NOTA DI LAVORO
40.2014

On the Mechanism of International Technology Diffusion for Energy Productivity Growth

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Climate Change and Sustainable Development
Series Editor: Carlo Carraro

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Summary

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Keywords: Technological Innovation, Energy Technology Diffusion, Solow Growth Model, Endogenous Growth Model

JEL Classification: Q55, Q58, Q43, Q48, O13, O31, O33, O44, F18

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Abstract
International diffusion of advanced environment and energy-related technologies has received much attention in recent environmental economics studies. As a much needed complement to the "black box" complex numerical modelling, this paper contributes to developing a simple, intuitive analytical framework to unveil the mechanism of international technology diffusion for energy productivity growth. We draw on the Solow growth model to build a benchmark exogenous framework to explore the basic mechanism of energy technology diffusion. This exogenous model is then extended to a Romer-type endogenous one where the R&D-induced expansion of energy technology varieties is used to represent the deep structure of technology diffusion. We show that the growth rates of energy productivity are the same across countries in the balanced growth path equilibrium, but the cross-country differences in the efficiency of foreign technology absorption and indigenous innovation lead to cross-country divergence in the levels of energy productivity. The economy that has a stronger capacity of assimilating foreign technology diffusion and undertaking indigenous innovation tends to gain a higher level of energy productivity.

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1. Introduction

To formulate effective strategies to address global energy and climate problems, the potential importance of cross-country technological interdependences and interactions should be explicitly considered (Gillingham et al., 2008; Popp et al., 2010a). On the one hand, the advanced economies in the developed world have taken the lead in technology exchanges and partnerships for building knowledge-based, low-carbon societies. On the other hand, the developing countries, particularly the emerging economies, direly call for foreign technology transfer to support their indigenous efforts in the course of decoupling energy use from rapid economic growth (IEA, 2012; World Bank, 2008; Popp, 2011).

In this context, the issue of international technology diffusion (ITD) has received much attention on current energy and climate policy agenda, and some international frameworks, such as the Asia-Pacific Partnership on Clean Development and Climate (APP), the International Energy Agency Implementing Agreements (IEA-IA), and the Technology Mechanism under the United Nations Climate Convention, have been institutionalized in recent years with an aim of accelerating energy technology diffusion. With ITD placed high upon policy agenda, there is a growing need in the research community to explore the fundamental mechanism of ITD for energy and carbon productivity improvement (Grubb et al., 2002; Philibert, 2004; Popp, 2006a).

Basically, the recent studies have progressed along two tracks. On the one side, numerous econometric analyses tend to use econometric methods to investigate the empirical evidences of environment-friendly technology diffusion across countries (e.g., Lanjouw and Mody, 1996; Popp, 2006b; Dechezleprêtre et al., 2008; Johnstone et al., 2010; Popp et al., 2010b; Lovely and Popp, 2011; Verdolini and Galeotti, 2011; Hall and Helmers, 2013). On the other side, environmental policy modelers basically use economic modelling methods to numerically simulate ITD and its effect on the economic and environmental system.

It is often argued that the economic modelling provides a solid framework that enables to represent the rich details of the ITD mechanism, and modelling ITD thus becomes a fruitful avenue for energy and climate economics and policy studies, with a variety of large-scale modelling works emerging in the recent literature. For example, multi-region, multi-sector CGE models are built as the platform to explore the effect of ITD across countries (e.g., Gerlagh and Kuik, 2007; Hübler 2011). The Ramsey growth model is employed to incorporate the mechanism of embodied technology diffusion (e.g., Leimbach and Baumstark, 2010; Leimbach and Edenhofer, 2007; Leimbach and Eisenack, 2009). The Integrated Assessment Model that combines the economic system with energy-climate one is also used to represent the disembodied knowledge spillovers (e.g., Buonanno et al., 2003; Bosetti et al., 2008, 2011; Parrado and De Cian, 2014).

While the large-scale structural modelling studies have the merit of comprehensiveness in representing the realistic economy and policy impacts, a common characteristic weakness is that inside the complex "black box" model structures, representations of specific economic mechanisms normally become unambiguous, making it difficult to understand and capture the underlying mechanism of ITD for energy and carbon savings. Hence, a helpful method is to simplify the unnecessary complexity inherent in these large-scale structural models and explore the underlying mechanism of ITD from an intuitive analytical framework. This paper contributes to providing an intuitive framework that analytically examines the mechanism of ITD for energy productivity changes. Such an analytical framework is particularly compelling in both helping comprehend the basic mechanism of ITD for energy efficiency improvement (positive issues) and providing methodological guidance on how to incorporate specifications of ITD in energy and climate policy modeling studies (normative issues).

The rest of this paper is organized as follows. Section 2 presents an analytical framework of ITD for energy productivity growth, where we first develop a benchmark Solow-type exogenous model in Section 2.1 and then extend it into a Romer-type endogenous model in Section 2.2. Section 3 presents a numerical example to illustrate the analytical model. Section 4 concludes.

2. An analytical framework

2.1 An exogenous model of energy technology diffusion

The benchmark analytical framework used draws on the Solow growth model to describe the mechanism of ITD for energy productivity growth. We suppose that the world economy consists of J countries, indexed by $j = 1, 2, ..., J$, and each economy admits a representative energy firm with access to a production function for producing final-use (secondary) energy products and services:

$$Y_j(t) = F\big(K_j(t), A_j(t) \cdot E_j(t)\big) \quad ,$$

where $Y_j(t)$ denotes the outputs of final energy products produced by the energy sector in country j at time t. $K_j(t)$ and $E_j(t)$ are capital and primary energy inputs into the energy sector in country j, respectively. $A_j(t)$ is the energy input-augmentation coefficient of country j at time t (country-specific, time-varying), as a measurement of the energy use efficiency level of the energy sector in country j. The production function $F(.,.)$ satisfies the standard neoclassical assumptions and exhibits constant returns to scale in K and E.[1]

We define the productivity, measured as the outputs per unit of physical primary energy input, of the energy sector in country j at time t as: [2]

$$\begin{aligned} y_j(t) &\equiv \frac{Y_j(t)}{E_j(t)} = \frac{F(K_j(t), A_j(t)\cdot E_j(t))}{E_j(t)} \\ &= \frac{A_j(t)\cdot E_j(t)}{E_j(t)}\cdot F\left[\frac{K_j(t)}{A_j(t)\cdot E_j(t)}, 1\right] \quad , \\ &= A_j(t)\cdot f(k_j(t)) \end{aligned} \tag{1}$$

where the second line uses the property of constant returns to scale of the function $F(.,.)$, and the third line defines output per effective energy input

$$\frac{Y_j(t)}{A_j(t)\cdot E_j(t)} = f(k_j(t)) \tag{2}$$

as a function $f(\cdot)$ of the effective capital-energy ratio defined as:

$$k_j(t) \equiv \frac{K_j(t)}{A_j(t)\cdot E_j(t)} \quad . \tag{3}$$

Suppose that, each economy $j = 1,2,...,J$ is in continuous time running to an infinite horizon. The supply of primary energy resources available to each country increases at a constant growth rate n_j. There is also a country-specific exogenous saving rate s_j for fixed capital investment in energy infrastructure and a depreciation rate of capital δ. Based on this standard Solow growth model assumption, we derive the following straightforward result:

Lemma 1 *In the above-described environment, the law of motion of the effective capital-energy ratio for each country* $j = 1,2,...,J$ *takes the form:*

$$\dot{k}_j(t) = s_j\cdot f(k_j(t)) - (n_j + g_j(t) + \delta)\cdot k_j(t) \quad , \tag{4}$$

where $g_j(t) \equiv \dot{A}_j(t)/A_j(t)$ *denotes the proportionate rate of change in the energy technology level of*

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[1] We also impose the standard assumptions on the aggregate production function, including continuity, differentiability, positive and diminishing marginal products, homogeneous of degree one, and the Inada conditions

[2] Note that, for the energy sectors the output denotes final secondary energy products/services for end-uses, while the energy input represents the inputs of primary energy resources.

country j *at time* t*. The initial conditions are* $k_j(0)$ *and* $A_j(0)$ *for each economy* j*.*

Proof. See Appendix A. ■

To represent the mechanism of ITD, we assume that there exists a "world technology frontier" that advances its technology level $A(t)$ at a constant exogenous rate: $g \equiv \dot{A}(t)/A(t)$, and each economy j advances its energy technology level by absorbing technology diffused from this world frontier at an exogenous knowledge absorption rate. The law of motion for country j's energy technology level thus takes the form as:

$$\dot{A}_j(t) \;=\; \sigma_j \cdot (A(t) - A_j(t)) + \lambda_j \cdot A_j(t) \quad , \tag{5}$$

where σ_j denotes the rate (capacity) of foreign knowledge absorption specific to country j, and this country-specific property reflects cross-country differences in institutional barriers (like R&D, human capital, national innovation system) that affect technology diffusion and absorption. Suppose that the technology level of the global frontier $A(t)$ is the world's maximal technology accessible to individual countries for diffusion and absorption, so that $A_j(t) \leq A(t)$ for all country j and time t. The technology gap relative to the world frontier $A(t) - A_j(t)$ remains to be absorbed by the country considered, suggesting that the countries that are relatively backward relative to the frontier tend to absorb more knowledge diffusion from abroad and thus advance their indigenous technology levels.[3]

Eq. (5) also suggests that TC benefits from indigenous innovation, which depends on the existing level of technology $A_j(t)$ and the efficiency of indigenous innovation λ_j (both are country-specific). Eq. (5) thus captures the two major sources of TC that a particular country experiences: ITD from the world technology frontier, and local indigenous innovation. To proceed in a tractable way, we define the proportional technology gap $a_j(t) = A_j(t)/A(t)$ as a measure of country j's technology distance relative to the world frontier at time t. We then obtain the following results.

Lemma 2 *In the above-described environment, the law of motion of the proportional technology gap for each country* $j = 1, 2, \ldots, J$ *takes the form:*

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[3] This potential advantage of relatively backward economies plays an important role in ensuring a stable world distribution of energy productivity across countries. But this does not necessarily mean that countries with access to energy technologies available in the world can immediately acquire all of the knowledge from the frontier, and the weaker knowledge absorptive capacities of the backward countries tend to inhibit effective absorption of foreign technologies.

$$\dot{a}_j(t) \; = \; \sigma_j - (\sigma_j + g - \lambda_j)\cdot a_j(t) \;, \tag{6}$$

where the initial condition of this differential equation $a_j(0) \equiv A_j(0)/A(0)$ *can be calculated given* $A(0)$ *and* $A_j(0)$.

Proof. See Appendix B. ■

The equilibrium of effective capital-energy ratios $[k_j(t)]_{j=1}^J$ and proportional technology gaps $[a_j(t)]_{j=1}^J$ in this world economy can be characterized by the dynamic system of $2J$ differential equations (Eq. (4), Eq. (6)). Given the exogenous parameters σ_j, g, λ_j and the initial condition $a_j(0)$, we can capture for the time path of the proportional technology gap $\{[a_j(t)]_{t=0}^{\infty}\}_{j=1}^J$. Given $\{[a_j(t)]_{t=0}^{\infty}\}_{j=1}^J$, the time sequence of the effective capital-energy ratio $\{[k_j(t)]_{t=0}^{\infty}\}_{j=1}^J$ is characterized as:

$$\dot{k}_j(t) \; = \; s_j\cdot f(k_j(t)) - (n_j + g_j(t) + \delta)\cdot k_j(t) = s_j\cdot f(k_j(t)) - \left[n_j + \frac{\dot{a}_j(t)}{a_j(t)} + g + \delta \right]\cdot k_j(t) \;. \tag{7}$$

where the proportionate rate of change in the energy technology level in country j at time t, $g_j(t)$, is expressed as:

$$g_j(t) = \frac{\dot{A}_j(t)}{A_j(t)} = \frac{\dot{(a_j(t)\cdot A(t))}}{A_j(t)} = \frac{a_j(t)\cdot \dot{A}(t)}{A_j(t)} + \frac{\dot{a}_j(t)\cdot A(t)}{A_j(t)} = \frac{\dot{A}(t)}{A(t)} + \frac{\dot{a}_j(t)}{a_j(t)} = g + \frac{\dot{a}_j(t)}{a_j(t)} \;.$$

Given the environment described above, we define a world equilibrium as an allocation $\{[k_j(t), a_j(t)]_{t=0}^{\infty}\}_{j=1}^J$ such that Eq. (6) and Eq. (7) are satisfied for each country j and time t, starting with the initial conditions $[k_j(0), a_j(0)]_{j=1}^J$. Based on the two Lemmas, we thus obtain the following proposition.

Proposition 1 *In the above-described exogenous model of energy technology diffusion, there exists a unique balanced growth path (BGP) world equilibrium in which the proportional technology gap* $a_j(t)$ *and the effective capital-energy ratio* $k_j(t)$ *in each country* $j = 1, 2, \ldots, J$ *remain unchanged. The proportional technology gap of country j relative to the world frontier has its BGP level as:*

$$a_j^* \; = \; \frac{\sigma_j}{\sigma_j + g - \lambda_j} \;,$$

and the BGP level of the effective capital-energy ratio k_j^* *is determined by*

$$\frac{s_j \cdot f(k_j^*)}{k_j^*} = n_j + g + \delta \ .$$

Proof. See Appendix C. ■

Proposition 1 states that an economy that has a weaker knowledge absorptive capacity of assimilating ITD from the world technology frontier ($\sigma_j \downarrow$), and those that are not efficient in indigenous innovation ($\lambda_j \downarrow$) will have a larger technology gap relative to the world frontier in the BGP equilibrium. It is also indicated that an economy that has a higher saving rate for capital investment ($s_j \uparrow$) and a lower growth rate of primary energy supply ($n_j \downarrow$) will have a higher BGP level of the effective capital-energy ratio. Building on the Proposition 1, we obtain the following result.

