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On the Mechanism of International Technology Diffusion for Energy Technological Process

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International diffusion of energy-saving technologies has received considerable attention in recent energy and climate economics studies. As a helpful methodological complement to the existing large-scale CGE/IAM–based modelling for energy and climate policy studies, this paper contributes to a transparent analytical model for an economically intuitive exposition on the fundamental mechanism of international technology diffusion for energy technological growth. We first develop an efficiency-improving vertical innovation model where energy technological progress is specified as an improvement in primary energy use efficiency. Then a variety-expanding horizontal innovation model is presented where energy technological progress is described as an expansion of energy technology variety. We show that in both models there is a cross-country convergence in the growth rate of energy technology in a long-run balanced growth path, but the absolute levels of energy technology tend to diverge due to cross-country differences in indigenous innovation efficiencies and knowledge absorptive capacities. An economy with a stronger capacity of absorbing foreign knowledge diffusion and undertaking indigenous research tends to have a higher level of energy technology.

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Technological Progress; Energy Technology; International Technology Diffusion; Endogenous Technological Change

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Abstract: International diffusion of energy-saving technologies has received considerable attention in recent energy and climate economics studies. As a helpful methodological complement to the existing large-scale CGE/IAM–based modelling for energy and climate policy studies, this paper contributes to a transparent analytical model for an economically intuitive exposition on the fundamental mechanism of international technology diffusion for energy technological growth. We first develop an efficiency-improving vertical innovation model where energy technological progress is specified as an improvement in primary energy use efficiency. Then a variety-expanding horizontal innovation model is presented where energy technological progress is described as an expansion of energy technology variety. We show that in both models there is a cross-country convergence in the growth rate of energy technology in a long-run balanced growth path, but the absolute levels of energy technology tend to diverge due to cross-country differences in indigenous innovation efficiencies and knowledge absorptive capacities. An economy with a stronger capacity of absorbing foreign knowledge diffusion and undertaking indigenous research tends to have a higher level of energy technology.

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1. Introduction

To formulate comprehensive strategies to address global energy and climate challenges, the potential importance of cross-country technological interdependence and interactions should be explicitly considered (Gillingham et al., 2008; Popp et al., 2010a). On the one hand, advanced countries have taken the lead in cross-country technology partnerships for building knowledge-based, energy-efficient economies. On the other hand, the developing world, particularly the emerging economies, direly calls for foreign technology transfers to support indigenous efforts such that their fossil energy uses can be decoupled from rapid economic growth in a cost-efficient way (World Bank, 2008; Popp, 2011).

In this context, the issue of international technology diffusion (ITD) has received considerable attention in current energy/climate policy agenda, and some international frameworks have recently been institutionalized for accelerating energy technology diffusion. For example, the Asia-Pacific Partnership on Clean Development and Climate, the IEA Implementing Agreements, and the Technology Mechanism under the United Nations Framework Convention on Climate Change (UNFCCC). With the issue of ITD placed high upon policy agenda, there is a growing need in our research community to offer deeper insight into the fundamental mechanism of ITD for energy technological progress, such that policies can be appropriately designed to stimulate the participation of individual countries in addressing global energy/climate challenges (Grubb et al., 2002; Philibert, 2004; Popp, 2006a).

Basically, the recent literature has progressed along two research tracks. On the one side, econometricians tend to use econometric methods to examine the empirical evidences of energy technology diffusion (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, energy and climate policy modelers often use large-scale economic modelling approaches to numerically simulate the economic and environmental effects of ITD. Arguably, large-scale economic modelling provides an enabling framework to represent the process details related to ITD, thus becoming a fruitful avenue for studying the issue of ITD in the context of energy economics and policy. For example, some studies build on multi-region, multi-sector computable general equilibrium (CGE) models to examine the impact of ITD for energy/climate issues (e.g., Gerlagh and Kuik, 2007; Hübler 2011; Leimbach and Baumstark, 2010; Leimbach and Edenhofer, 2007; Leimbach and Eisenack, 2009). Others choose Integrated Assessment Model (IAM) as the platform to investigate the potential of international knowledge spillovers for global energy/carbon savings (e.g., Buonanno et al., 2003; Bosetti et al., 2008, 2011; De Cian and Tavoni, 2012; Parrado and De Cian, 2014).

While the above-mentioned large-scale economic modelling have the merit of comprehensiveness in representing the real-world economy for energy/climate policy analysis, a common characteristic weakness is that inside the "black box" complex modelling structure, it is often ambiguous to capture and understand the fundamental mechanism of ITD for global energy/carbon savings. In this context, there is a need in our research community to develop a transparent analytical framework - as a helpful methodological complement to the existing complex large-scale economic modelling - for an economically intuitive exposition of the basic mechanism of ITD for energy technological progress.

Therefore, the main contribution of this paper is to offer transparent, theoretical insights into the fundamental mechanism of ITD for energy technological progress. In particular, we provide two complementary perspectives to explore the underlying process of energy technology diffusion. We first develop an efficiency-improving vertical innovation model where energy technological progress is specified as an improvement in energy use efficiency driven by indigenous innovation and foreign technology diffusion. We further present a variety-expanding horizontal innovation model where energy technological progress is represented by an expansion of energy technology varieties driven by indigenous R&D and foreign technology variety spillover. Throughout the theoretical analysis in both models, we aim to highlight a trend that there is a potential force in the world economy – here working through ITD– that pulls individual countries towards energy technological progress, thus ensuring a relatively similar growth rate across country in the long-run balanced growth path (BGP). This trend predicted on the long-run cross-country convergence in growth rates of energy technology is basically consistent with empirical evidences as documented in IEA's *World Energy Outlook 2012* (IEA, 2012). That is, differences in cross-country growth rates of energy technology are present during transitional dynamic periods, but there are only small differences in sustained growth rate in the long-run BGP when cross-country technology diffusion is present at the world level. With this specific emphasis, our model would become helpful to demonstrate the potential importance of ITD to fostering energy technological growth and improving the participation of individual countries in global energy and climate governance.

