Examining a Green Growth Model for Policy Implications

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Utilizing a simple growth model that includes the energy resource as an essential input, the possibility of a cleaner environment as well as larger income is demonstrated. Growth rates need not be lowered to have a cleaner environment, and the energy output ratio may be reduced. Pollution generated as side effects makes it necessary for policy makers to come up with suitable policies. In this regard, several policy options are proposed. Pollution tax (more generally, an environment tax) and a subsidy for energy and anti-pollution (environment) related technological progresses are such examples. A judicious mix of those policies can make income larger, energy usage smaller, and pollution level lower.

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I. Introduction

Is it possible to achieve increases in income without compromising (or, better still, while improving) environmental qualities? Are lower growth rates an unavoidable price to pay to have a better environment? Is ever increasing energy input needed to sustain economic growth? Mixed views exist on these issues.

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Regarding the first question, two opposing views are observed. One group of scholars (notably, environmentalists) argues that environmental values are routinely sacrificed in the pursuit of greater wealth, which, they argue, is wrong. They would rather pursue no growth or negative growth goals to better promote environmental values (Meadows *et al.* 2004). As evidence for the seemingly inevitable trade-off between growth and environment, they cite the finding that when countries start to grow vigorously, their environments tend to deteriorate very rapidly. The other group (notably, economists), however, argues that growth need not be sacrificed to better protect the environment. They point out that once past the threshold level, further income growth is accompanied by a steady improvement in the environment. Thus, they argue, advanced countries have not only higher income, but also a cleaner environment.[1]

Regarding the second question, environmentalists as well as economists acknowledge a negative relation between environmental qualities and growth rates. Countries with above average growth rates tend to have environments worse than average, and countries with environments better than average tend to have lower than average growth rates. Although they agree on the observation, their interpretations are different. Environmentalists consider the relation as causal; lower growth rates lead to cleaner environment. If we want to have cleaner environment, they argue that we must prepare to accept lower growth rates (Daly and Townsend 1993; Norton 2005). Economists regard this observation as just a correlation, and do not attribute causal relations to them. As such, they contend that lower growth rates do not necessarily lead to a cleaner environment, nor does pursuing a cleaner environment necessitate lower growth rates (Ekins 2000; Lee 2010).

Regarding the third issue, most scholars agree that income growth necessitates an increased usage of resources, that most of these resources are non-renewable hence exhaustible, and that someday they may run out. The possibility for resources to run out impels scholars to seek solutions. Again, there are different views on this issue. Most economists seek ways to reduce resource usages, to better utilize resources, and to come up with alternative and possibly renewable resources. They do not see the urgent need to forego economic growth (Chung and Quah 2010). However, most environmentalists see the situation as one more

[1] In terms of the environmental Kuznets curve, environmentalists seem to focus on the initial phase, whereas economists seem to focus on the latter phase, of income growth.

reason for pursuing moderate or negative growth strategies. They suggest that we cannot avoid resource shortages, unless we forego growth targets (see Meadows *et al.* 2004; Ehrlich and Ehrlich 2008).

Resource usage, particularly the use of fossil fuels, entails additional problems: They emit greenhouse gases. Accumulation of greenhouse gases, if unchecked in time, could lead to global warming, which may cause severe weather disasters. Many scholars argue that this phenomenon may upset the global climate system and seriously disrupt human lives. (For greenhouse gas problems in East Asia, see Iwami 2004.) Hence, they argue, dire needs to cut them down. But how can we do that? Economists propose to reduce fossil fuels uses, to better utilize them, and to come up with less (or no) greenhouse gas emitting alternatives. But environmentalists argue, yet again, that unless we forego growth targets, we cannot solve greenhouse gas problems. (For skeptical views on this, see Lomborg 1998.)

This is the second in a series of papers that deals with the aforementioned issues in a unified framework. The first (Lee 2010), considers choice problems for decentralized agents who treat pollution as purely external. The present paper considers choice problems for a social planner who fully internalizes pollution. As both papers utilize identical frameworks, implications regarding growth and environment that we derive from them are the same. They demonstrate the possibility of achieving income growth without sacrificing environmental values, that there is no need to accept lower growth rates even when we aim for a cleaner environment, and that we can deal with greenhouse gas issues without sacrificing income growth targets. These implications are derived with a growth model in which energy resources play two roles: good and bad. The energy resources help produce outputs (good), but their use entails pollution (bad).

Of course, not everything is identical. First of all, the resulting resource allocations are different. For example, when pollution is internalized, the per capita energy inputs, the per capita income, and the capita pollution all become smaller. However, the per capita green GDP, which is defined as the per capita income minus the per capita pollution, becomes larger. Although both output and pollution decrease, pollution decreases much more than income does.[2]

More importantly, in this study, we can discuss policy options that would induce citizens to fully internalize pollution. What is needed is to

[2] Here we assume that pollution is measured in units of output.

get the prices of environmental resources correct. This move is necessary to redress "market failures" owing to externalities, tragedy of commons problems, and public goods aspects, associated with the use of environmental resources. Getting the prices correct can be done directly by imposing taxes a la Pigou on the use of environmental resources. Otherwise, the procedure can be done indirectly by promoting the development of energy-related and/or pollution-related technologies.

The most important finding of our research is that, when we get the prices correct with appropriate taxes and, utilizing the tax revenues, when we foster the development of output production technologies, energy-related technologies, and pollution- (or more generally, environment-) related technologies, we can make income larger, energy input smaller, and pollution level lower.

The current study has the following components. In Chapter II, we propose a dynamic model of green growth and derive two alternative growth paths. One is a growth path derived under the assumption that agents behave as if pollution is completely external to their decision problems. The other is a growth path derived under the assumption that agents behave as if pollution is completely internal to their decision problems. In Chapter III, we discuss the aspects in which the two alternatives are similar or dissimilar. In Chapter IV, a key chapter of this study, we investigate several policy alternatives that would induce agents to behave as if they are de facto fully internalizing pollution. Getting the prices right, promoting green R&D, imposing an eco-tax, subsidizing less polluting factors of input, and outright restrictions are policy alternatives we consider. Chapter V concludes the study.

II. A Model of Green Growth

This chapter investigates the kinds of steady state growth paths we can derive in a model where physical capital, human capital, and energy resources are indispensable factors of input. One essential aspect to consider here is the fact that the use of energy resources generates pollution.

The important issue is not the fact that pollution is generated, but how pollution is treated by agents. If pollution is perceived by agents as completely external, they would not do anything about it. Consequently, they would use too much energy resources, and thereby would experience too much pollution. Citizens would likely behave in such a manner.

However, the public agents who are supposed to design and implement socially desirable policies cannot do the same. They must take pollution into account. If they do so and their policies are effective, a smaller amount of energy use and a smaller amount of pollution would result. The goal of the current paper is to propose the simplest possible growth model that can exhibit such outcomes.

