-and-growth models have a common shortcoming that they assume the technological change is exogenous. This drawback is addressed by the endogenous models, which prevail in the 1990s and consider human capital, knowledge spillovers, and constant return to investment as the engines of economic growth. The conventional endogenous R&D model (e.g., Romer, 1990) linked sustained endogenous growth with the idea of expanding product variety. It was extended by examining the innovations as expanding varieties or improvement of quality (Grossman and Helpman, 1991). Though exploring the relationship between endogenous technological changes and the economic growth, these studies do not include energy in their models.

More recently, non-renewable resources are present in various endogenous growth models. The AK approach and Schumpeterian approach connect nonrenewable resources to endogenous growth (Aghion and Howitt, 1998). However, the previous growth models have a common drawback that natural resources neither appear in the “growth engine” (e.g., the education sector producing human capital, the R&D sector providing blueprints), nor act as a necessary ingredient in the production of physical capital which are then used in the R&D sector (Groth and Schou, 2002). They argue that the absence of resources is unlikely, because the educational institutions and research labs use fossil fuels for heating and transportation purposes, or minerals and oil products for machinery, computers, etc. Then their model addresses this shortcoming by applying an increasing return to scale Cobb-Douglas production function with capital, natural resources and increasing labor as inputs.

The conventional R&D model (e.g., Romer, 1990) was extended by assuming energy and physical capital as inputs for intermediate goods (van Zon and Yetkiner, 2003). The model finds that the increasing energy prices erode the profits of producing intermediate goods, discourages the R&D activities, and finally impede the rate of economic growth. Though their model does not include energy as the input for R&D activities, energy contributes to the R&D sector indirectly because the labor doing R&D are compensated by the profit of producing intermediate goods, which use energy as input. At the same time, it breaks the symmetry suggested by the Romer model (1990) and shows an energy-saving technological improvement caused by the growth of energy price. Following van Zon and Yetkiner's suggestion, this study assumes that the intermediate goods are produced by a Cobb-Douglas production function, using raw energy and physical capital as inputs. One may interpret that the "intermediate goods" within this study are actually composite energy services, which are provided by using capital to exploit, extract raw energy. However, unlike the model by van Zon and Yetkiner (2003), the present model follows the symmetry assumption for simplicity.

Furthermore, this study modifies the endogenous R&D model (e.g., Romer, 1990) by introducing the idea of division of capital. Most of the existing R&D models suggest that the capital services of all intermediate goods accumulate the effective capital stock, that is, the whole capital stock only presents in the intermediate goods sector. Nevertheless, it is more realistic to suggest that capital goods might be used in not only the production of intermediate goods but final goods. The suggestion of capital division goes back to researches of the R&D activities for energy (Davison, 1978). It suggests that a proportion of capital is invested for R&D, unlike the previous energy economics literature that usually assumes that the investments for R&D come from forsaking consumption. The present model adopts Davison's assumption — the total capital stock divides into two types of capital: one is used to exploit, extract raw energy, which is used in the production of intermediate goods; the other is invested directly in final good production, in the form of machinery, for example.

By linking energy use and the division of capital with endogenous R&D model, this study gets a result contrasting with the previous literature focusing on energy prices and growth (e.g., van Zon and Yetkiner, 2003). It finds that the growth rate of energy price may stimulate the economic growth. The result consists with the view of “induced technological change” (ITC) or “induced innovation”. The normal ITC models concentrate on the transfer between the normal energy technology and the low-carbon energy technology (or the backstop technology). The main view within ITC models is that energy price shock and policy regulation induce the innovations of energy-related technology. One of empirical evidences is found in the research that examines the effect of energy price shock on the energy-efficient innovations using U.S. patent form 1974 to 1994 (Popp, 2002). It finds that the rising energy prices have strongly significant effect on energy-related innovations. But it is pointed out that the ITC literatures concern the innovation in two ways: one focuses on the learning-by-doing effect, which considers the technological progress as black box and ignores the opportunity cost; the other models the R&D, but this kind of models are outside the general macroeconomic framework (Popp, 2004). This study incorporates the R&D for energy technology within the aggregate economic framework and gets a similar conclusion as conventional ITC models.

3. MODEL

This model considers a closed economy that produces a composite final good. Inputs in the production process are labor, capital and energy, which are denoted by L, K, and E respectively. L is exogenous and constant over time as within the conventional resource economic models. In this study, “energy” may have a broader interpretation, e.g., fuels, precious metals and minerals; and it can be renewable or nonrenewable. It is used in combination with physical capital to produce the intermediate goods. The paper assumes that the quantity (E) and price (p_e) of energy supply are exogenous.

3.1. The Final Output Sector

This study applies a Cobb-Douglas production function for final output. It is linear homogeneous in the production factors labor, energy, and intermediate goods. Capital stock is divided into two classes — the capital invested directly in final good production, K_P, and the capital allocated for intermediate goods, K_D. The total capital stock is represented by $K = K_p + K_D$. Hence the output of a representative firm is:

$$Y = AL_P^{\alpha} K_P^{\beta} \int_0^N x_i^{1-\alpha-\beta}. \tag{1}$$

In equation (1), L_P is the labor allocated for final goods production; x_i is the *i*th intermediate goods; α, β, and $(1-\alpha-\beta)$ are the partial output elasticity (i.e., the marginal productivity of factor input) of L_P, K_P, and x_i respectively; A is an overall measure of productivity; and N denotes the number of innovations. As within literature of energy economics, labor is assumed to be constant over time because the pressure of sustainability eliminates the possibility of an exponential growth of population.

