



A dynamic optimization on economic energy efficiency in development: A numerical case of China



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ABSTRACT

This paper is based on dynamic optimization methodology to investigate the economic energy efficiency issues in developing countries. The paper introduces some definitions about energy efficiency both in economics and physics, and establishes a quantitative way for measuring the economic energy efficiency. The linkage between economic energy efficiency, energy consumption and other macroeconomic variables is demonstrated primarily. Using the methodology of dynamic optimization, a maximum problem of economic energy efficiency over time, which is subjected to the extended Solow growth model and instantaneous investment rate, is modelled. In this model, the energy consumption is set as a control variable and the capital is regarded as a state variable. The analytic solutions can be derived and the diagrammatic analysis provides saddle-point equilibrium. A numerical simulation based on China is also presented; meanwhile, the optimal paths of investment and energy consumption can be drawn. The dynamic optimization encourages governments in developing countries to pursue higher economic energy efficiency by controlling the energy consumption and regulating the investment state as it can conserve energy without influencing the achievement of steady state in terms of Solow model. If that, a sustainable development will be achieved.

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1. Introduction

Social planners and policymakers have been attracted by dynamic optimization issues for many years. To some degree, 'optimization' always lies in the centre of policy debate not only in developed countries, but especially in developing countries. Although a large quantity of researches have discussed on the optimal path of economic growth, energy consumption or pollution reduction, seldom economists have set their feet in the energy efficiency issues under the view of dynamics. In fact, the improvement of energy efficiency is a dynamic procedure in the development and it is always related to growth, investment, technology change and many other economic variables.

Energy efficiency can be defined in three dimensions. The first definition stems from the laws of thermodynamics in physics. It is defined as a ratio of best practice energy input over energy input, *ceteris paribus*, which refers to technical efficiency [1], and cannot be greater than one. The second definition is based on economic concepts and named energy intensity, which is the ratio of energy input over aggregate output [2]. However, this definition only

considers energy as a unique input with ignoring the other factors in the production such as capital and labour. Stern [3] has developed this definition of economic energy efficiency under the multi-input framework. In his work, the economic technical efficiency is on the basis of Pareto principle and is associated with capital as another input. He stated that any economy has two inputs for production: the one is energy and the other is capital. People should utilize the input composition to attain the goal of output and growth given the level of technology. Thus, by this argument, there must be an optimal solution about the input combination in development, which can be seen as the economic energy efficiency. The things people need to do are to make the economy operating under the best energy efficiency condition. In this paper, the meaning is adapted based on the Stern's definition. In other words, It is considered how to allocate and utilize energy and capital as two inputs efficiently for achieving the desired output and growth in development.

The attendant question is why the economic energy efficiency is crucial? In many developing countries, it is inevitable that the energy consumption is increasing with a rapid economic growth and the improvement of living standards. This may lead to energy security and environmental problems meanwhile. For one thing, energy consumption cannot increase infinitely because of energy scarcity; for another thing, energy exploitation and utilization

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usually need larger capital investment, which is also scarce in developing countries; in addition, intensive energy consumption tends to result in more environmental pollution and energy waste in these countries than that in developed countries. Probably, an increase in energy efficiency is an appropriate solution for this dilemma, even though technical efficiency cannot be increased infinitely in terms of the second law of thermodynamics, economic energy efficiency can be improved continuously in theory.

Apparently, advanced technology applications can increase energy efficiency. Besides that, the underlying drivers are capital, human resources and even energy itself. Firstly, increasing the quantity of investment and skilled labour can promote energy technology whether in exploitation or utilization, thereby increasing energy efficiency; secondly, different types of energy have different potential for energy efficiency promotion, as the modern energy contains more exergy. Exergy is available energy, which is the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir [4]. It means that higher energy efficiency could be achieved if people use more modern energy. However, the transition from conventional energy to modern energy results from the increases of income, which is referred by ‘energy ladder’ theory. In other words, the modern energy consumption in developing countries also needs sufficient capital accumulation and adequate economic growth. Hence, the improvement of energy efficiency is interlinked with capital stock, investment capacity, labour force quality and economic growth stages.