The present model, which investigates the dynamic relationship between economic growth and environment by focusing on energy use and the pollution generated from this use, is only a small example of the general class of models on economic growth and environment. More general models would treat physical, human, and environmental capital as state variables, and study how these state variables would behave as agents make relevant decisions for production, consumption, and investment.[3]

Environmental capital refers to natural objects, such as forest, soil, water, air, and mineral resources. Climate and geographical conditions of a country are also important constituents of environmental capital.

If the environmental capital is taken as a state variable, its evolution over time must be specified. The environmental capital of a country would change over time as a result of depletion and regeneration, use and destruction, and repair and investment. If the reduction of the environmental capital due to depletion, destruction, and use is larger than the addition *via* regeneration, repair, and investment, the stock of environmental capital would decline over time. In this case, the possibility that the environmental capital might run out should be a concern. Pollution tends to hasten the depletion process by making a substantial portion of the environmental capital less usable.

Our model is much simpler in that we focus on one component of the environmental capital, energy resources, and we assume that one can buy any amount of energy resources in the global market. As we study the green growth problem of a small open economy, our problem is vastly simpler than the problems dealt with in more general models.[4]

[3] Many papers deal with economic growth and environment. See Taylor and Brock (2005) for an intelligent survey of recent literature.

[4] See also Grossman and Krueger (1995), Kim (1996), and Stokey (1998) for a few examples of green growth models.

A. Setup of the Model[5]

(a) Brief Description of Economic Activities

Consider an economy that consists of a large number of households and firms. Households determine how much to work, consume, and save. Firms decide how much to procure, produce, and invest. What firms buy as inputs is supplied by households (human capital and physical capital). What firms produce is sold to other consumers as consumption goods and capital goods.

Firms produce outputs using physical capital, human capital, and energy inputs, and sell the products to households. The physical capital and human capital are rented from households, and energy inputs are purchased in the global market.

Households lease physical capital and human capital to firms and, in return, get labor income and asset income. With this income, households buy consumption goods and capital goods. Buying capital goods in this case amounts to household savings. Households use human capital for two purposes: to lease it to firms, and use it to accumulate human capital. From the portion leased to firms, households get current income. From the portion used for human capital accumulation, households get future income.

From the revenue made, firms first pay the costs of energy purchased in the global markets. From the remainder, firms pay the rental fees for the physical capital and human capital leased from the households. Profits, if any, are also returned to the households as dividends. As a result, the total revenue minus the energy cost is nothing but the income of households. Households use this income for consumption and savings/investment.

Four markets are in operation here: a market for human capital, physical capital, energy inputs, and outputs. The energy market is external to the economy. The other three markets are competitively operated. When we normalize output price, we have real wage and real interest rate as endogenous prices to determine. We do not consider international trade, except for the importation of the energy inputs. Until we study the public choice problems, we do not include a government in our model.

Three time-varying components exist in the economy. First, population grows at the rate of n. Second, human capital grows as a result of human capital investment. Third, physical capital grows as a result of physical

[5] The model and the procedure to derive the balanced growth solutions are essentially the same as those obtained in Lee (2010).

capital investment. In addition, technological progress may be included. However, for simplicity, we assume the level of technology as fixed and given. The total income of the economy would grow as a result of the growth in physical capital per person, human capital per person, and the population. The per capita income would grow as a result of the growth in physical capital per person and human capital per person.[6]

(b) Decision Problem of Households

Each household has $L(t)$ members. Each member "owns" human capital $h(t)$, and hence the total owned by a household is $H(t)=h(t)L(t)$. (We will drop the time variable "t," unless it is needed explicitly.) The human capital is attached to the worker, and the two cannot be separated. That is, h is used always together with L. (In principle many households exist. Nevertheless, without loss of generality, we normalize households to one.) The member of households L, which is the population when the normalization is made, grows at an exogenous population growth rate n.

The household uses its human capital $H=hL$ for two purposes. uhL is leased to firms in return for wages w, and $(1-u)hL$ is used for human capital accumulation. The labor income a household earns is $wuhL$. In addition, the household owns physical capital Q, which the household rents out to firms, and from which the household receives a rental income RQ. The household uses total income $wuhL+RQ$ for consumption C and gross physical capital accumulation $\delta Q+\dot{Q}$. Here δQ is depreciation, and $\dot{Q}$ is net addition to physical capital.

Reflecting these, we can represent the budget constraint of the household as:

$$C+\dot{Q}+\delta Q=RQ+wuhL \tag{1}$$

The human capital of the household grows according to the following:

$$\dot{H}=\xi(1-u)H \tag{2}$$

$(1-u)H$ is the amount of human capital used for human capital accumulation (new human capital is produced using existing human capital as an input), and the parameter ξ stands for the productivity of human capital production. ξ is assumed to be exogenously given. Finally, we assume $0\leq u\leq 1$ and $\xi>0$.

[6] Here we assume that everyone who is alive works.

Finally, the lifetime utility function of the household is specified as follows:

$$\int_0^\infty e^{-\rho t}\frac{c^{1-\theta}-1}{1-\theta}dt \tag{3}$$

We use a conventional constant elasticity of inter-temporal substitution utility function. θ is a parameter related to the elasticity of substitution, and ρ is the time discount rate.

(c) Decision Problem of Firms

A large number of identical firms exist. The production function of the firm j is as follows:

$$Y_j = A_j[K_j^\phi + (B_jX_j)^\phi]^{\frac{\alpha}{\phi}}[(uhL)_j]^{1-\alpha} \tag{4}$$

K_j stands for the physical capital, and X_j for the energy resources used as inputs by the firm j. Likewise, $(uhL)_j$ stands for the human capital input used by the firm j. A_j stands for the productivity of the output production, and B_j for the effectiveness of energy inputs. The larger A_j is, the higher is the output production productivity. Similarly, the higher B_j is, the more effective are the energy inputs. (B_jX_j), not X_j, enters into the production function as inputs.[7] Finally, α and ϕ are parameters of the production function. We assume that $0 \leq \alpha \leq 1$ and $\phi > 0$.

We will use the same functional form for the aggregate production function, as we are not concerned about industrial organization issues. The aggregate production function is given by the following:

$$Y = A[K^\phi + (BX)^\phi]^{\frac{\alpha}{\phi}}[(uhL)]^{1-\alpha} \tag{5}$$

All variables are economy-wide aggregates. For example, A stands for the overall productivity level of the economy, and B stands for the economy-wide productivity related to the efficient use of energy inputs. When A gets larger, an equal amount of inputs would produce a larger amount of outputs. When B gets larger, an equal amount of energy input X would contribute more to output production.

[7] X and BX may be viewed as “raw” and “processed” energy, respectively.