3.2. The Intermediate Goods Sector

A key view within the neoclassical energy economics is that the economic sustainability depends on the degree of substitution between physical capital and energy (or in a broader interpretation, resources) (Victor, 1991). The existing literature indicates that energy is essential for production, that is, the elasticity of substitution between energy and other inputs is less than unity (Dasgupta and Heal, 1974; André and Smulders, 2004; Bretschger and Smulders, 2006). However, energy conservation, energy saving are achieved by substituting capital for energy in general (Nakada, 2005); the present model suggests that the improvements of energy-related technology make the substitution smooth.

Each intermediate goods is produced by a monopolist. Following van Zon and Yetkiner's (2003) model, the present model assumes that the effective services of the intermediate goods are supplied by using K_{Di} and e_i; where K_{Di} and e_i are the capital and raw energy allocated for the *i*th intermediate goods respectively. One may regard the production of x_i as the process of using physical capital to exploit, extract raw energy.

This study assumes that the innovations invented by the R&D sector show the energy technologies that make the substitution between capital and energy easy. Hence the production of x_i is represented by a constant return to scale Cobb-Douglas function:

$$x_i = DK_{Di}^{\delta} e_i^{1-\delta}, \tag{2}$$

where δ measures the partial elasticity of capital, and $(1-\delta)$ is the partial elasticity of raw energy; D denotes the 'total-factor' productivity of capital and raw energy.

Substituting (2) into (1), a final output function with two classes of capital and raw energy, besides labor as inputs is obtained as:

$$Y = AL_P^{\alpha} K_P^{\beta} \int_0^N x_i^{1-\alpha-\beta} = AL_P^{\alpha} K_P^{\beta} \int_0^N (DK_{Di}^{\delta} e_i^{1-\delta})^{1-\alpha-\beta}. \tag{3}$$

The level of demand for each intermediate follows the first order conditions for a profit maximum of the final output sector. Let $\prod_Y$ denote the profit of the representative final-goods producer, it can be given by

$$\prod_Y = Y - wL_P - rK_P - \int_0^N P_{xi} x_i, \tag{4}$$

where w is the wage-rate in the final-goods sector, *r* is the interest rate, P_{xi} represents the price of the effective energy services of the *i*th intermediate goods. And the price of one unit of final output is normalized as 1.

With the perfect competition on the final output market and the factor input markets, the first order conditions for profit maximization are given by

$$\frac{\partial \Pi_Y}{\partial L_P} = \alpha \frac{Y}{L_P} - w = 0, \tag{5}$$

$$\frac{\partial \Pi_Y}{\partial K_P} = \beta \frac{Y}{K_P} - r = 0, \tag{6}$$

$$\frac{\partial \Pi_Y}{\partial x_i} = (1-\alpha-\beta) A L_P^{\alpha} K_P^{\beta} x_i^{-\alpha-\beta} - P_{xi} = 0. \tag{7}$$

Equation (5) and (6) describe that the labor and direct capital input are compensated by their marginal products. This study suggests that the final goods sector determines the interest rate, and the intermediate goods sector takes the interest rate as given.

With (7), the price of x_i is obtained:

$$P_{xi} = (1-\alpha-\beta) A L_P^{\alpha} K_P^{\beta} x_i^{-\alpha-\beta}. \tag{8}$$

Equation (8) also shows the demand for x_i given the price P_{xi} required by the monopolist that provides the *i*th intermediate goods. Each intermediate goods is provided by a monopolist; hence, the firm may require a price higher than the cost of producing x_i.

Given the Cobb-Douglas production function for x_i, the cost of producing x_i is denoted by

$$C_{xi} = rK_{Di} + p_e e_i. \tag{9}$$

To maximize profits, the monopolist providing intermediates should choose the optimal levels of K_{Di} and e_i that would minimize cost at given factor prices. Therefore, the firms solve the following question:

$$\text{Min } C_{xi} = rK_{Di} + p_e e_i \quad \text{s.t. } x_i = DK_{Di}^{\delta} e_i^{1-\delta}. \tag{10}$$

By solving (10), the trade-off between capital and raw energy is showed by

$$e_i = K_{Di}\left(\frac{r}{p_e}\right)\left(\frac{1-\delta}{\delta}\right), \tag{11}$$

$$K_{Di} = e_i\left(\frac{p_e}{r}\right)\left(\frac{\delta}{1-\delta}\right). \tag{12}$$

Equation (11) indicates that an increase in energy price makes the physical capital more attractive, hence the monopolists may minimize their cost to produce intermediate goods by substituting capital for energy; and vice versa.

Substituting equation (11) and (12) into (9), the cost of producing the *i*th intermediate goods is given by

$$C_{x_i} = \frac{1}{D}\left(\frac{r}{\delta}\right)^{\delta}\left(\frac{p_e}{1-\delta}\right)^{1-\delta} x_i. \tag{13}$$

Then the cost for one unit of x_i is represented by $\frac{1}{D}\left(\frac{r}{\delta}\right)^{\delta}\left(\frac{p_e}{1-\delta}\right)^{1-\delta}$. It implies that the rises of interest rate and energy price cause the cost of producing one unit of intermediate goods to grow.

In the intermediate goods sector, the firm solves the profit maximizing problem given equation (8) and (13):

$$\Pi_{xi} = P_{xi}x_i - C_{x_i}. \tag{14}$$

Then the price of the effective services of the *i*th intermediate good — P_{xi} and the level of the intermediate good — x_i are as follows:

$$P_{xi} = \frac{1}{1-\alpha-\beta}\left[\frac{1}{D}\left(\frac{r}{\delta}\right)^{\delta}\left(\frac{P_e}{1-\delta}\right)^{1-\delta}\right], \tag{15}$$

$$x_i = \left[\frac{(1-\alpha-\beta)^2 A L_P^{\alpha} K_P^{\beta}}{\frac{1}{D}\left(\frac{r}{\delta}\right)^{\delta}\left(\frac{P_e}{1-\delta}\right)^{1-\delta}}\right]^{\frac{1}{\alpha+\beta}}. \tag{16}$$

Equations (15) and (16) state that the rising factor prices, would cause the price of intermediate goods to increase, and then reduce the demand for intermediate goods.