Proposition 2 *In the BGP world equilibrium, the time path of the primary energy use efficiency of the country* $j = 1, 2, ..., J$ *can be described as* $A_j(t) = \exp(g \cdot t) \cdot A_j^*$ *with*

$$A_j^* = A^* \cdot \frac{\sigma_j}{\sigma_j + g - \lambda_j} \ ,$$

and the time path of the energy productivity level of country j can be written as $y_j(t) = \exp(g \cdot t) \cdot y_j^*$*, with*

$$y_j^* = A^* \cdot \frac{\sigma_j}{\sigma_j + g - \lambda_j} \cdot f(k_j^*) \ ,$$

where A^* *is the level of the primary energy use efficiency of the world technology frontier in the BGP equilibrium. Both* A_j^* *and* y_j^* *are increasing in knowledge absorptive capacity* σ_j *and indigenous innovative capacity* λ_j.

Proof. See Appendix D. ■

Proposition 2 suggests that, despite the cross-country differences in the rates of foreign technology absorption and indigenous innovation, the improvement rate of primary energy use efficiency $A_j(t)$ and energy productivity level $y_j(t)$ are the same across countries in the BGP equilibrium, which all equal the growth rate of the world technology frontier g. The reason is that foreign technology diffusion and absorption is higher when the technology gap of a particular country relative to the world frontier is greater, and there is a force pulling the backward economies toward the technology frontier, ensuring that individual countries grow at the same rate in the BGP equilibrium.

However, the same growth rate does not imply a cross-country convergence to the same level of energy productivity. Differences in the rates of technology absorption and indigenous innovation translate into notable differences in energy productivity levels across countries. In particular, an economy that imposes the barriers slowing technology diffusion and absorption from the external world ($\sigma_j \downarrow$), and those that are not efficient in indigenous innovation ($\lambda_j \downarrow$) will have a lower level of energy productivity.

2.2 An endogenous model of energy technology diffusion

In the exogenous model introduced in Section 2.1, the feature of model exogeneity lies in two aspects. First, the model directly adopts the parameters of energy input efficiency to exogenously represent energy technology level, without offering insights into the deep structure of technology and the endogenous process of TC. Second, specifications of the innovation possibility frontier (the law of motion of technology in Eq. (3)) use the exogenous knowledge absorption rate in describing the process of ITD, taking no account of the endogenous factors that may affect the technology diffusion and absorption.

In fact, private firms often engage in R&D-related activities for advancing technologies, suggesting that the dual drivers of TC (indigenous innovation, and ITD) occur endogenously. This section thus introduces these types of purposeful R&D activities directed at improving energy technology. The analytical framework is building on the endogenous growth models with expanding input varieties (Romer, 1987, 1990). That is, energy R&D plays an important role in creating new varieties of energy inputs,[4] and a larger number of intermediate energy input varieties boosts the productivity of the energy sector producing final energy products and services. As compared to the exogenous model where technology levels are described by exogenous parameters, a notable feature of the endogenous model is to represent technology and TC as input variety creation/expansion induced by R&D-related activities.

We begin by specifying that the final energy product is produced competitively in the energy sector in each economy $j = 1, 2, \ldots, J$ at time t with the production function:

$$Y_j(t) = \frac{1}{1-\alpha_j} \cdot K_j(t)^{\alpha_j} \cdot E_j(t)^{1-\alpha_j} \quad , \tag{8}$$

where

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[4] For example, in addition to traditional fossil fuel-based energy (coal, oil, and natural gas), these new varieties of primary energy resources include nuclear energy, hydropower, solar energy, wind power, ocean wave power, bioenergy, and geothermal.

$$E_j(t) = \left[\int_0^{N_j^E(t)} x_j^E(v,t)^{\frac{\varepsilon_j - 1}{\varepsilon_j}} dv \right]^{\frac{\varepsilon_j}{\varepsilon_j - 1}} \tag{9}$$

with $\varepsilon_j \equiv 1/a_j$ denoting the elasticity of substitution between different primary energy input varieties. The Cobb-Douglas function in Eq. (8) reflects constant returns to scale in capital K_j and the aggregate energy input bundle E_j. The term $(1-a_j)$ in the denominator is used for notional simplicity. $N_j^E(t)$ measures the number of different varieties of intermediate energy inputs into the energy sector in country j at time t. The energy input bundle is specified as a CES aggregator of the N_j^E differentiated varieties of primary energy inputs. $x_j^E(v,t)$ is the amount of primary energy input variety v into the energy sector in country j at time t.

In each economy $j = 1,2,...,J$, any given variety $v \in [0, N_j^E(t)]$ of intermediate primary energy input fully depreciates after use in the energy sector that produces final (secondary) energy goods and services. Energy input of each variety is owned and supplied by an energy technology monopolist, which sells its differentiated energy input variety at a price $p_j^E(v,t)$. This monopolistic supplier produces each unit of this energy input variety at a marginal cost of $\psi_j \equiv 1 - a_j$ units of the final energy goods (normalization for notional simplicity). In the presence of a fully enforced perpetual patenting system, this monopolistic energy firm has the value of owing each differentiated energy variety $v \in [0, N_j^E(t)]$ as:

$$\begin{aligned} V_j^E(v,t) &= \int_t^\infty \exp\left[-\int_t^s r_j(s') \cdot ds' \right] \cdot \pi_j^E(v,s) \cdot ds \\ s.t. \;\; \pi_j^E(v,t) &\equiv p_j^E(v,t) \cdot x_j^E(v,t) - \psi_j \cdot x_j^E(c,t) \;\; , \end{aligned} \tag{10}$$

where $V_j^E(v,t)$ is expressed as a discounted present value of future profit streams from time t to the infinite future, with the interest rate $r_j(t)$ as the discounting factor. $\pi_j^E(v,t)$ is the current flow profit, with $p_j^E(v,t)$ and $x_j^E(v,t)$ denoting the profit-maximizing price and quantity choices of this energy technology monopolist. The value of owing the energy variety v can be rewritten in the form of a Hamilton-Jacobi-Bellman (HJB) equation as:

$$\pi_j^E(v,t) + \dot{V}_j^E(v,t) - r_j(t) \cdot V_j^E(v,t) = 0 \;\; ,$$

where the first term represents the gain of current profit flow. The second term comes from the fact that the maximized value can vary over time. The last term corresponds to the loss of value due to losses of interest rates. We then obtain the following result.