As can be seen from Equation (5), the final output Y is produced using physical capital K, effective (or processed) energy (BX), and human capital uhL. The function is the constant elasticity of substitution in K and BX, and a Cobb-Douglas in the mix of K & (BX) and human capital $uhL=uH$. The production function (5) is constant returns to scale in K, (BX), and L. However, what is used for production is hL and not L. Thus, in terms of K, (BX), L, and h, the production function exhibits an increasing return to scale property.

(d) Pollution

We assume a very simple mechanism for pollution generation. Thus, pollution Z is generated when energy resources are used in production. Pollution is generated not only during the production process, but also during the entire process of production, delivery, and consumption of goods and services. Furthermore, many instances of pollution are being generated during production processes even when resources other than energy are used. Nevertheless, in this paper we assume the following pollution generating function to simplify the discussion:

$$Z = \frac{1}{D} X \tag{6}$$

D indicates the level of technologies regarding pollution prevention and cleanup. The larger D is, the smaller the generation of pollution Z would be from a given amount of energy use X. When we measure Z in units of Y, $Y-Z$ becomes a measure for net outputs. (This is usually called the green GDP.)

B. Derivation of solutions

(a) Decentralized Agents' Problems and Solutions: When Pollution Is Ignored

This part of the problem is identical to that studied in Lee (2010); hence, we will simply state the problem and summarize the steady state solutions. The representative consumer-producer solves the following problem:

$$\text{Max} \int_0^\infty e^{-\tilde{\rho} t} \frac{c^{1-\theta} - 1}{1-\theta} dt \tag{7}$$

Subject to:

$$\dot{k} = A[k^{\phi} + (Bx)^{\phi}]^{\frac{\alpha}{\phi}}(uh)^{1-\alpha} - c - (n+\delta)k - p_x(Bx) \quad (8)$$

$$\dot{h} = [\xi(1-u) - n]h \quad (9)$$

$$c \geqq 0,\ 0 \leqq u \leqq 1 \text{ and } k \geqq 0,\ h \geqq 0 \quad (10)$$

where $\tilde{\rho} = \rho - n > 0$, $0 < \alpha < 1$, θ, ϕ, $\xi > 0$, $A > 0$, $B > 0$, $k(0) > 0$, $h(0) > 0$ are given. The energy price p_x is determined in the global market, hence is given for domestic consumer-producers. The small letters stand for per capita values of each variable. For example, c stands for C/L.

The steady state solutions for the problem are as follows:[8]

$$u^* = \frac{\rho - \xi + \theta\xi - \theta n}{\theta\xi} \quad (11)$$

$$\tilde{c}^* = [\frac{\xi+\delta}{\alpha} + \frac{\rho - \xi}{\theta} - (n+\delta)]\tilde{k}^* \quad (12)$$

$$\tilde{y}^* = [\frac{(\xi+\delta)(1+\eta^*)}{\alpha}]\tilde{k}^* \quad (13)$$

$$\tilde{x}^* = \frac{1}{B}\left(\frac{\xi+\delta}{p_x}\right)^{\frac{1}{1-\phi}}\tilde{k}^* \equiv \frac{1}{B}(\eta^*)^{\frac{1}{\phi}}\tilde{k}^* \quad (14)$$

$$\tilde{k}^* = \left(\frac{\alpha A}{\xi+\delta}\right)^{\frac{1}{1-\alpha}}(1+\eta^*)^{\frac{\alpha-\phi}{\phi(1-\alpha)}}u^* \quad (15)$$

Tilde variables stand for the amount per effective worker. For example, $\tilde{c} = c/h = C/(hL)$. In (13) to (15), the variable η^* is given as follows:

[8] See Lee (2010) for a formal derivation of the solutions.

$$\eta^* = \left(\frac{\xi + \delta}{p_x} \right)^{\frac{\phi}{1-\phi}} \tag{16}$$

Note that η^* is increasing in ξ and decreasing in p_x. Finally, pollution per effective worker, $\tilde{z} = Z/(hL)$, is determined as follows:

$$\tilde{z} = \frac{1}{BD} (\eta^*)^{\frac{1}{\phi}} \tilde{k}^* \tag{17}$$

(b) A Social Planner's Problem and Its Solutions: When Pollution Is Fully Internalized.

A social planner's problem is summarized as follows:

$$\text{Max} \int_0^\infty e^{-\tilde{\rho}t} \frac{c^{1-\theta} - 1}{1-\theta} dt \tag{18}$$

Subject to:

$$\dot{k} = A[k^\phi + (Bx)^\phi]^{\frac{\alpha}{\phi}} (uh)^{1-\alpha} - c - (n+\delta)k - (p_x + \frac{1}{BD})(Bx) \tag{19}$$

$$\dot{h} = [\xi(1-u) - n]h \tag{20}$$

$$c \geqq 0,\ 0 \leqq u \leqq 1 \text{ and } k \geqq 0,\ h \geqq 0 \tag{21}$$

where $\tilde{\rho} = \rho - n > 0$, $0 < \alpha < 1$, θ, ϕ, $\xi > 0$, $A > 0$, $B > 0$, $k(0) > 0$, $h(0) > 0$ are given.

The social planner's problem is almost identical to that of the decentralized agents. In fact, Equations (18), (20), and (21) are exactly the same as Equations (7), (9), and (10). However, there is a crucial difference between Equations (8) and (19). The decentralized agents regard only the market price p_x as the price of the processed energy input (Bx), whereas the social planner takes the cost of pollution $1/BD$ into account, too. Thus for the social planner, the price of the processed energy input (Bx) becomes ($p_x + 1/BD$). In essence, the social planner maximizes the net profit, whereas decentralized agents maximize the gross profit. (Gross profit minus the cost of pollution is the net profit.)

The steady state solutions for the social planner's problem are as follows:

$$u^{**}=\frac{\rho-\xi+\theta\xi-\theta n}{\theta\xi} \tag{22}$$

$$\tilde{c}^{**}=[\frac{(1-\alpha\eta^{**}+\eta^{**})(\xi+\delta)}{\alpha}+\frac{\rho-\xi}{\theta}-(n+\delta)]\tilde{k}^{**} \tag{23}$$

$$\tilde{y}^{**}=[\frac{(\xi+\delta)(1+\eta^{**})}{\alpha}]\tilde{k}^{**} \tag{24}$$

$$\tilde{x}^{**}=\frac{1}{B}\left(\frac{\xi+\delta}{p_x+\frac{1}{BD}}\right)^{\frac{1}{1-\phi}}\tilde{k}^{**}\equiv\frac{1}{B}(\eta^{**})^{\frac{1}{\phi}}\tilde{k}^{**} \tag{25}$$

$$\tilde{k}^{**}=\left(\frac{\alpha A}{\xi+\delta}\right)^{\frac{1}{1-\alpha}}(1+\eta^{**})^{\frac{\alpha-\phi}{\phi(1-\alpha)}}u^{**} \tag{26}$$

$$\tilde{z}^{**}=\frac{1}{D}\tilde{x}^{**}=\frac{1}{BD}\left(\frac{\xi+\delta}{p_x+\frac{1}{BD}}\right)^{\frac{1}{1-\phi}}\tilde{k}^{**}\equiv\frac{1}{BD}(\eta^{**})^{\frac{1}{\phi}}\tilde{k}^{**} \tag{27}$$