The profit of providing x_i is given by

$$\prod_{xi} = (\alpha+\beta)(1-\alpha-\beta)^{\frac{2}{\alpha+\beta}-1}\left[\frac{1}{D}\left(\frac{r}{\delta}\right)^{\delta}\left(\frac{P_e}{1-\delta}\right)^{1-\delta}\right]^{1-\frac{1}{\alpha+\beta}}(AL_P^{\alpha}K_P^{\beta})^{\frac{1}{\alpha+\beta}}. \tag{17}$$

This study follows the symmetry assumption (Romer, 1990) that in equilibrium $x_1 = x_2 = x_3 = ... = x_i$, for $1 \le i \le N$; hence, the final output is represented by $Y = AL_P^{\alpha}K_P^{\beta}Nx_i^{1-\alpha-\beta}$. Therefore the final goods function is obtained by substituting equation (16) into $Y = AL_P^{\alpha}K_P^{\beta}Nx_i^{1-\alpha-\beta}$:

$$Y = (1-\alpha-\beta)^{\frac{2(1-\alpha-\beta)}{\alpha+\beta}}\left[\frac{1}{D}\left(\frac{r}{\delta}\right)^{\delta}\left(\frac{P_e}{1-\delta}\right)^{1-\delta}\right]^{-\left(\frac{1-\alpha-\beta}{\alpha+\beta}\right)} N(AL_P^{\alpha}K_P^{\beta})^{\frac{1}{\alpha+\beta}}. \tag{18}$$

With equation (17) and (18), final output can be represented by

$$Y = \frac{N\prod_{xi}}{(\alpha+\beta)(1-\alpha-\beta)}. \tag{19}$$

Equation (20) implies that the growth rate of output equals the sum of the growth rate of innovations and the growth rate of profits for intermediate goods:

$$\hat{Y} = \hat{N} + \hat{\prod}_{xi}, \tag{20}$$

where a "$\wedge$" denotes the growth rate. The result is consistent to the common notion. Any factor that favors innovations or the oligopolistic rent for providing intermediate goods is likely to promote economic growth. But how the interest rate and energy prices would affect $\hat{N}$ and $\hat{\prod}_{xi}$ is not clear so far. The conventional view is that the rising energy prices deduct the profits of supplying intermediate goods, so energy price shock is harmful to economic growth (van Zon and Yetkiner, 2003). But if the price shock spurs the improvements of energy technology, as ITC models show, the economic growth need not to be hindered.

3.3. The R&D Sector

In the R&D sector, research firms carry out R&D activities for energy-related technologies, which support the smooth substitution between capital and raw energy. The only input for R&D activities is labor L_N (or in a broader interpretation, human capital). As in the literature, the change in inventions will be equal to the number of workers in R&D model times the rate at which these workers develop the inventions:

$$\frac{dN}{dt} = \varphi N L_N = \varphi N(L - L_P) \Rightarrow \hat{N} = \varphi(L - L_P), \tag{21}$$

where φ represents the productivity of the R&D process, while a "$\wedge$" denotes the growth rate.

The R&D activities are compensated by the oligopolistic profits of providing intermediate goods. Note that the flow of the expected profits is the present value of profit flows for the current latest innovation ($\prod_{xi}$) discounted by the interest rate (r) less the expected growth rate of ex-post profit flows ($\hat{\prod}_{xi}$). Therefore, the expected present value of the *i*th innovation is represented by $\prod_{xi}/(r-\hat{\prod}_{xi})$ (van Zon and Yetkiner, 2003). An existing work concentrates on the effect of creative destruction represents the present value of an innovation in the form of $\prod_{xi}/(r+\hat{N})$, but the one this study applies is more straightforward: it implies that if the profit flow of an innovation grows over time, its expected present value would increase (Aghion and Howitt, 1992).

The total cost for R&D is represented by $w_N L_N$, where L_N is the labor allocated for R&D sector, w_N is the wage rate for the workers in R&D sector. Following the free-entry condition of the R&D sector, the cost of doing R&D equals the expected value of the newly developed technologies:

$$w_N L_N = \frac{\prod_{xi}}{r-\hat{\prod}_{xi}}\frac{dN}{dt} = \frac{\prod_{xi}}{r-\hat{\prod}_{xi}}\phi N L_N \Rightarrow w_N = \frac{\prod_{xi}}{r-\hat{\prod}_{xi}}\phi N. \tag{22}$$

Labor market reaches its equilibrium when the labor allocated in final output sector earns the same wage rate as that of labor doing R&D:

$$w_N = w_P = \alpha \frac{Y}{L_P}. \tag{23}$$

With (19), (22) and (23), the labor allocated in final goods sector is obtained as:

$$L_P = \frac{\alpha(r-\hat{\prod}_{xi})}{\phi(\alpha+\beta)(1-\alpha-\beta)}. \tag{24}$$

Equation (24) states that the labor allocated for final good production is negatively affected by the expected growth rate of the profit flow of innovations. As the profit flow rises over time, doing R&D is more attractive, less labor is allocated for the final goods sector.