Lemma 3 *In the above-described environment, a BGP world equilibrium exists in which interest rate and flow profits are hold constant at some level* $r_j(t) = r_j^*$, $\pi_j^E(c,t) = \pi_j^{E*}$. *The BGP equilibrium also implies a constant maximized value* $\dot{V}_j^E(v,t) = 0$, *and the maximized value possessed by the technology monopolist owing each energy input variety* $v \in [0, N_j^E(t)]$ *takes a form as:*

$$V_j^{E*} = \frac{\pi_j^{E*}}{r_j^*} = \frac{a_j \cdot K_j^*}{r_j^*} \quad . \tag{11}$$

Proof. See Appendix E. ■

As the other departure from the exogenous model, the endogenous model specifies the innovation possibility frontier as an expansion of energy input variety induced by R&D:

$$\dot{N}_j^E(t) = \eta_j \cdot Z_j^E(t) + \left(\frac{N^E(t)}{N_j^E(t)}\right)^{\varphi_j} \cdot Z_j^E(t) \quad , \tag{12}$$

where $Z_j^E(t)$ denotes energy R&D investment in country j at time t, and the innovation possibility gains from R&D are harvested from two sources: R&D not only creates in-house new energy varieties, but also enhances indigenous capacity to assimilate foreign technology diffusion – the so-called dual faces of R&D in innovation (Cohen and Levinthal, 1989; Keller, 1996, 2004). η_j denotes the country-specific efficiency in creating in-house energy varieties. Country j with access to ITD will learn and assimilate foreign energy technology varieties according to its proportional gap relative to the world technology frontier $N^E(t)/N_j^E(t)$. φ_j governs the efficiency at which country j absorbs foreign energy varieties. The number of energy input varieties of the world frontier grow at an exogenous rate $\dot{N}^E(t)/N^E(t) = g$.

The endogenous representation of the innovation possibility frontier, Eq. (12), implies that countries that are relatively technologically backward (having a small number of energy technology varieties and thus a larger technology gap compared to the world frontier) tend to learn and assimilate more varieties from the world frontier. This specification thus reflects the same basic idea as in the exogenous model: technological progress in a particular economy is driven by both local indigenous innovation and technology diffusion from the world frontier.

Based on the innovation possibility frontier, Eq. (12), we suppose that there is free entry into energy technology R&D. That is, once spending one unit of R&D, the energy firm in each economy j can create a rate $\eta_j + (N^E(t)/N_j^E(t))^{\varphi_j}$ of new energy technology varieties, with each variety having a value given by Eq. (10). Thus, the free entry (no-arbitrage) condition in energy R&D takes the form as:

$$\left[\eta_j + \left(\frac{N^E(t)}{N_j^E(t)}\right)^{\varphi_j}\right] \cdot V_j^E(v,t) = \tau_j \quad , \tag{13}$$

where the LHS denotes the marginal benefit of R&D: one unit of R&D spending leads to the creation of $\eta_j + (N^E(t)/N_j^E(t))^{\varphi_j}$ units of new energy varieties, each with a value of $V_j^E(v,t)$. The RHS denotes the marginal cost of R&D spending in country j, and the parameter $\tau_j \neq 1$ is introduced to represent country-specific unit costs in R&D investment, reflecting potential cross-country difference in innovation policy settings (e.g., R&D grant, R&D tax credit).

Based on the Lemma 3 and the endogenous treatment of innovation possibility frontier described above, we thus obtain the following proposition.

Proposition 3 *In the endogenous model of energy technology diffusion presented above, there exists a BGP world equilibrium where each country's energy technology variety relative to the world frontier is given by,*

$$\frac{N_j^{E^*}}{N^{E^*}} = \left[\frac{\tau_j \cdot r_j^*}{a_j \cdot K_j^*} - \eta_j\right]^{-\frac{1}{\varphi_j}} \quad . \tag{14}$$

In the BGP world equilibrium, the energy input varieties owned by each economy $j = 1,2,\ldots,J$ *grow at the same rate as the world technology frontier:*

$$\frac{\dot{N}_j^{E^*}}{N_j^{E^*}} = \frac{\dot{N}^{E^*}}{N^{E^*}} = g \quad ,$$

and an economy with more energy input varieties (hence a lower proportional gap relative to the world frontier) will have a higher level of productivity in the energy sector.

Proof. See Appendix F. ■

Proposition 3 states that, in the BGP equilibrium each country's energy technology gap relative to the world frontier (measured as the proportional gap of energy input varieties) depends on three determinants: the efficiency of indigenous innovation (η_j), the capacity of absorbing foreign technology diffusion (φ_j), and the cost of R&D investment (τ_j). It is thus implied that countries that are more efficient in indigenous energy innovation ($\eta_j \uparrow$), those with stronger capacities of assimilating technology diffusion ($\varphi_j \uparrow$) and lower costs of R&D

($\tau_j \downarrow$) tend to have more energy technology varieties and smaller gaps as compared to the world technology frontier. The country with more differentiated energy technology varieties (a higher level of $N_j^{E^*}/N^{E^*}$) is more productive in producing final energy goods/services.

3. A numerical example

To illustrate the analytical results presented in Section 2.1, we provide a numerical example. To start with, we solve the first-order linear differential equation Eq. (6) for the time paths of the proportional technology gaps $\{[a_j(t)]_{t=0}^{\infty}\}_{j=1}^{J}$. The analytical solution expressing $a_j(t)$ as a function of time t is derived as:

$$a_j(t) = a_j(0) \cdot \mathrm{e}^{-(\sigma_j + g - \lambda_j)\cdot t} + \frac{\sigma_j}{\sigma_j + g - \lambda_j} \cdot [1 - \mathrm{e}^{-(\sigma_j + g - \lambda_j)\cdot t}] \;, \tag{15}$$

where $a_j(0)$ gives the initial condition for country j's proportional technology gap relative to the world technology frontier. $a_j^* = \sigma_j/(\sigma_j + g - \lambda_j)$ denotes the BGP level of $a_j(t)$ (see Proposition 1). $\sigma_j + g - \lambda_j$ measures the rate at which the dynamics of $a_j(t)$ approaches its BGP equilibrium level a_j^*.