These solutions again look exactly the same as those for the private agents. Nevertheless, the similarity is misleading. The η^{**} that enters Equations (23) to (27) differs from the η^{*} that enters Equations (12) to (15) and (17); hence, the social planner's choices for consumption, output, energy input, capital stock, and pollution are different from those for the decentralized agents. The value of η^{**} is given as follows:

$$\eta^{**}=[\frac{\xi+\delta}{p_x+\frac{1}{BD}}]^{\frac{\phi}{1-\phi}} \tag{28}$$

Recall that for η^*, the denominator in the bracket is p_x, whereas for η^{**}, it is $(p_x)'=p_x+1/BD$. Given that the latter's denominator is larger than that for the former, it is evident that η^{**} is smaller than η^*. That is, the social planner makes choices so that the key variable η becomes smaller than what would entail under private choices.

III. Characterization of the Steady State Solutions

We investigate the properties of the steady state solutions just derived. Recall that there are two sets of solutions: one for private choices and the other for social choice.

A. Cases When the Solutions Coincide

For several variables, their long run steady state values are identical. The human capital allocation variable u, the long run steady state growth rate (of output) g, and the long run real interest rate r are such variables.[9]

(a) Human Capital Allocation

Equations (11) and (22) are solutions for u for the two cases. Observe that u^* is the same as u^{**}. This condition shows that the allocation rule for human capital between "work" and "learning" is invariant to whether or not pollution is internalized. That is, regardless of whether the price of effective energy is p_x or $(p_x)'=p_x+1/BD$, the economy would end up dividing human capital in an identical manner.

Observe that $u^*=u^{**}$ is decreasing in ξ and θ, and increasing in $(\rho-n)$. When human capital-forming activities become more productive (ξ gets larger), people would allocate more of their human capital to such activities ($1-u^*$ becomes larger). Likewise, when people become more time impatient (ρ gets smaller) and/or more willing to substitute intertemporally (θ becomes smaller), they will put more human capital into human-capital forming activities ($1-u^*$ becomes larger).

(b) Long Run Growth Rate

Recall that the output per effective worker $\tilde{y}$ was defined as $Y/hL=y/h$. Therefore, we have $y=\tilde{y}h$. This suggests that the per capita income

[9] The results discussed here could be due to the specificity of the model. Further study is needed to check whether the results go through in a wider class of models.

would grow at the rate given below.

$$\frac{\dot{y}}{y} = g(t) = \frac{\dot{\tilde{y}}}{\tilde{y}}(t) + \frac{\dot{h}}{h}(t) = \frac{\dot{\tilde{y}}}{\tilde{y}}(t) + \xi[1 - u(t)] - n \tag{29}$$

In the long run, as the economy moves toward the steady state growth path, the growth rate of $\tilde{y}$ converges to zero, and the growth rate of h converges to $\xi(1-u^*)-n$, where u^* is the long run value of u given in (11). This means that in the long run, $g(t)$ would converge to g^* given below.

$$g^* = \xi[1 - u^*] - n = \frac{\xi - \rho}{\theta} \tag{30}$$

In (30), the second equality is derived by substituting u^* given in (11). The output per effective worker $\tilde{y}$ would grow to $\tilde{y}^*$ or $\tilde{y}^{**}$. However, once $\tilde{y}^*$ reaches at $\tilde{y}^*$ or $\tilde{y}^{**}$, it will not grow any further. Thus, the growth rate $g(t)$ of $y(t)$, starting from a value higher than g^*, would steadily decline toward g^*, which is nothing but the long run growth rate of human capital h.

In this case too, the long run steady state growth rate g^* is independent of the energy price p_x. Thus, as it was the case for u^*, whether energy prices are high or low will not affect the long run steady state growth rate of the economy. This phenomenon suggests that we would have the same long run growth rates regardless of whether we ignore or internalize pollution. Hence, there is no need to accept lower growth rates to have a cleaner environment.

In our model, as it is in other balanced growth models, c, k, x, z, and y all would grow at the same rate as h grows. That is, the long run steady state growth rate of c, k, x, and z would be identical to the long run steady state growth rate g^* of y.

(c) Long Run Real Interest Rate

We can infer how the real interest is determined from the equilibrium condition for the physical capital rental market. Recall that we had the following first order condition for the physical capital per person k[10]:

[10] For a derivation, see Lee (2010).

$$r = \left(\frac{\alpha}{1+\eta}\right)\frac{y}{k} - \delta \tag{31}$$

From either (13) or (24), we see that the long run steady state value of y/k is just $(\xi+\delta)(1+\eta)/\alpha$. Substituting this into (31), we get the following:

$$r^{*} = \xi \tag{32}$$

This is the long run real interest rate r^{*}. Observe that r^{*} is not dependent on the energy price p_x. Hence, it does not matter for the determination of r^{*} whether pollution is internalized or not. With $\xi =$ 0.08, we would have a long run real interest rate of 8%.

B. Cases When the Results Differ

Expecting to have different outcomes depending on whether or not agents internalize pollution is natural. The three cases of identical outcomes above might be exceptions. The result might be merely an artifact of the specificity of our model. We turn to outcomes that are different.

(a) Steady State Level of Per Capita Output, Consumption, Energy Uses, Capital Stock, and Pollution

The steady state values of consumption, energy input, output, and pollution per effective worker are as follows:

$$\tilde{c}^{*} = [\frac{(1-\alpha\eta^{*}+\eta^{*})(\xi+\delta)}{\alpha} + \frac{\rho-\xi}{\theta} - (n+\delta)]\tilde{k}^{*} \tag{12}$$

$$\tilde{y}^{*} = [\frac{(\xi+\delta)(1+\eta^{*})}{\alpha}]\tilde{k}^{*} \tag{13}$$

$$\tilde{x}^{*} = \frac{1}{B}(\eta)^{\frac{1}{\phi}}\tilde{k}^{*} \tag{14}$$

$$\tilde{z}^{*} = \frac{1}{D}\tilde{x}^{*} = \frac{1}{BD}\left(\frac{\xi+\delta}{p_x}\right)^{\frac{1}{1-\phi}}\tilde{k}^{*} \tag{17}$$

In addition, the steady state value of the physical capital per effective worker is given by:

$$\tilde{k}^* = \left(\frac{\alpha A}{\xi + \delta}\right)^{\frac{1}{1-\alpha}} (1+\eta^*)^{\frac{\alpha-\phi}{\phi(1-\alpha)}} u^* \tag{15}$$

These are the steady state values for the market-based solution. When we replace η^* in the above expressions with η^{**}, we get steady state values for the plan based solution.