3.4. The Steady State

This study focuses on the long run status, hence it assumes the steady state exists and pays less attention to the economy along the transition path. If one looks at the adjustment paths leading to long-run equilibrium, factor prices, e.g., the interest rate and the price of energy are allowed to vary. But at the steady state the growth rate of interest is zero, i.e., $\hat{r}=0$ (Romer, 1990; van Zon and Yetkiner, 2003).

The final output function is derived by substituting $K_P=\beta(Y/r)$ into equation (18):

$$Y=GN^{\frac{\alpha+\beta}{\alpha}}r^{-\left[\frac{\beta+\delta(1-\alpha-\beta)}{\alpha}\right]}P_e^{-\left[\frac{(1-\delta)(1-\alpha-\beta)}{\alpha}\right]}L_P, \tag{25}$$

where $G=(1-\alpha-\beta)^{\frac{2(1-\alpha-\beta)}{\alpha}}\left[\frac{1}{D}\left(\frac{1}{\delta}\right)^{\delta}\left(\frac{1}{1-\delta}\right)^{1-\delta}\right]^{-\left(\frac{1-\alpha-\beta}{\alpha}\right)}A^{\frac{1}{\alpha}}\beta^{\frac{\beta}{\alpha}}$. G is constant given the constant values of A, D, α, β, φ and δ.

At the steady state, the rate of interest and labor in the final output sector are constant. With $\hat{L}_P=0$, $\hat{r}=0$ and equation (25), the growth rate of output at steady state can be represented by

$$\hat{Y}=\frac{\alpha+\beta}{\alpha}\hat{N}-\frac{(1-\delta)(1-\alpha-\beta)}{\alpha}\hat{P}_e. \tag{26}$$

It seems that the growth of energy price has a negative effect on economic growth. However, if the energy price shock stimulates the innovations for energy technology, the conclusion is converted.

With equation (20), (21), (24), and (26), the growth rates of output, innovation and profit flow are respectively given by

$$\hat{Y}=\frac{\alpha+\beta}{\alpha}\phi L\left(1+\frac{\beta}{z}\right)-\frac{\alpha+\beta}{z}r-\frac{(1-\delta)(1-\alpha-\beta)}{\alpha}\left(1+\frac{\alpha+\beta}{z}\right)\hat{P}_e, \quad (27)$$

where $z=(\alpha+\beta)(1-\alpha-\beta)-\beta.$

So far this study shows the supply side of the economy; the demand side can be presented by the Ramsey model that solves the problem of maximizing utility of consumption. Assuming the constant relative risk aversion (CRRA) utility function $\left(\text{i.e., } u(c)=\frac{c^{(1-\theta)}-1}{(1-\theta)}, \text{ where } \theta>0\right)$, the individual's utility function takes the form $U=\int_{t=0}^{\infty}e^{-\rho t}u(C(t))dt,$ where ρ is the discount rate, $C(t)$ is the individual's consumption. Following the Ramsey model, the growth rates of output and consumption are given by

$$\hat{Y}=\hat{C}=\frac{r-\rho}{\theta}. \quad (28)$$

In equation (28), $\sigma=1/\theta$ represents the elasticity of substitution between consumption at any two points in time.

Hence with equation (27) and (28), the interest rate, the growth rates of output, innovations and profits of producing intermediate goods at the steady state are obtained as follows:

$$r^{*}=\left(\frac{\theta}{z+\theta(\alpha+\beta)}\right)\cdot \left[\frac{\alpha+\beta}{\alpha}\phi L(z+\beta)-\frac{(1-\delta)(1-\alpha-\beta)}{\alpha}(z+\alpha+\beta)\hat{P}_e+\frac{z\rho}{\theta}\right], \quad (29)$$

$$\hat{Y}^* = \left(\frac{1}{z+\theta(\alpha+\beta)}\right) \cdot \left[\frac{\alpha+\beta}{\alpha}\phi L(z+\beta) - \frac{(1-\delta)(1-\alpha-\beta)}{\alpha}(z+\alpha+\beta)\hat{P}_e - (\alpha+\beta)\rho\right], \tag{30}$$

$$\hat{N}^* = \left(\frac{1}{z+\theta(\alpha+\beta)}\right)[\phi L(z+\beta) + (1-\delta)(1-\alpha-\beta)(\theta-1)\hat{P}_e - \alpha\rho], \tag{31}$$

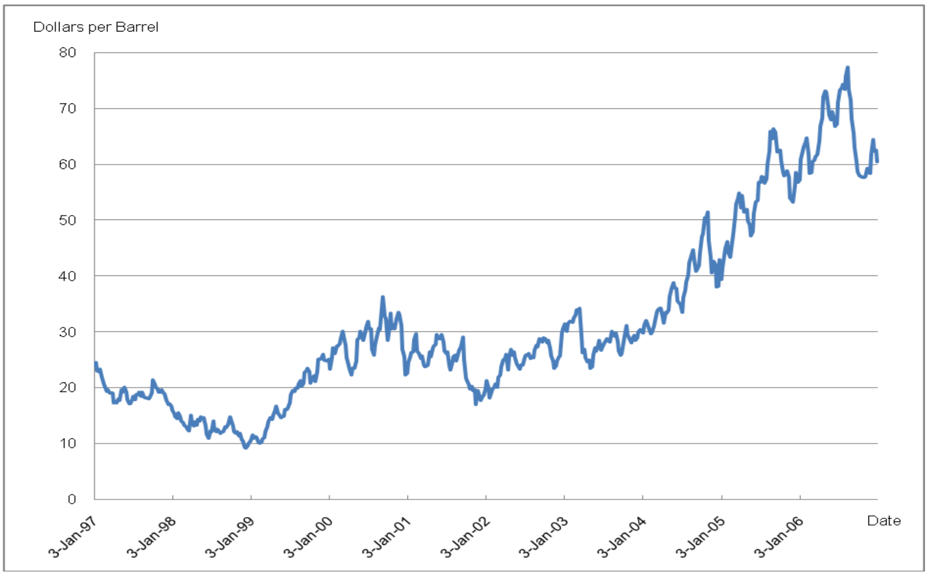
$$\hat{\Pi}^*_{xi} = \left(\frac{1}{z+\theta(\alpha+\beta)}\right) \cdot \left[\frac{\beta}{\alpha}\phi L(z+\beta) - \frac{(1-\delta)(1-\alpha-\beta)}{\alpha}(z+\beta+\alpha\theta)\hat{P}_e - \beta\rho\right]. \tag{32}$$