Nonetheless, the improvement of labour force quality may happen in the long term and spontaneously to some degree; moreover it could not be controlled or planned by public policy implement easily. While the investment whether in scale or speed, is controllable in most circumstances. Policymakers can regulate the investment as a flow variable and the capital stock in energy sector thereby. Additionally, investment can influence the improvement of energy efficiency by means of technology and furthermore, influence the energy consumption and economic growth. That is to say, the pace of energy efficiency improvement should reflect some dynamic features and be restricted by capital, growth and energy itself. Consequently, there may be a dynamic optimization of energy efficiency improvement in development. The mechanism is illustrated as Fig. 1.

Fig. 1 demonstrates a system consisting of economic growth, energy consumption, energy efficiency and capital. The arrows in the diagram indicate the causal relationship among these factors. The classical Solow model presents that capital is a key driver for economic growth but it neglects energy as another input. Many

energy economics researches extended Solow model with encompassing energy as input. Typically, Stern [5] established an extended Solow model revealing that energy can be seen as another driver for growth. Conversely, economic growth has led to the increase in energy consumption in many empirical studies. So there is a reciprocal causation between them. On the right of the figure, increase in energy efficiency will decrease energy consumption on the basis of the definition of energy technical efficiency which is from the second law of thermodynamics, and energy consumption also can influence energy efficiency in terms of the attributes of different energy. On the bottom of the figure, energy efficiency is linked with capital by the definition of economic energy efficiency.

Fig. 1 is meaningful in both theory and practice. In theory, if we can model the dynamic optimization of energy efficiency improvement linking with energy consumption and economic growth, we can introduce energy efficiency into traditional ‘3E’ (energy–economy–environment) analysis. Furthermore, the 3E analysis on energy technology transformation, production factors allocation and energy transition could access to energy efficiency discussion. In practice, the modelling could reveal the best choice of energy policy for developing countries on how to enhance energy efficiency given the limited capital stock and investment and achieve their goals of development.

The purpose of this paper is to model the dynamic optimization of energy efficiency improvement in development given the investment movement and production function. Firstly, a function is established for measuring the level of energy efficiency. Secondly, Solow growth is extended by adding energy consumption and deriving the instantaneous state of investment. Lastly, the steady-state solution can be solved by dynamic optimization method and furthermore, we can get the optimal path of energy consumption and investments under the condition of maximum energy efficiency over the periods in development. The paper is organized by six parts. The Literature review follows the Introduction, and then the methodology is introduced in Section 3. Results and a numerical simulation are presented in Section 4 followed by some discussions in Section 5. The Conclusion is arranged at the end of the paper.

2. Literature review

The reviewed literature includes three categories: the application of dynamic optimization in exhaustible resource economics; the recent work on the dynamic relationship among energy, economy and environment; and some important literature on energy efficiency.

Dynamic optimization has been applied for resource exploitation problems since 1970s by Pindyck. He established a basic model on the optimal exploration of non-renewable resources in 1978 [6] and developed it in 1980 with adding uncertainty into exhaustible resource market analysis [7]. Both of the two models are based on cost benefit analysis. Basically, they are general models and they only focus on the optimization in production. The limitation is that the energy depletion in the models has not been linked with economic growth and any other macroeconomic variables. Some other economists including Stiglitz [8], Garg and Sweeney [9], Dasgupta and Heal [10] brought the optimal exploration problem into the framework of neoclassical model of growth. They have discussed well on the optimal sustainable growth path under the condition that the resources are scarce and diminishing all the time. But the technology element was assumed exogenous in their models, which has aroused a wide controversy. Having the endogenous growth model been raised by Romer [11] and Lucas [12], the technology change became endogenous so that the long-run analysis

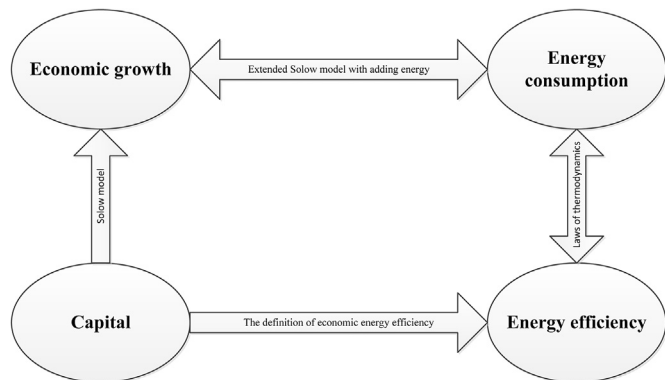


Fig. 1. The mechanism and linkage between energy efficiency and other economic variables.

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