Equations (12) and (13) show that both consumption and output per effective worker are increasing in η^* for any given value of $\tilde{k}^*$. Thus, if $\tilde{k}^*$ is increasing in η^*, we can conclude that $\tilde{c}^*$ and $\tilde{y}^*$ are also increasing in η. Furthermore, considering that $\tilde{x}^*$ and $\tilde{z}^*$ given in (14) and (17) are directly proportional to $\tilde{k}^*$, $\tilde{x}^*$, and $\tilde{z}^*$ are also increasing in η^*, if $\tilde{k}^*$ is increasing in η^*. Equation (15) suggests $\tilde{k}^*$ would be increasing in η^* if $\alpha \geq \phi$ holds. (Recall that u^* is independent of η^*.) Therefore, when $\alpha \geq \phi$ holds, all the steady state variables $\tilde{c}^*$, $\tilde{k}^*$, $\tilde{y}^*$, $\tilde{x}^*$, and $\tilde{z}^*$ turn out to be increasing in η^*.

Recall that earlier we have shown that $\eta^* > \eta^{**}$ holds. This outcome, together with the fact that $\tilde{c}^*$, $\tilde{k}^*$, $\tilde{y}^*$, $\tilde{x}^*$, and $\tilde{z}^*$ are increasing in η^*, indicate that the steady state values of the key variables for the planner's problem are smaller than those for the market-based solution. That is, the double-starred variables $\tilde{c}^{**}$, $\tilde{k}^{**}$, $\tilde{y}^{**}$, $\tilde{x}^{**}$, and $\tilde{z}^{**}$ are all smaller than their single-starred counterparts. The steady state values of consumption, physical capital stock, output, energy input, and pollution, all in terms of per effective worker chosen by the social planner, are smaller than their counterparts that would be chosen by citizens.[11]

(b) Pollution-Output Ratio

Given that $z/y = (z/h)/(y/h) = \tilde{z}/\tilde{y}$ holds, we can easily calculate z/y using Equations (17) and (13). The equation is given as follows:

$$\frac{z^*}{y^*} = \frac{1}{BD} \cdot \frac{1}{p_x} \cdot \frac{\alpha\eta^*}{1+\eta^*} \tag{33}$$

[11] This shows that we must pay costs to have a cleaner environment. Nevertheless, we can have a better environment as well as a larger income. See the discussion in Chapter IV.

Equation (33) indicates the long run steady state pollution output ratio implied by the market-based solution. Its social planner's counterpart is obtained when we replace p_x with $(p_x)'$ and η^* with η^{**}. Given that the right-hand side of (33) is decreasing in p_x, increasing in η^*, and η^* is decreasing in p_x, the pollution output ratio z/y is decreasing in p_x. That is, whenever the price of energy becomes more expensive, the economy would end up lowering pollution energy ratio. The declining pollution output ratio means that whenever energy resources become more expensive, agents tend to adopt behaviors that rely less on energy inputs, thereby reducing pollution.

The pollution output ratio becoming smaller with an increase in energy price suggests that the pollution output ratio obtained under the planner's choice would be smaller than that obtained under the market-based choice. That is, when pollution is internalized, the long run steady state pollution output ratio turns out to be smaller than the level that would prevail when pollution is ignored.

The above-mentioned observation implies that when pollution is internalized, the long run steady state values of pollution as well as output would become smaller than those that would prevail when pollution is not internalized. The observation that the pollution output ratio gets lower, when pollution is internalized, suggests that when pollution is internalized, pollution per person would decline more than output per person.

Another interesting feature of pollution output ratio given in (33) is that it is independent of y. Its significance is that when the energy price gets higher, the ratio z/y declines. This condition, together with the fact that z/y is independent of y, suggest that the ratio z/y becomes smaller for all levels of income y, when energy resources become more expensive. If we re-interpret this in light of the environmental Kuznets curve (EKC), it means that whenever energy prices go up, the EKC itself will shift down. In our model, the social planner pays higher price for energy resources; hence, his choice would result in the EKC located below the one that would prevail under the market-based solution.[12]

IV. Implications for Green Growth Policies

We now investigate the implications of our model for green growth

[12] This concept shows that we do not have to accept a lower income to have a better environment.

policies. For convenience, we will divide our discussion into three groups. First, we will discuss how we might induce citizens to behave as if they were under the direct influence of the social planner. Second, we will discuss how we might alter the long run steady state growth rate. Third, we will discuss how we may change the pollution output ratio.

A. How to Align Private Choices with Public Choices

In our model, the only thing that differentiates private choices from public choices is whether the pollution, incurred when energy input is used, is fully internalized or not. Private choices ignore pollution, whereas public choices do not.

The energy price faced by private decision makers is p_x, the globally determined price of energy resources. In contrast, the energy price faced by a social decision maker is $p_x + 1/BD$, which is the private cost plus the cost of pollution. Recall that B and D indicate the level of energy-related technology and pollution-related technology, respectively. A higher B means a given amount of raw energy becomes more productive. A higher D means that from the given amount of energy uses, we get less pollution. In any case, B and/or D can never be infinitely large. Hence, $1/BD$ must be a finite positive number. Therefore, $p_x + 1/BD$ must be higher than p_x. That is why in the above, the social planner chooses economic activities, so that the resulting pollution is smaller than what would prevail under private choices.

If that is the case, then we may induce citizens to behave in exactly the same way as they would under the social planner dictum. One possible way of doing that is altering the energy price faced by citizens from p_x to $p_x + 1/BD$. Another possibility is to force citizens to follow the planner's dictum.

(a) Imposition of an Energy Tax

When an energy tax of $1/BD$ is added to the market price p_x, the de facto energy price citizens would pay becomes $p_x + 1/BD$. When such an energy tax is imposed, citizens would behave exactly the same as they would do under the planner's dictum. What is important here is that nobody forces citizens to do so. They would voluntarily do so. In addition, there is no need to ascertain who emits pollution and how much. Simply making energy more expensive is all that is needed. (Of course, finding out the right amount of energy tax is by no means an easy task.) Thus, energy taxation is a very cost efficient method to align private choices to the public choices.

Meanwhile, we want to point out that the energy price we have been considering in this paper is the price of "effective" energy. That is, p_x is the price of BX, not raw energy X. The price of raw energy $\bar{p}_x$ we observe in the market is obtained as follows:

$$\bar{p}_x = p_x B \tag{34}$$

This is the private marginal cost of energy inputs. The social marginal cost, which should include the cost of pollution, is then given by $\bar{p}_x + 1/D$. Note that B no longer appears. In terms of raw energy, the energy tax is merely $1/D$.