Within the endogenous growth literatures that focus on R&D effect, the increase in factor prices usually discourage economic growth (Romer, 1990; van Zon and Yetkiner, 2003). The reason is that the rising factor prices (e.g., interest rate and energy prices) erode the pay back of doing R&D, and then impede economic growth. But the present paper needs not to follow the previous views. Given $1-\delta>0$, $1-\alpha-\beta>0$, and $z+\alpha+\beta = (\alpha+\beta)(1-\alpha-\beta)+\alpha>0$, equation (30) shows that whether the growth rate of energy prices has positive or negative impact on the rate of economic growth depends on the sigh of $z+\theta(\alpha+\beta)$, or in others words, depends on the values of α, β, and θ. Section 3.5 presents how the values of α, β, and θ affect the sign of $d\hat{Y}/d\hat{P}_e$ (i.e., how energy price increases affect the growth rate of output).

3.5. Discussions

Figure 1 presents the world prices of crude oil from 1997 to 2006. It shows that the prices keep rising, especially since 2003. The price reached a new

Figure 1 Brent Crude Oil Price (1997.1.3-2006.12.29)



Source: Energy Information Administration.

historical high on July 14, 2006 (76.80$/Barrel, Cushing, OK WTI Spot Price FOB; 76.13$/Barrel, Europe Brent Spot Price FOB; source: EIA). Notwithstanding the increasing energy prices, world output growth rate is not bad: 5.3% for 2004, 4.8% for 2005, and 4.9% for 2006 (projected) (*World Economic Outlook Globalization and Inflation*, April 2006, IMF). Other than applying an econometric approach, the present paper sets values for parameters and discusses how the growth rate of energy prices affect the rate of output growth.

Before it sets the values for parameters, this study reviews the values that are used in previous literature. Frequently, in a constant return to scale Cobb-Douglas production function with labor and capital as inputs (e.g., $Y = AL^{\alpha}K^{\beta}$; K is the capital and L is the labor, including human capital, α and β are the partial output elasticity of capital and labor respectively and A is the overall measure of productivity), the values of parameters used are $\alpha = 2/3$ and $\beta = 1/3$ (Barro and Sala-i-Martin, 1995), the output elasticity of labor is about two times of that of capital. In the cases that resources (or energy) are included in the production function (e.g., $Y = AL^{\alpha}K^{\beta}E^{1-\alpha-\beta}$), the existing literatures suggest that the productivity of capital is as about four times large as that of resources (Solow, 1974b; Hartwick, 1977; Dasgupta and Heal, 1979). An econometric estimation by Slade (1987) reports that output share of capital and that of resources are approximately equal. But Neumayer (2000) suggests that the share of capital is considerably higher than that of resources; Slade ignores the intermediate goods that are produced by capital, and gets the inaccurate result. In an article considering two models of energy use and using annual data for the U.S. economy for the period 1960-1994 (Atkeson and J. Kehoe, 1999), the output elasticities with respect to labor, capital and energy are 0.57, 0.387, and 0.043 respectively. A more current study applying an increasing return to scale production function (Groth and Schou, 2002) suggests a case in which the output elasticity of energy can be a larger value (greater than 0.05), if the environment is considered. However, this study uses a constant return in scale; the output elasticity of energy cannot be a very large value.

Hence, summing the suggestions of Dasgupta and Heal (1979), Barro and Sala-i-Martin (1995), Atkeson and Kehoe (1999), Groth and Schou (2002), this study sets the baseline values of parameters as follows: $\alpha = 0.6$, $\beta = 0.3$. And the output elasticity for the intermediate goods is 0.1.

At the equilibrium, the final output function that is used in this study is rewritten as $Y = AL_P^{\alpha}K_P^{\beta}ND^{1-\alpha-\beta}K_{Di}^{\delta(1-\alpha-\beta)}e_i^{(1-\delta)(1-\alpha-\beta)}$; hence, the output elasticity with respect to energy is represented by $(1-\delta)(1-\alpha-\beta)$. Given $\alpha = 0.6$, $\beta = 0.3$, and $0 < 1-\delta < 1$, the range of $(1-\delta)(1-\alpha-\beta)$ is 0~0.1, which reconciles the values reported by literature. Since the sign of $z + \theta(\alpha+\beta)$, which this study is going to discuss in this section, is independent on the value of δ, this study supposes that δ is constant. One might expect that a higher/lower $(1-\alpha-\beta)$ leads to a higher/lower output elasticity of energy. Hence, for simplicity, this study uses $(1-\alpha-\beta)$ rather than $(1-\delta)(1-\alpha-\beta)$ to represent the output elasticity of energy. Furthermore, since this study concentrates on the substitution between capital and energy, it suggests that α is fixed, and discusses the

Table 1 Effects of the Values of Output Elasticities of Labor, Capital and Energy with $\sigma = 5$

Cases	$\frac{d\hat{N}}{d\hat{P}_e}$	$\frac{d\hat{\prod}_{xi}}{d\hat{P}_e}$	$\frac{d\hat{Y}}{d\hat{P}_e}$
Baseline $\alpha = 0.6,\ \beta = 0.3,\ \sigma = 5$	+	+	+
Higher output elasticity of capital, β Fixed σ and output elasticity of labor $\alpha = 0.6,\ \beta = 0.35,\ \sigma = 5$	+	+	+
Lower output elasticity of capital, β Fixed σ and output elasticity of labor $\alpha = 0.6,\ \beta = 0.25,\ \sigma = 5$ $\alpha = 0.6,\ \beta = 0.20,\ \sigma = 5$	– –	– –	– –

trade-off between β and $(1-\alpha-\beta)$, which may cause a greater of smaller output elasticity of energy.