In terms of parameterization, we start by imposing the condition $g \equiv \dot{A}(t)/A(t) = 0.02$, that is, the world technology frontier advances its energy input efficiency level at a rate of 2%.[5] Furthermore, individual country's energy input efficiency level is always less than the world frontier's maximal level, $A_j(t) < A(t)$ for all country $j = 1, 2, ..., J$ and time t. This implies that country j's proportional technology gap relative to the world frontier is less than unity, $a_j^* = \sigma_j/(\sigma_j + g - \lambda_j) < 1$, that is, $\lambda_j < g$. Finally, suppose that indigenous innovative efforts are more important than absorbing foreign knowledge diffusion in fostering domestic TC, we thus impose the condition $\sigma_j < \lambda_j$.[6]

The parameterization is summarized in Tab. 1, where we divide the world economy into three world regions, including the developed countries (OECD), the emerging economies including Brazil, Russia, India, and China (BRICs), and the developing world (ROW). Given the parameter values, we solve the first-order differential equations, Eq. (6), and capture the

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[5] The world technology frontier is based on the U.S. which has achieved the biggest improvement in energy input efficiency in recent decades within technologically advanced countries. The U.S. improves its energy input efficiency at an annual average rate of 2% from 1980-2010 (IEA, 2012).

[6] This reflects the "no free lunch" assumptions: to benefit from innovation and TC, domestic countries should commit to undertake indigenous innovative activities and not solely free ride on foreign knowledge diffusion.

time paths of the proportional technology gap of the three world regions relative to the world technology frontier $\{[a_j(t)]_{t=0}^{\infty}\}_{j=1}^{J}$.[7]

Table 1
Parameter values assumed in solving the differential equation Eq. (3) for the time paths of the proportional technology gap of the three world regions $\{[a_j(t)]_{t=0}^{\infty}\}_{j=1}^{J}$

	g	σ_j	λ_j	$a_j(0)$
OECD	0.02	0.015	0.018	0.8
BRICs	0.02	0.010	0.015	0.15
ROW	0.02	0.005	0.008	0.05

g : The growth rate of energy productivity of the world technology frontier.
σ_j : The region j's capacity of absorbing technology diffusion from the world frontier
λ_j : The region j's capacity of indigenous innovation.
$a_j(0)$: The region j's initial values of proportional technology gap relative to the world technology frontier. The values are calculated based on the share of R&D expenditure of the three world regions relative to the global R&D totals.

As Fig. 1(a) shows, the advanced OECD has the smallest energy technology gap relative to the world frontier, approaching a level of 0.9 in the BGP equilibrium. The emerging BRICs follow, with a BGP energy technology gap between 0.6-0.7 relative to the world frontier. The developing ROW is in the most technologically backward position in global technology ladder, and its proportional technology gap relative to the world frontier just reaches a level of 0.3 in the BGP equilibrium. These numerical results thus coincide with the analytical findings (see Proposition 1), in the sense that the technologically advanced OECD has stronger capacities in both indigenous innovation and foreign knowledge absorption (with the highest values of σ_j, λ_j, see Tab.1), and thus create the smaller gap relative to the world technology frontier. In contrast, the technologically backward ROW, with the lowest level of indigenous innovation λ_j and knowledge absorptive capacity σ_j, tends to have the largest technology gap.

Once the time sequence of the proportional technology gap $\{[a_j(t)]_{t=0}^{\infty}\}_{j=1}^{J}$ is determined, we can immediately calculate the level of energy input use efficiency $\{[A_j(t)]_{t=0}^{\infty}\}_{j=1}^{J}$ using the formula $A_j(t) = a_j(t) \cdot A(t)$, where $A(t)$ is the energy input efficiency of the world frontier that

---

[7] The MATLAB built-in ODE45 solver is used to solve the first-order ordinary differential equation (ODE). The ODE45 solver is based on explicit Runge-Kutta methods, and is best suited for solving non-stiff ODE problems. The MATLAB codes for our model are available upon request.

evolves exponentially according to $A(t) = A(0) \cdot \exp(g \cdot t)$, as the world frontier advances its energy technology level A(t) at a constant exogenous rate: $g \equiv \dot{A}(t)/A(t)$.

Fig. 1(b) illustrates the time paths of the energy use efficiency levels for the three regions and the world technology frontier. Over the time frame of simulation, the world technology frontier advances its energy input efficiency level $A(t)$ at a constant exogenous rate of 2%, and that efficiency improvement rates for OECD, BRICs, and ROW average to 2.03%, 2.32%, and 2.38%, respectively, Note that, despite the cross-country differences in the rates of technology absorption and indigenous innovation, the growth rates of energy input efficiency converge in the BGP equilibrium, which equal the growth rate of the world frontier g=2%. The reason is that a higher level of ITD occurs when the technology gap of backward economies relative to the world frontier is greater. There is thus a force pulling both BRICs and ROW toward the world technology frontier, ensuring the same rate of energy input efficiency improvement in the long-run BGP equilibrium. This numerical result fits well with Proposition 2.

However, the levels of energy input efficiency tend to diverge across countries due to cross-country differences in the capacity of technology absorption and indigenous innovation. As Fig. 1(b) shows, the OECD with a techno-economic system in favor of foreign technology diffusion ($\sigma_j \uparrow$) and indigenous innovation ($\lambda_j \uparrow$) will have the highest level of energy input use efficiency. Again this result is consistent with Proposition 2.

Turning to the other half of the differential equations that characterize the equilibrium, we proceed by solving for the law of motion for the effective capital-energy ratios of the three world regions $\{[k_j(t)]_{t=0}^{\infty}\}_{j=1}^{J}$ as:

$$\begin{aligned} \dot{k}_j(t) &= s_j \cdot f(k_j(t)) - \left[n_j + \frac{\dot{a}_j(t)}{a_j(t)} + g + \delta \right] \cdot k_j(t) \\ \textit{with} \ \frac{\dot{a}_j(t)}{a_j(t)} &= \frac{-(\sigma_j + g - \lambda_j) \cdot \left[a_j(0) - \dfrac{\sigma_j}{\sigma_j + g - \lambda_j} \right] \cdot \mathrm{e}^{-(\sigma_j + g - \lambda_j) \cdot t}}{\left[a_j(0) - \dfrac{\sigma_j}{\sigma_j + g - \lambda_j} \right] \cdot \mathrm{e}^{-(\sigma_j + g - \lambda_j) \cdot t} + \dfrac{\sigma_j}{\sigma_j + g - \lambda_j}} \ , \end{aligned} \tag{16}$$

where the proportional growth rate of $a_j(t)$ is written explicitly using Eq. (15). Substituting $\dot{a}_j(t)/a_j(t)$ into Eq. (16), the law of motion of $[k_j(t)]_{t=0}^{¥}$ is a first-order ordinary differential equation which can be easily solved using the MATLAB ode45 solver. The parameter values assumed in solving Eq. (16) are listed in Tab. 2, and Fig. 2(a) illustrates the time sequences of the effective capital-energy ratios for the three world regions $\{[k_j(t)]_{t=0}^{\infty}\}_{j=1}^{J}$.