(b) Promotion of the Pollution Prevention/Treatment Technologies

An alternative method to make the private marginal cost of energy inputs equal to the social marginal cost is adopt policies that might lower the social cost. The social marginal cost $\bar{p}_x + 1/D$ could be brought closer to the private marginal cost $\bar{p}_x$, if the technology index D can be made larger. Making D larger means improving pollution-related technologies. A larger D means that the society would experience less pollution from a given amount of energy uses. D is concerned with pollution prevention and cleanup technologies.

There are options to improve D (*i.e.*, how to make D larger). We can improve D through learning by doing, imitation and improvement, technology transfer, and R&D activities. Therefore, policies that would promote such activities would make D larger, leading to a reduction in the social cost of energy. The reduction in the social cost of energy narrows the gap between the private and public cost, and thereby mitigate the sub-optimality arising from such gaps. Promoting green technologies, green products, and green industries are practical examples of policies that can make D larger.

The policy of making D larger (*i.e.*, promoting the development of anti-pollution knowhow and technologies, or more generally, promoting pro-environment technologies) is not perfect as a policy to eliminate the gap between private vs. social marginal cost. The gap will be completely eliminated only when the technology D becomes infinitely best (*i.e.*, only when D becomes infinite). Needless to say, D becoming infinite is impossible. Furthermore, making D larger is costly. In a more general model, we have to weigh the benefits of making D large against the costs of doing so. The "optimal" level of D arrived in such model would certainly be finite.

(c) Subsidizing Non-Energy Green Inputs

Among several possible alternatives of making η^* equal to η^{**}, we have considered only the options for making the denominator of η^*, $\bar{p}_x$, equal to the denominator of η^{**}, $\bar{p}_x + 1/D$. Altering the numerator so as to make η^* equal to η^{**} is another option. This procedure can be done by subsidizing the use of physical capital inputs. The subsidy, which can be called as investment subsidy, can be determined as the amount ζ that solves the following:

$$\frac{r-\zeta+\delta}{\bar{p}_x} = \frac{r+\delta}{\bar{p}_x + 1/D} \tag{35}$$

The ζ value that satisfies Equation (35) is as follows:

$$\zeta = \frac{r+\delta}{\bar{p}_x + 1/D} \cdot \frac{1}{D} = \frac{\xi+\delta}{\bar{p}_x + 1/D} \cdot \frac{1}{D} \tag{36}$$

The second inequality reflects the fact that in the steady state, the real interest rate is equal to ξ. This condition illustrates that whenever an interest rate subsidy of ζ, indicated in (36), is given to the users of the physical capital, they will veer away from using x toward using k, and thereby bring η^* down to η^{**}. This option would make the private choices identical to public choices.[13]

Subsidizing the use of physical capital k amounts to giving subsidies for investment in machines that would reduce energy uses, improve energy efficiency, and help replace pollution-prone energy sources with cleaner and renewable energy sources. Tax credits conferred on green investors are good examples of such a subsidy.

(d) Outright Restrictions

A government, if it wants, may force citizens to choose $\tilde{c}^{**}$, $\tilde{k}^{**}$, $\tilde{y}^{**}$, $\tilde{x}^{**}$, and $\tilde{z}^{**}$. For this course of action, various regulatory devices could be employed.

An example of such a policy is allocating quotas for green house gas

[13] Needless to say, the effective real interest rate goes down when the subsidy is given.

emission, and allowing them to trade the quotas. This policy amounts to setting targets at $\tilde{x}^{**}$ or $\tilde{z}^{**}$ for firms, and giving awards when they meet the targets, but imposing penalties when they do not meet the targets. Firms that exceed the targets, that is, those that reduce energy or pollution below the targets, are allowed to sell their unused quotas. On the other hand, firms that cannot meet the targets are required to make up for the shortage with quotas purchased from others or with fines.

The use of forces (*i.e.*, direct controls or interventions) can have immediate effects that everyone can see. As such, policy makers who want to get immediate results favor this policy. This situation would be especially evident in an economy that is used to controls and interventions.

However, relying on outright forces is the worst kind of policies. Determining what should be the right level of, say, pollution, would be very difficult. Thus, setting targets or giving quotas is a very difficult job. Setting the wrong targets is highly likely. In addition, ascertaining whether agents really adhere to the targets would be equally difficult. The verification costs tend to be very high. Furthermore, when quantitative restrictions are imposed, agents would invariably try to avoid such restrictions. That move would make the policy less effective and incur costs of avoiding restrictions.

B. Policies Regarding the Long Run Steady State Growth Rate

The long run steady state growth rate is determined in our model as follows:

$$g^* = \frac{\xi - \rho}{\theta} \tag{30}$$

The parameters of the utility function ρ and θ are not easily changeable; thus, the key parameter is ξ, the productivity of human capital-forming activities. The long run steady state growth rate g^* is directly proportional to ξ.

Many economists regard ρ=0.02 and θ=2 as good estimates of the preference parameters.[14] We can take estimates of “returns to schooling” as good approximates for ξ. Estimates for the returns are generally in the range of 8% to 12%.[15] These estimates suggest values of g^* ranging

[14] See for example, Barro and Sala-i-Martin (2004).

from 3% to 5%. They are reasonable estimates for medium-term growth rates of per capita income. However, they seem to be somewhat high for estimates of the long run steady state growth rate. Perhaps the returns to schooling may not be maintained at such high rates. If the latter comes down eventually to the 4% to 6% range, then g^* would be somewhere between 2% to 3%, which looks more reasonable.

What is important, though, is that g^* is increasing in ξ. The long run steady state growth rate g^* goes up when the human capital forming activities of the society become more productive. The best pro-growth policy suggested by our model is a policy to enhance the productivity of schooling, training, on-the-job training, and continuing education-related activities. Health is an important constituent of human capital; hence, raising the productivity of health enhancing activities is important, too. Thus, if we want to enhance the growth potential of the economy, paying attention to human capital-forming activities so that they would become more productive is crucial.

Notably, g^* is independent of energy prices. This concept suggests that, as far as g^* is concerned, it does not matter whether or not the society internalizes pollution. In particular, the concept suggests that internalizing pollution will not decrease the long run growth rate of the economy. This matter answers the critical question, "If we want to protect environment or prevent pollution, we have to sacrifice economic development. Don't we?" Our answer is "No."

Attempts to enhance the broadly defined environmental capital affect ξ adversely would be a different matter. Although we are not sure whether this would indeed happen, it is still a possibility, and we have to guard against such outcomes. In contrast, if efforts to go green can be made in such a way as to make human capital-forming activities more productive, the long run growth rate could increase.

C. Policies Concerning the Pollution Output Ratio

In our model, both y and z would grow at the same rate g^* in the long run. In the above, g^* is invariant to green growth policies. That is, the usual kinds of green growth policies will not influence the long run steady state growth rate g^*. This condition does not imply, however, that the ratio z/y, the pollution output ratio, is also independent of such policies. We bring Equation (33) here to see the point.