Although the literatures set lower value for $\sigma(\sigma = (1/\theta))$, e.g., $\sigma = 0.5$ (Barro and Sala-i-Martin, 1995), $0.33 < \sigma < 0.9$ (Fullerton and Kim, 2006), this study chooses a higher value for σ. It suggests that the society requires a sufficiently large intertemporal substitution elasticity to postpone current consumption, investing more for production to overcome the negative impact of the increasing energy prices. It is obvious that if σ is only 1, definitely the sign of $z + \theta(\alpha + \beta)$ is positive, which implies that the society could not deal with the energy shocks. Therefore, the baseline value for σ is 5 within the present model.

Table 1 summarizes the results under the cases with different values for β given $\alpha = 0.6$ and $\sigma = 5$. In the table, '+' and '–' represent the sign of $d\hat{Y}/d\hat{P}_e$, $d\hat{N}/d\hat{P}_e$, and $d\hat{\prod}_{xi}/d\hat{P}_e$. The baseline case shows that the growth rate of energy prices is possibly to stimulate economic growth, because it has positive impacts on innovations and the profits for doing R&D.

Table 2 Effects of the Value of σ given $\alpha = 0.6$ and $\beta = 0.3$

Cases	$\frac{d\hat{N}}{d\hat{P}_e}$	$\frac{d\,\hat{\Pi}_{xi}}{d\hat{P}_e}$	$\frac{d\hat{Y}}{d\hat{P}_e}$
Baseline $\alpha = 0.6,\ \beta = 0.3,\ \sigma = 5$	+	+	+
Higher output elasticity of energy, σ Fixed output elasticities of labor and capital $\alpha = 0.6,\ \beta = 0.3,\ \sigma = 6$	+	+	+
Lower output elasticity of energy, σ Fixed output elasticities of labor and capital $\alpha = 0.6,\ \beta = 0.3,\ \sigma = 4$ $\alpha = 0.6,\ \beta = 0.3,\ \sigma = 3$	– –	– –	– –

In the case that the output elasticity of energy is sufficient small (low $(1-\alpha-\beta)$ given δ is fixed), energy is not so crucial to production. On the other hand, if the output elasticity of energy is sufficiently large, the continuously increasing prices of energy are harmful to the growth rate of output.

Table 2 summarizes the results of the cases with different values of σ given $\alpha = 0.6$ and $\beta = 0.3$. In the present model, σ represents the intertemporal substitution elasticity. A higher σ implies that consumers put a lower weight on smoothing utility over time, and are more willing to postpone consumption to a later date. Hence, the society would invest more in production, and anticipate a higher rate of economic growth in the future. The baseline case shows that given a sufficiently high value of σ, the growth rate of energy prices may has positive effect on the rate of economic growth, because it favorites innovations and increases the profits for producing innovations. In the case that the intertemporal substitution elasticity is low ($\sigma = 4,\ 3,\ 2,\ 1...$), the substitution between consumption at any two points in time is relatively difficult. In such cases, the investment, and then the economic growth are impeded by the growth rate of energy prices.

Comparing to the baseline values, one may find that if $(1-\alpha-\beta)$ is lower, say, 0.05, the value of $1/\sigma$ required to hold $z+\theta(\alpha+\beta)<0$ and $(d\hat{Y}/d\hat{P}_e)>0$ is lower ($\sigma>2.98$). On the other hand, if σ is larger, say, 6, $(d\hat{Y}/d\hat{P}_e)>0$ is held even though $(1-\alpha-\beta)$ is 0.13. It implies that if a society has a low output elasticity of raw energy, relatively lower intertemporal substitution elasticity is required to sustain economic growth under the shock of energy price. If a society puts a low weight on smoothing utility over time and are eager to anticipate future gains by decreasing current consumption and investing, energy price shock would not obstruct the rate of economic growth, even if the output elasticity of raw energy is high and vice versa.

So far, this study shows that if σ is sufficiently large, $(1-\alpha-\beta)$ is sufficiently small, or both conditions are held, one may get $z+\theta(\alpha+\beta)<0$, where $z=(\alpha+\beta)(1-\alpha-\beta)-\beta$. Hence, $(d\hat{Y}/d\hat{P}_e)>0$, $(d\hat{N}/d\hat{P}_e)>0$, and $(d\hat{\prod}_{xi}/d\hat{P}_e)>0$ are obtained. It implies that the rate of economic growth may depend positively on the rate of growth of energy prices, suggesting that the continuously rising energy prices will tend to spur economic growth. The result contrasts with the modern endogenous growth literature. However, the result verifies the view of ITC: to counteract the energy price impact, more inputs are allocated for R&D, which supply the technology to alleviate the negative effect of price shock; therefore, more innovations are created and the economic growth is accelerated.