Table 2
Parameter values assumed in solving the differential equation Eq. (4) for the time paths of the effective capital-energy ratios of the three world regions $\{[k_j(t)]_{t=0}^{\infty}\}_{j=1}^{J}$

	s_j	a_j	n_j	δ	$k_j(0)$
OECD	0.3	0.7	0.02	0.1	2.33
BRICs	0.28	0.65	0.025	0.1	1.86
ROW	0.25	0.6	0.03	0.1	1.5

s_j: The region j's exogenous saving rate.

a_j: The region j's output elasticity of capital (including physical capital, human capital, and R&D capital), it also denotes the capital input share of the output in a Cobb-Douglas production function.

n_j: The region j's growth rate of primary energy input supply.

δ: The depreciation rate of capital.

$k_j(0)$: The initial values of region j's effective capital-energy ratio, and the values are calculated based on the capital share of total output: $k_j(0) = a_j/(1- a_j)$.

As Fig. 2(a) shows, the highest BGP level of the effective capital-energy ratio is obtained in the developed OECD, followed by the emerging BRICs, and finally the developing ROW. This simulation result is consistent with Proposition 1. In this regard, the OECD has the highest saving rate $s_j \uparrow$ (for capital investments including physical capital, human capital, and knowledge capital), the lowest growth rate of primary energy supply $n_j \downarrow$, and the highest shares of capital use in production $a_j \uparrow$. The OECD thus has the highest level of the effective capital-energy ratio in the BGP equilibrium. In contrast, both BRICs and ROW tend to have a lower level of effective capital-energy ratio due to the fact that they have relatively a lower saving rate for the capital investment especially human and R&D capital, a higher rate of energy inputs supply, and a higher cost share of energy use in production.

Once the time path of the effective capital-energy ratio $[k_j(t)]_{t=0}^{\infty}$ is captured, we turn to calculating the output per effective energy input using the following formula:

$$\frac{Y_j(t)}{A_j(t)\cdot E_j(t)} = f(k_j(t)) = k_j(t)^{a_j}.$$

where we impose a Cobb-Douglas form of production technology, with a_j denoting country j's output elasticity of capital in the function $f(.)$. Finally, given the time paths of $[A_j(t)]_{t=0}^{\infty}$ and $[f(k_j(t))]_{t=0}^{\infty}$, we calculate the output per unit of energy input $[y_j(t)]_{t=0}^{\infty}$ as:

$$y_j(t) \equiv \frac{Y_j(t)}{E_j(t)} = A_j(t) \cdot f(k_j(t)).$$

Fig. 2(b) and Fig. 2(c) show the time paths of output per effective energy input and output per physical energy input, respectively.

It is shown that, for each world region the output per effective unit of energy input $[f(k_j(t))]_{t=0}^{\infty}$ remains constant, but the output per unit of physical energy input $[y_j(t)]_{t=0}^{\infty}$ is growing in the BGP equilibrium. This trend suggests that by raising the efficiency of physical primary energy input use, energy-augmenting TC plays an important role in sustaining final energy goods/services productions (for the purpose of meeting the growing market demand) under the constraint of the decline in primary energy resources available in the long run.

Moreover, Fig. 2(c) shows that, over the time frame the average annual growth rates of output per physical energy input for OECD, BRICs, and ROW are 2.22%, 2.41%, and 2.44%, respectively, all three converging to 2% (the growth rate of energy use efficiency of the world frontier) in the BGP equilibrium. The reason is that when the backward economies has larger technology gaps as compared to the world frontier, the force of foreign technology diffusion serves to pull the technologically backward countries toward the world frontier, ensuring that all countries grow at the same rate in the long run. However, the levels of output per unit of physical energy input tend to diverge due to the cross-country differences in the capacities of foreign technology absorption and indigenous innovation. The advanced OECD has a highest level of output per physical energy input in the BGP equilibrium for the reason that it has a stronger capacity in foreign technology absorption ($\sigma_j \uparrow$) and indigenous innovation ($\lambda_j \uparrow$). These results thus echo the findings in Proposition 2.

4. Concluding remarks

The importance of cross-country technological interdependences and diffusions has received much attention in formulating policies to address global energy and climate problems. A detailed exposition of the mechanism of ITD for energy productivity growth has been placed high upon research agenda. The existing literature involves numerous large-scale numerical modelling that simulates the effect of energy technology diffusion, but a common weakness of these works is that inside the complex “black box” modeling structures, the representations of ITD are unambiguous, making it difficult to identify and analyze the mechanism of energy technology diffusion. This paper contributes to a helpful complement by providing an intuitive framework that analytically examines the general mechanism of ITD for energy productivity growth.

We draw on the Solow growth model to build an exogenous framework that describes the mechanism of energy technology diffusion where the energy input use efficiency is used to represent the country-specific, time-varying energy technology level. We find that, in the BGP equilibrium the growth rate of energy input efficiency and energy productivity level are the same across countries, which all equal the growth rate of the world technology frontier. The reason is that more foreign technology inflows may occur when the technology gap of a particular country relative to the world frontier is larger. There is thus a force pulling the technologically backward economies toward the world frontier, ensuring that all countries grow at the same rate in the BGP equilibrium. However, the cross-country differences in the capacity of foreign technology absorption and indigenous innovation lead to a cross-country divergence in the levels of energy productivity. Economies with stronger capacities of foreign technology absorption and efficient indigenous innovations tend to have the highest levels of energy use efficiency and energy productivity.

The exogenous framework is then extended to a Romer-type endogenous model where R&D-induced expansions of energy input varieties are used to represent the deep structure of energy technology diffusion. We find that in the BGP equilibrium each country’s proportional gap of energy technology varieties relative to the world frontier depends on three factors: the efficiency of indigenous R&D, the capacity of absorbing foreign knowledge, and the cost of R&D spending. Countries with higher efficiencies in indigenous innovation, stronger capacity of foreign technology absorption, and lower costs of R&D tend to have more differentiated energy technology varieties and thus smaller technology gaps relative to the world frontier. As a consequence, the country with more energy technology varieties tends to be more productive in producing final energy goods/services.