[15] See for example, Mincer (1974).

$$\left(\frac{z}{y}\right)^{*} = \frac{1}{\bar{p}_x} \cdot \frac{1}{D} \cdot \frac{\alpha\eta^{*}}{1+\eta^{*}} \tag{33'}$$

We have replaced the price of effective energy (BX), $p_x B$, with the price of raw energy X, $\bar{p}_x$, in moving from (33) to (33)′. The ratio $(z/y)^*$ given above is the ratio that would prevail under market-based solutions. In a similar fashion, we can derive the ratio $(z/y)^{**}$ that would prevail under the plan-based solutions as follows:

$$\left(\frac{z}{y}\right)^{**} = \frac{1}{\bar{p}_x + \frac{1}{D}} \frac{1}{D} \frac{\alpha\eta^{**}}{1+\eta^{**}} \tag{37}$$

A comparison of (33)′ and (37) reveals several interesting facts. First, $(z/y)^{**}$ is smaller than $(z/y)^{*}$, for all values of $\bar{p}_x$, and other parameters. The ratio (z/y) is increasing in η. Recall that η is decreasing in energy prices. Therefore, higher energy prices would make the ratio (z/y) smaller first through their effect on η and, second, through their direct negative effect on. Considering that $(z/y)^{**}$ is determined under higher energy prices than $(z/y)^{*}$, the former should be smaller than the latter. This outcome suggests that when pollution is taken into account, we would have a smaller pollution output ratio. As pointed out in the previous section, this outcome also means that the social planner's solution would entail the EKC located everywhere lower than its counterpart that would ensue under market-based solutions.

Policies that would make private choices identical to the social choices are also policies to make the pollution output ratios identical. Thus, environment (energy) taxes and environment-related technological progresses would not only bring y^* and z^* to their two-starred counterparts, but would also bring $(z/y)^*$ to $(z/y)^{**}$.

D. Policies that May Affect the Long Run Steady State Values of Output and Pollution Per Capita

(a) The Steady State Values Restated

We want to understand how the two important variables, output and pollution per person, behave in the steady state. The steady state level of output per effective worker is determined as follows:[16]

[16] This is derived by combining Equations (13) and (15).

$$\tilde{y}^* = (\frac{\alpha}{\xi + \delta})^{\frac{\alpha}{1-\alpha}} A^{\frac{1}{1-\alpha}} (1 + \eta^*)^{\frac{\alpha(1-\phi)}{\phi(1-\alpha)}} u^* \tag{38}$$

Steady state pollution per effective worker is determined as follows:[17]

$$\tilde{z}^* = \frac{1}{BD} \cdot (\frac{\alpha A}{p_x})^{\frac{1}{1-\alpha}} \cdot (\frac{1+\eta^*}{\eta^*})^{\frac{\alpha-\phi}{\phi(1-\alpha)}} u^* \tag{39}$$

We have already derived the long run steady state value of u^* as follows:

$$u^* = \frac{\rho - \xi + \theta\xi - \theta n}{\theta\xi} \tag{11}$$

(b) Comparative Analyses

Equations (38) and (11) clearly show that the real price of energy p_x together with parameters A, ρ, θ, ξ, n, and δ, crucially affect the determination of $\tilde{y}^*$. (Recall that η^* is decreasing in p_x.) Among these parameters, preference parameters ρ and θ are not easily changed, and the population growth rate or the depreciation rate is regarded as exogenous to our model. Thus, A, ξ, and p_x are important for our purposes.

Given that $y = \tilde{y}h$, we can deduce how y would evolve from the knowledge of how $\tilde{y}$ and h evolve. $\tilde{y} \to \tilde{y}^*$ and h grows at the rate of g^*. Therefore, from the knowledge on how $\tilde{y}^*$ and g^* are determined, we can deduce how y evolves. The relevant information contained in Equations (38), (11), (16), and (30) reveals the following.

The per capita income y is increasing in A. Therefore, if A can be repeatedly made bigger, y would keep on growing. When this occurs, then the observed economic growth rate g would surely increase.

When ξ increases, that is, when human capital creation becomes more productive, $\tilde{y}^*$ declines but g^* goes up. As learning becomes more productive, people would devote more efforts to human capital formation. This move means a decrease in the efforts allocated to output production. Hence, y decreases as ξ gets larger. However, when ξ is raised, income would grow faster. Therefore, an increase in ξ would make the current income smaller, but make the future income much larger.

[17] This is derived by combining Equations (17) and (15).

The per capita income y is a decreasing function of the energy price p_x. Thus, when the real price of energy falls, y would increase. If p_x keeps on falling, y would keep on increasing, raising the observed growth rates. In the latter half of the 20^{th} century, the real price of energy kept on falling except for the oil shock years of the 1970s and 1980s. This event may partly explain the long run prosperity that people all over the world have enjoyed since the 1960s. Of course, the event could explain why during the oil shock years, the world average economic growth rate was lowered.

Equations (39) and (11) clearly show that the real price of energy p_x together with parameters A, ρ, θ, ξ, n, and δ, crucially affect the determination of $\tilde{z}^*$. (Recall that η^* is increasing in ξ.) In addition, the technology parameters B and D affect $\tilde{z}^*$ directly. Among these parameters, B and D are particularly important as policy targets.

Improvements in B or D have definite effects. First, they do not affect income. Second, when B or D improves, pollution would definitely decrease. Hence, when improvements in B or D are made, the pollution per person would decrease, whereas the output per person will not be affected. A reduction in pollution is desirable; thus, improving environment-related technologies B and D can be an important component of the green growth initiatives.

Nevertheless, we also want to have a larger income, together with a decrease in pollution. According to our model, the only way is to make improvements in the overall productivity A and the environment-related productivity B and/or D. That is, when we promote the conventional R&D so that the economy becomes more productive and simultaneously promote the green R&D so that the economy becomes environmentally more productive, we can have a larger income together with a smaller pollution.[18]

(c) Energy Prices Are Crucial

One thing becomes clear. If the energy prices are kept arbitrarily low for whatever reason, people would use too much energy and create too much pollution. The low energy price policy is very detrimental to environment, because it increases the per capita pollution.

The meaning of keeping the energy prices low has two aspects. One has to do with subsidies and tax breaks given to users of energies. Sub-

[18] Generally, improving A, B, or D is a costly business. When we subtract such costs, we may end up having a smaller income.

sidies and tax breaks would make the user cost of energy lower than its marginal cost of supply. This lower price would induce people to use up more energy resources. The other has to do with pollution externality. When we use energy resources, we create pollution. Nevertheless, in most cases pollution is external to private decision. Polluters simply do not take pollution into account. This phenomenon means that the social marginal cost of energy uses is higher than their private marginal cost.