This study finds that the growth rate of energy prices does not need to impede the rate of economic growth. It applies a Cobb-Douglas production function that allows smooth substitution between different factors. As the price of raw energy rises, within the intermediate goods sector, the firms substitute capital for raw energy; while in the final goods sector, the firms substitute capital for intermediate goods. However, three conditions have to be met to avoid the crisis caused by energy price shock: first, the partial output elasticity of energy should be sufficiently small; secondly, the elasticity of substitution between consumption at any two points in time, σ, is sufficiently high; finally, the growth rate of energy prices should not be too high for the following reason:

The labor allocated for the R&D sector is given by

$$L_P = \frac{1}{z+\theta(\alpha+\beta)}\left[L(\theta(\alpha+\beta)-\beta) - \frac{(1-\delta)(1-\alpha-\beta)(\theta-1)}{\phi}\hat{P}_e + \frac{\alpha}{\phi}\rho\right]. \quad (33)$$

Given the baseline values for parameters that is used within the present paper, one might get $z+\theta(\alpha+\beta)<0$, $(1-\delta)(1-\alpha-\beta)>0$, and $\theta-1<0$. Hence, equation (33) implies that $(dL_P / d\hat{P}_e)<0$ can be held. As $\hat{P}_e$ keeps increasing, more and more labor are allocated for R&D activities to overcome the negative impact of continuously rising energy prices, the labor allocated for the final output sector would be close to zero; and then the economy is broken down because labor is essential to the production of final goods. Note that the domain of L_P should be $L>L_P>0$.

4. THE POLICY IMPLICATIONS

A common view within the endogenous growth literature is that interest income taxes discourage economic growth while investment subsidies promote economic growth (Lucas, 1990; King and Rebelo, 1990; Rebelo, 1991; Jones *et al*., 1993; Barro and Sala-i-Martin, 1995; Stokey and Rebelo, 1995; Milesi-Ferretti and Roubini, 1998; Aghion and Howitt, 1998). By introducing the idea of capital division and including energy into the production of intermediate goods, this study shows that the common view may be held but some conditions are required.

The impacts of energy conservation policies have been discussed for a long time. There are disagreements as to the sign of the effects: one side holds that imposing taxes on energy use (e.g., a carbon tax) works as increasing energy prices, which lowers the profits of using new intermediate goods and the profits of doing research, therefore impedes the growth rate of output (Smulders and de Nooij, 2003; van Zon and Yetkiner, 2003). But the studies focusing on ITC have reported that environmental policies induce the improvements of energy-related technologies that make the regulations less costly (Lanjouw and Mody, 1996; Jaffe and Palmer, 1997; Newell, Jaffe, and Stavins, 1999; Popp, 2002 and 2004). Within the framework of endogenous R&D growth, the present model gets the similar result as that of ITC models, but it also indicates that the energy conservation tax promotes economic growth only if the tax rate is increasing over time, and the values of ($\alpha+\beta$), and σ are sufficiently high.

In general, energy conservation is achieved by substituting capital for energy (Nakada, 2005). Therefore, this study suggests a conservation policy that taxes energy consumption and subsidizes capital use. The tax rate is $\tau(\tau > 0)$; let $\tau' = (1+\tau)$, then the cost of using one unit of energy after tax is represented by $\tau' P_e$. Note that the present model suggests that the tax rate can be time-varying, that is, $\hat{\tau}' = 0$ is not required. This study demonstrates that such a tax promotes economic growth as it finds there is a positively sloped relation between the rate of economic growth and the growth rate of energy prices (given $\alpha+\beta$ and σ are high enough to ensure $z+\theta(\alpha+\beta) < 0$). A time-increasing energy tax works as a device that accelerates the growth rate of energy prices.

Similarly, the subsidy rate is $s(s > 0)$; let $s' = 1+s$, so the cost of using one unit of capital is $s'r$. This study assumes that $\hat{s}' = 0$ is not necessary to be held. The budget constraint is given by $\tau P_e E + T = srK$, where *T* is a lump sum tax (amounting to a transfer, if negative).

Under the regulation, the demand for the *i*th intermediate goods and the profit of providing the *i*th intermediate goods are given as follows:

$$x_i = \left[\frac{(1-\alpha-\beta)^2 A L_P{}^{\alpha} K_P{}^{\beta}}{\frac{1}{D}\left(\frac{(1+\tau)P_e}{1-\delta}\right)^{1-\delta}\left(\frac{(1-s)r}{\delta}\right)^{\delta}} \right]^{\frac{1}{\alpha+\beta}}, \tag{34}$$

$$\Pi_{xi} = \left((\alpha+\beta)(1-\alpha-\beta)^{\frac{2}{\alpha+\beta}-1} \left(AL_P{}^{\alpha} K_P{}^{\beta} \right)^{\frac{1}{\alpha+\beta}} \right) \cdot \left[\frac{1}{D} \left(\frac{(1+\tau)P_e}{1-\delta} \right)^{1-\delta} \left(\frac{(1-s)r}{\delta} \right)^{\delta} \right]^{1-\frac{1}{\alpha+\beta}} . \quad (35)$$

Following the process presented before to derive economic growth, the new economic growth rate under the regulation is given by

$$\hat{Y} = \frac{\alpha+\beta}{\alpha}\phi L\left(1+\frac{\beta}{z}\right) - \frac{\alpha+\beta}{z} r - \frac{(1-\alpha-\beta)}{\alpha}\left(1+\frac{\alpha+\beta}{z}\right)[(1-\delta)(\hat{\tau}'+\hat{P}_e)+\delta\hat{s}']. \quad (36)$$