Appendix

Appendix A: Proof of Lemma 1

$$k_j(t)=\frac{K_j(t)}{A_j(t)\cdot E_j(t)}$$

$$\Rightarrow\quad In(k_j(t))=In(K_j(t))-In(A_j(t))-In(E_j(t))$$

$$\Rightarrow\quad \frac{\dot{k}_j(t)}{k_j(t)}=\frac{\dot{K}_j(t)}{K_j(t)}-\frac{\dot{A}_j(t)}{A_j(t)}-\frac{\dot{E}_j(t)}{E_j(t)}=\frac{s_j\cdot Y_j(t)-\delta\cdot K_j(t)}{K_j(t)}-g_j(t)-n_j=\frac{s_j\cdot Y_j(t)}{K_j(t)}-\delta-g_j(t)-n_j$$

$$\Rightarrow\quad \dot{k}_j(t)=s_j\cdot f(k_j(t))-(\delta+g_j(t)+n_j)\cdot k_j(t)$$

where the second line imposes logarithmic treatments on the equation defining the effective capital-energy ratio. The third line carries out differentiation and uses the law of motion for capital in the spirit of the Solow model. The last line uses the function that defines output per effective energy input. ■

Appendix B: Proof of Lemma 2

$$
\begin{aligned}
& a_j(t) = \frac{A_j(t)}{A(t)} \\
\Rightarrow \quad & In(a_j(t)) = In(A_j(t)) - In(A(t)) \\
\Rightarrow \quad & \frac{\dot{a}_j(t)}{a_j(t)} = \frac{\dot{A}_j(t)}{A_j(t)} - \frac{\dot{A}(t)}{A(t)} = \frac{\sigma_j \cdot (A(t) - A_j(t)) + \lambda_j \cdot A_j(t)}{A_j(t)} - g \\
\Rightarrow \quad & \dot{a}_j(t) = \sigma_j - (\sigma_j - \lambda_j + g) \cdot a_j(t)
\end{aligned}
$$

where the second line imposes logarithmic treatments on the equation defining proportional technology gap. In the third line carries out differentiation and uses the law of motion for energy input efficiency level, Eq. (5). The last line uses the function defining the proportional technology gap. ■

Appendix C: Proof of Proposition 1

For the law of motion of the proportional technology gap, we impose the BGP condition $\dot{a}_j(t) = 0$ on Eq. (6), which yields the unique BGP level, $a_j^* = \sigma_j / (\sigma_j + g - \lambda_j)$. For the law of motion of the effective capital-energy ratio, Eq. (7), we impose the BGP conditions $\dot{k}_j(t) = 0$ and $\dot{a}_j(t) = 0$, and yield the unique BGP equilibrium for k_j^* that satisfies $[s_j \cdot f(k_j^*)] / k_j^* = n_j + g + \delta$. ■

Appendix D: Proof of Proposition 2

For the first part of this proposition, from the equation that define proportional technology gap $a_j(t) = A_j(t)/A(t)$, we have $\dot{a}_j(t)/a_j(t) = \dot{A}_j(t)/A_j(t) - \dot{A}(t)/A(t)$ for all j and time t. In the BGP equilibrium with $\dot{a}_j(t) = 0$, we have $\dot{A}_j^*/A_j^* = \dot{A}^*/A^* = g$, that is, energy input efficiency levels of individual country j grow at the same rate as the world technology frontier.

For the second part, given the definition of energy productivity $y_j(t) = A_j(t) \cdot f(k_j(t))$, we have the BGP equilibrium level $y_j^* = A_j^* \cdot f(k_j^*)$ and the proportional growth rate $\dot{y}_j^*/y_j^* = \dot{A}_j^*/A_j^* - \dot{f}(k_j^*)/f(k_j^*)$. From Proposition 1, in the BGP equilibrium we impose the condition $\dot{k}_j^* = 0, \dot{f}(k_j^*) = 0$, we hence have $\dot{y}_j^*/y_j^* = \dot{A}_j^*/A_j^* = \dot{A}^*/A^* = g$, that is, $y_j(t) = exp(g \cdot t) \cdot y_j^*$, where y_j^* denotes the initial condition of $y_j(t)$ in the BGP equilibrium, $y_j^* = A_j^* \cdot f(k_j^*) = A^* \cdot a_j^* \cdot f(k_j^*)$. Consider that $a_j^* = \sigma_j/(\sigma_j + g - \lambda_j)$ (see Proposition 1), we thus have $y_j^* = A^* \cdot f(k_j^*) \cdot \sigma_j/(\sigma_j + g - \lambda_j)$. ■

Appendix E: Proof of Lemma 3

Consider in the BGP equilibrium, interest rate and flow profit are constant over time, $r_j(t) = r_j^*$, $\pi_j^E(v,t) = \pi_j^{E*}$. A BGP also implies a constant value $\dot{V}_j^E(v,t) = 0$. Following the HJB equation, we then derive $V_j^{E*} = \pi_j^{E*}/r_j^*$, where "*" denotes the BGP value of corresponding variables. To determine the value of current profit flow $\pi_j^E(v,t)$ enjoyed by the technology monopolist owing each energy input variety $v \in [0, N_j^E(t)]$, we first solve the maximization problem of the energy sector producing final goods/services. The problem simply requires the maximization of the instantaneous profits of the representative energy firm. These instantaneous profits can be obtained by subtracting total costs – the costs of renting capitals and using primary energy inputs – from the value of production. Therefore, the maximization problem at time t is

$$\max \ \frac{1}{1-a_j} \cdot \left[\int_0^{N_j^E(t)} x_j^E(v,t)^{1-a_j} dv \right] \cdot K_j(t)^{a_j} - \int_0^{N_j^E(t)} p_j^E(v,t) \cdot x_j^E(v,t) \cdot dv - r_j(t) \cdot K_j(t)$$

The first order condition of this maximization problem with respect to $x_j^E(v,t)$ for any variety $v \in [0, N_j^E(t)]$ yields the demands for each energy input variety from the final energy sector, which takes the isoelastic form: $x_j^E(v,t) = p_j^E(v,t)^{-1/a} \cdot K_j(t)$.

Next we consider the value possessed by the technology monopolist owing each energy input variety, Eq. (10), maximization of this intertemporal profit streams is equivalent to maximizing the instantaneous profit for each point in time:

$$\pi_j^E(v,t) = [p_j^E(v,t) - \psi] \cdot x_j^E(c,t) = [p_j^E(v,t) - \psi] \cdot p_j^E(v,t)^{-1/a} \cdot K_j(t).$$

The first order condition of this maximization problem with respect to $p_j^E(v,t)$ yields a profit-maximizing monopolistic price as a constant markup over the marginal cost of production: $p_j^E(v,t) = \psi_j/(1-a_j) = 1$ (normalization $\psi_j \equiv 1 - a_j$) and supplies the quantity of energy input variety $x_j^E(v,t) = p_j^E(v,t)^{-1/a} \cdot K_j(t) = K_j(t)$. This gives the monopolistic profit flows possessed by the technology monopolist owing each energy input variety $v \in [0, N_j^E(t)]$, as $\pi_j^E(v,t)=x_j^E(v,t)\cdot[p_j^E(v,t)-\psi_j]=(1-\psi_j)\cdot K_j(t)=a_j\cdot K_j(t)$. ■