V. Further Discussion and Concluding Remarks

We have proposed and studied a growth model that incorporates the environmental aspects as essential components. As a sequel to Lee (2010), the current research focuses on policy options that can induce economic agents, who tend to ignore damages they are creating to the environment, to behave more responsibly toward the environment. The key issue is how to induce citizens to fully internalize pollution they are creating and simultaneously enhance the growth potential of the economy. That is, our main concerns are finding out pragmatic policy options to foster green growth — growth whose processes and outcomes are green, and growth powered by greens. Our key findings are as follows.

As general principles, we point out two. First, not under-pricing the environment-related goods and services is crucial. For instance, the distorted energy price structure currently in place in many countries encourages people to use too much energy, thereby creating too much pollution. Therefore, phasing out subsidies and tax breaks should become the first priority. Moreover, the pollution costs associated with economic activities are generally not reflected in the prices of environment-related goods and services. This phenomenon makes people use too much environmental resources and create too much pollution. Thus, pricing environmental resources correctly is very important.

Second, by promoting repeated improvements in the overall productivity level of the economy, in resource-saving technologies and pollution prevention/cleanup technologies, we can achieve the twin goals of green growth: raising income and reducing pollution. Furthermore, if technological breakthroughs are made repeatedly, income growth rate could be raised, and pollution growth rate could be lowered. Resource-saving technologies include technologies that can produce the same amount of output with fewer resources, technologies that can make the distribution and uses of resources more efficient, resource-economizing knowhow and technologies, better recycling technologies, and technologies related to renewable sources of energies, to name a few. These are the so-called "green technologies."

As a practical guide, we have studied several policy options that can induce citizens to behave more responsibly toward the environment. To discourage unnecessarily large amounts of resource uses, we can impose surcharges or taxes on energy resources. To encourage the advancement of pollution prevention/cleanup (or, more generally pro-environment) knowhow and technologies, we can provide subsidies (and other forms of help) for the relevant R&D sector. To encourage the use of cleaner inputs, we can provide subsidies (and other forms of help) for clean inputs. These are market-based policy options. Mixing the three options is better. This way, the energy tax can be imposed at a modest rate, and tax revenues thus mobilized can be used to finance the subsidy schemes.

We have also studied the policy option of imposing an outright restriction on energy uses (or more generally, on activities that hurt the environment.) The idea is to force citizens to choose the same outcomes as the outcomes that would prevail under the planner's solution. Regulation, controls, and interventions are practical means for outright restrictions. On-site inspection, verification, and imposing penalties or conferring rewards will be needed. These are very cost-ineffective means.

The policy option of "allocating quotas for green house gas emission and allowing free trade of the quotas as rights" is an example of outright restriction policies. Of the two parts of the policy, allowing the trading of the rights is market-friendly and sensible. However, the allocation of quotas or rights is a very tricky business. Coming up with a market-friendly allocation rule would be difficult.

Being a very simple model, there are many limitations in our model. For a better model, we have to amend the present model in several important directions.

First, although the most important determinant for the long run steady state growth rate in our model is the productivity of the human capital-forming activities, we have treated it very lightly. By exploring how to make the education/training system of a country more productive, we can shed light on this issue. This concern is intimately related to that of reforming the education system of the country. Further development of the model in this direction is clearly needed.

Second, we have to overcome the limitation of the one-sector model. With the one-sector model of this research, we cannot address important issues, such as brown industries vs. green ones, brown technologies vs. green ones, and brown workers/jobs vs. green workers/jobs. At a minimum, a two-sector model is needed to examine these issues.

Even in our model, we can investigate how the long run growth is affected when the industrial structure changes from an energy-intensive brown one to an energy-saving green one, by slightly altering our production function as follows:

$$Y = A[bK^{\phi} + (1-b)(BX)^{\phi}]^{\frac{\alpha}{\phi}}(uhL)^{1-\alpha} \tag{40}$$

We can represent the change in industrial structure by varying the parameter *b*: A larger a means a shift toward a more energy-saving industrial structure.

Third, there is a need to extend the model so that we can deal with issues of introducing entirely new technologies or products that are hitherto nonexistent. For green growth to succeed, coming up with new green technologies and products that can be engines of green growth is very important. An expanding variety model of Ethier (1982) or Romer (1987, 1990), or a quality model of Aghion and Howitt (1992), could be utilized for this purpose.

Fourth, we can easily extend the model toward an open economy version. We can then deal with international trade issues other than energy resource importation. The international diffusion of green technologies can then be dealt with, too.

Fifth, the main difference between private vs. public choices arises from the difference in the targets that are being optimized. We have studied this issue by focusing on the difference in the profit functions. The social planner includes the cost of pollution as an important part of the total cost, whereas individual firms do not do so. As an alternative to this strategy, we can approach the problem by focusing on the difference in the utility function. In this case, citizens would ignore pollution in their welfare considerations, whereas the social planner will include it as an essential component of the social welfare function. For example, we can easily study a model with the following setup:

$$\text{Max}\int_0^{\infty} e^{-(\rho-n)t}\,\frac{(c/z)^{1-\theta}-1}{1-\theta}\,dt \tag{41}$$

Subject to:

$$c + \dot{k} = y - (n + \delta)k - p_x(Bx) \tag{42}$$

where

$$Y = A[bK^{\phi} + (1-b)(BX)^{\phi}]^{\frac{\alpha}{\phi}}(uh)^{1-\alpha} \tag{43}$$

$$z = \frac{1}{D_1}x + \frac{1}{D_2}y \tag{44}$$

Equation (41) differs from the utility function we examined in this research in that in place of the usual consumption per person c, we have the consumption/pollution ratio. This is the simplest way to include pollution as a bad in the utility function. It is not the usual consumption c but the consumption pollution ratio that enters the utility function. The consumption pollution ratio c/x stands for "true" goods consumed.

Equation (42) is the usual budget constraint we have had for private decision makers. This budget constraint is different from that for the social planner: the latter subtracts the cost of pollution and maximizes the net profit. That is, for the social planner, the net output $(y-z)$ was the available resources for consumption, investment, and energy costs. In (42), the gross output y is the available resource. Of course, we can treat $(y-z)$ or some portion of it as the available resource.

Equation (43) is a slightly extended production function mentioned in (40) expressed in per capita terms. Finally, Equation (44) is a slightly extended pollution-generating function. We have one more source of pollution: production, delivery, and uses of y do generate pollution, too. As long as we stick to a linear function, utilizing a pollution function such as (40) will not pose difficulties. D_2 stands for the knowhow and technology concerning pollution prevention/cleanup associated with final output y.

Sixth, we have not studied the transition process of the economy moving toward from the initial position toward the long run steady state. Thus, we cannot say anything about whether the economy will actually move toward the steady state, and if so, at what speed and in what manner. Likewise, we cannot say anything useful about the transition from one steady state to another steady state in response to policy interventions, for example. This is a serious drawback, and it must be squarely dealt with. We leave it as a future task.

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