The return of capital is shown by $r = \beta(Y / K_P)$; hence the demand side of the economy is represented by $\hat{Y} = (r-\rho)/\theta$. Substituting it into equation (36), the long run interest rate and the growth rate of output under the regulation are obtained

$$r^{**} = \left(\frac{\theta}{z+\theta(\alpha+\beta)} \right) \cdot \left[\frac{\alpha+\beta}{\alpha}\phi L(z+\beta) - \frac{(z+\alpha+\beta)(1-\alpha-\beta)}{\alpha}[(1-\delta)(\hat{\tau}'+\hat{P}_e)+\delta\hat{s}'] + \frac{z\rho}{\theta} \right], \quad (37)$$

$$\hat{Y}^{**} = \left(\frac{1}{z+\theta(\alpha+\beta)} \right) \cdot \left[\frac{\alpha+\beta}{\alpha}\phi L(z+\beta) - \frac{(z+\alpha+\beta)(1-\alpha-\beta)}{\alpha}[(1-\delta)(\hat{\tau}'+\hat{P}_e)+\delta\hat{s}'] - (\alpha+\beta)\rho \right]. \quad (38)$$

Equation (38) shows the effects of capital subsidy and energy tax on the growth rate of output. It implies that the subsidy and tax do not affect long run rate of economic growth unless their rates are time-varying.

As the discussions in section 3.5, given a sufficiently low value for $(1-\alpha-\beta)$ or a sufficiently high σ or both, $z+\theta(\alpha+\beta)<0$ is obtained; hence, $(d\hat{Y}^{**}/d\hat{P}_e)>0$, $(d\hat{Y}^{**}/d\hat{\tau}')>0$, $(d\hat{Y}^{**}/d\hat{\tau})>0$ (note that $\tau'=1+\tau$), $(d\hat{Y}^{**}/d\hat{s}')>0$ and $(d\hat{Y}^{**}/d\hat{s})<0$ (note that $s'=1-s$). In this case, the tax for energy use promotes the growth rate of output. The reason lies in that the energy conservation policy has two kinds of effects: the tax causes the cost of producing the intermediate goods to rise, and hence reduces the demand for the composite energy services provided by the intermediates; on the other hand, the tax means the real energy price grows, and then stimulates the innovations. Given low $(1-\alpha-\beta)$ and/or high σ, the positive impact overcomes the negative one; a higher growth rate of output is obtained. However, the subsidy for capital has a negative effect in this case. Therefore, in the case that the effect of induced technological change (caused by energy price shock) dominates, an increasing tax on energy use and a constant subsidy for capital use are called for.

Similarly, if $z+\theta(\alpha+\beta)>0$, equation (38) implies that $(d\hat{Y}^{**}/d\hat{P}_e)<0$, $(d\hat{Y}^{**}/d\hat{\tau}')<0$, $(d\hat{Y}^{**}/d\hat{\tau})<0$, $(d\hat{Y}^{**}/d\hat{s}')<0$, and $(d\hat{Y}^{**}/d\hat{s})>0$. In this case, the increasing subsidy on capital use results in a higher growth rate of output. On the contrary, the energy tax has a negative effect on the growth rate of output. The reason lies in that in this case, the contribution of energy to output is large; and the energy tax are transferred into corresponding output shock through the channel of energy use in the intermediate goods sector, and the composite energy services in the final output level. Therefore, if $z+\theta(\alpha+\beta)>0$, the policy maker should apply an increasing subsidy for capital use and a constant tax rate for energy use.

Note that the subsidy for capital use and the tax on energy consumption should be moderate even though they might favor the rate of economic growth. The reason lies in that the subsidy and the tax may have negative impacts on labor allocated in the final output sector as follow:

$$L_P = \left(\frac{1}{z + \theta(\alpha + \beta)} \right) \cdot \left[L(\theta(\alpha + \beta) - \beta) - \frac{(1 - \alpha - \beta)(\theta - 1)}{\phi} [(1 - \delta)(\hat{\tau}' + \hat{P}_e) + \delta \hat{s}'] + \frac{\alpha}{\phi} \rho \right]. \quad (39)$$

In the case that $z + \theta(\alpha + \beta) < 0$, $(dL_P / d\hat{\tau}) < 0$ is held,; while if $z + \theta(\alpha + \beta) > 0$, $(dL_P / d\hat{s}) < 0$. An extremely high tax/subsidy rate results in insufficient labor is allocated for the final output sector and destroys the economy; therefore, a moderate policy is called for.

5. CONCLUDING REMARKS

This study links energy use and the division of capital stock with endogenous R&D model. The conventional endogenous R&D model (Romer, 1990) is modified by including energy use in the production of intermediate goods; meanwhile, capital is divided into two classes — one is invested in final goods sector directly, the other is allocated for the production of intermediate goods. It assumes that the energy-related innovations carried by the R&D sector support the smooth substitution between capital and energy, hence both intermediate and final goods production sectors apply the Cobb-Douglas production function.

Contrasting with the existing literature, the present model finds that the growth rate of energy prices needs not to impede the rate of output growth. If the partial output elasticity of energy is sufficiently low or the elasticity of substitution of consumption between any two points in time is sufficiently large, or both conditions are satisfied, the continuously increasing energy price has an effect similar to so called induced technological change (ITC), which spurs the innovations for energy technology and then promotes the rate of economic growth.

For the sake of energy conservation, this study suggests a policy that imposes a tax on energy use and subsidizes capital use. Unlike existing literature asserting that capital subsidy stimulates economic growth, this study finds that such a subsidy works only if it is time-varying, and the output elasticity of energy is high, and/or the elasticity of intertemporal substitution is low. If the conditions are not met, an increasing energy conservation tax and a constant capital subsidy rate are required to stimulate innovations, and then favor the growth rate of output. Besides, the policy should be moderate, because the high energy tax or capital subsidy rate causes more and more labor to enter the R&D sector and therefore the labor in the final output sector is insufficient.

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