Appendix F: Proof of Proposition 3

To prove the first part of Proposition 3, we substitute Eq. (11) into the free entry condition, Eq. (13), and yield each country's energy technology variety relative to the world frontier in the BGP equilibrium, Eq. (14). For the second part of Proposition 3, the BGP equilibrium involves a constant gap of energy technology variety for each country $N_j^{E^*}/N^{E^*}=n_j^{E^*}$, with $n_j^{E^*}$ at some constant level. This implies that the energy varieties of each country j should grow at the same rate as the world frontier g.

$$N_j^{E^*}/N^{E^*}=n_j^{E^*} \qquad \Rightarrow \qquad In(N_j^{E^*})-In(N^{E^*})=In(n_j^{E^*})$$
$$\Rightarrow \qquad \frac{\dot{N}_j^{E^*}}{N_j^{E^*}}-\frac{\dot{N}^{E^*}}{N^{E^*}}=0 \qquad \Rightarrow \qquad \frac{\dot{N}_j^{E^*}}{N_j^{E^*}}=\frac{\dot{N}^{E^*}}{N^{E^*}}=g$$

To examine the effect of expanding energy input varieties on the productivity of energy sector producing final energy goods, we need to examine the behaviors of the technology monopolist that supplies each energy input variety. As discussed in the proof of Lemma 3, to maximize the value given by Eq. (10), each energy technology monopolist v Î $[0,N_j^E(t)]$ will set the profit-maximizing monopolist price as:

$$p_j^E(v,t)=p_j^E=\frac{\psi_j}{1-a_j}=1 \quad \text{for all} \quad v\in[0,N_j^E(t)] \quad \text{and} \quad t.$$

and supplies the same quantity of energy input varieties as:

$$x_j^E(v,t)=p_j^E(v,t)^{-\frac{1}{a}}\cdot K_j=K_j(t)=x_j^E(t) \qquad \text{for all} \quad v\in[0,N_j^E(t)] \quad \text{and} \quad t.$$

With the same quantity of each energy input variety supplied in the energy sector producing final energy goods/services, the production function of the energy sector in each economy $j=1,2,\ldots,J$ at time t, Eqs. (8)-(9), can be rewritten as:

$$Y_j(t)=\frac{1}{1-a_j}\cdot\left[\int_0^{N_j^E(t)}x_j^E(v,t)^{1-a}dv\right]\cdot K_j(t)^a=\frac{1}{1-a_j}\cdot\left[N_j^E(t)\cdot K_j(t)^{1-a}\right]\cdot K_j(t)^a$$
$$=\frac{1}{1-a_j}\cdot N_j^E(t)\cdot K_j(t)=\frac{1}{1-a_j}\cdot N_j^E(t)\cdot x_j^E \qquad .$$

It makes it clear that expanding the energy input varieties, $N_j^E(t)$, will raise the efficiency of using each energy variety x_j^E. When the number of energy input variety $N_j^E(t)$ increases at a constant rate g, the productivity/efficiency of using each energy input variety in the final energy sector will also grow at such a constant rate g. ■

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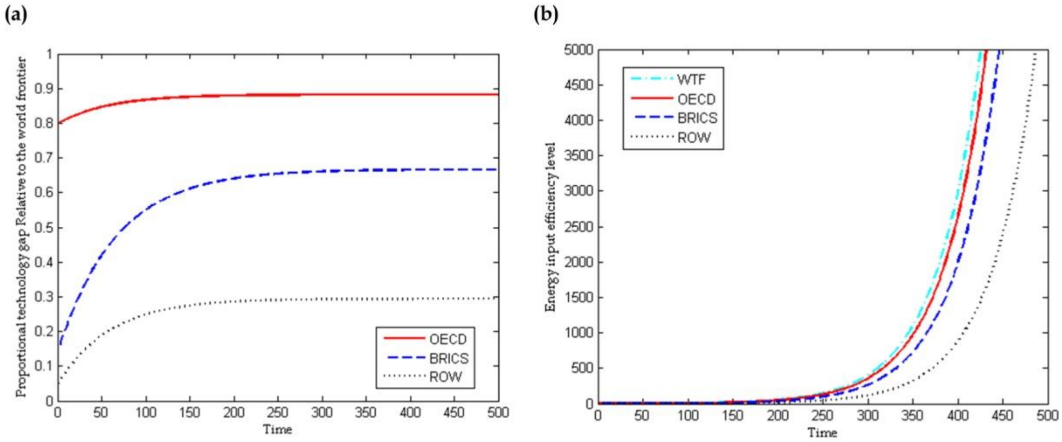

Figure 1: (a) The time paths of the proportional technology gap of the three world regions (OECD, BRICs, and ROW) relative to the world technology frontier, derived from solving the differential equations, Eq. (3), given the parameterization in Tab. 1. The values lie within an range [0, 1], a value of 0 (the lower bound) implies that the region has the largest gap relative to the world frontier, and a value of 1 (the upper bound) means the region is the world technology frontier;
(b) The time paths of the energy input efficiency levels for the world technology frontier (WTF) and the three world regions (OECD, BRICs, and ROW). The unit of the Y axis is the benchmark initial year's energy input efficiency level of the world technology frontier (The initial year's energy input efficiency level of the world technology frontier is normalized to unity).

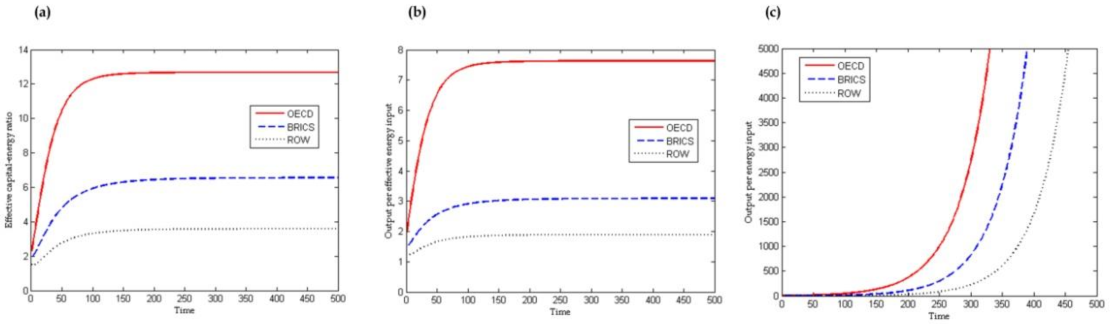

Figure 2: (a) The time paths of the effective capital-energy ratios for the three world regions (OECD, BRICs, ROW), derived from solving the differential equations, Eq. (4), given the parameterization in Tab. 2.. The effective capital-energy ratio is defined by Eq. (3);
(b) The time paths of the output per effective energy input for the three world regions (OECD, BRICs, ROW). The output per unit of effective energy input is defined by Eq. (2);
(c) The time paths of the output per physical energy input for the three world regions (OECD, BRICs, ROW). The output per unit of physical energy input is defined by Eq. (1).

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