The rest of this paper is organized as follows. Section 2 presents an efficiency-improving vertical innovation model of ITD for energy technological progress. As a complement, Section 3 develops a variety-expanding horizontal innovation model of ITD for energy technological progress. Section 4 presents some concluding remarks.

2. An efficiency-improving vertical model of energy technological progress

Before turning to the formal analysis, we clarify that the model presented in this section focuses on an efficiency-improving vertical pattern of innovation, i.e., energy technological progress is represented as an improvement of primary energy use efficiency in energy sectors. Hence, technology considered in this model is specific to primary energy-saving technology used in energy sectors for the purpose of improving the efficiency of converting primary energy resources (i.e., coal, oil, natural gas) into end-use, secondary energy products/services (i.e., electric utility). In addition to the energy input-augmenting technologies, we acknowledge that there also exist alternative technological solutions to climate change such as carbon-reduction technologies that reduce carbon emissions from fossil fuel combustion. Since our focus is on efficiency-improving technological innovation, emission-reducing technology is beyond the scope of our analysis. Furthermore, it is because our analysis focuses on the innovative behaviors of private firms that public policy incentives (such as feed-in tariffs, quotas) are not explicitly considered. Thus our analytical framework is building on the market-driven view of innovation, that is, private firms undertake purposeful innovative activities for the purpose of cost savings or profit gains, and technological innovation is largely an economic activity which is pursued by profit-seeking private firms for exploiting economic opportunities (cost reduction or profit gains).[1]

In a multi-country framework, we suppose that the world economy consists of N countries, indexed by $i=1,2,...,N$, and each country involves an energy sector that admits a representative energy firm producing end-use, secondary energy products with an aggregate production function as:

$$Y_i(t)=F(K_i(t),A_i(t)\cdot E_i(t)) \quad , \tag{1}$$

where $Y_i(t)$ is the outputs of end-use, secondary energy products/services (i.e., electricity) produced by the energy sector in country i at time t. $K_i(t)$ and $E_i(t)$ denote the inputs of capital (power generating machines and equipments) and primary energy resource (coal, oil, natural gas) into the energy sector for producing final-use energy products in country i at time t, respectively. Given the empirical evidence, labor or human capital is not explicitly considered as a separate factor of energy production, and for simplicity our analysis focuses on the interaction of the two major inputs – capital and primary energy.[2] $A_i(t)$ is primary energy-augmenting coefficient in country i at time t, which measures the efficiency of converting primary energy into end-use, secondary energy products. As shown later, $A_i(t)$ is treated as a time-varying stock variable that is determined by the dual drivers of endogenous technological progress - indigenous innovation and foreign technology diffusion. Note that, the variable of energy-augmenting technological progress bears a close resemblance, in an implicit way, to human capital with the same attribute of improving primary energy productivity.[3] For further

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[1] The market-driven view that economic opportunities are the primary determinant of innovation is articulated in the works of Schmookler (1966), Griliches (1957), and Griliches and Schmookler (1963).

[2] For the empirical evidence, we refer to GTAP energy sector data (Narayanan and Walmsley, 2008) and calculate the input cost share of production factors. We find a stylized fact that the important factor inputs in production in energy sectors are capital (power generating equipments) and primary energy resource (coal, oil, natural gas), and labor and human capital are basically not significant factor inputs.

[3] Accordingly to the human capital theory as developed primarily by Yoram Ben-Porath (1967), Mincer (1974), Nelson and Phelps, 1966), and Becker et al. (1990), the term of capital was coined because human capital are accumulable (through education or R&D) as a stock variable. In our model, the variable of

readings on an extended model that considers human capital as an explicit production input, see Appendix A, where we show that whether human capital is included in or excluded from the model makes no difference to the main results of the subsequent analysis. Finally, the production function $F(.,.)$ of this representative energy firm in energy sector satisfies the standard neoclassical assumptions, exhibits constant returns to scale in K and E and energy/capital substitutability.[4]

We proceed by defining the productivity of energy sector as secondary energy product outputs per physical unit of primary energy input in country i at time t,

$$\begin{aligned} y_i(t) &\equiv \frac{Y_i(t)}{E_i(t)} \\ &= \frac{A_i(t)\cdot E_i(t)}{E_i(t)}\cdot F\left[\frac{K_i(t)}{A_i(t)\cdot E_i(t)},1\right] \\ &= A_i(t)\cdot f(k_i(t)) \end{aligned} \quad , \tag{2}$$

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

$$\tilde{y}_i(t) \equiv \frac{Y_i(t)}{A_i(t)\cdot E_i(t)} = f(k_i(t)) \quad , \tag{3}$$

where the effective primary energy input is a product of physical primary energy input $E_i(t)$ and primary energy input-augmenting technology $A_i(t)$, and $\tilde{y}_i(t)$ is rewritten as a function $f(\cdot)$ of the effective capital-energy ratio that is given by

$$k_i(t) \equiv \frac{K_i(t)}{A_i(t)\cdot E_i(t)} \quad . \tag{4}$$

Suppose that each economy $i = 1,2,...,N$ is in continuous time running to an infinite time horizon. The supply of primary energy resources available in country i increases at a constant positive rate,

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energy-augmenting technological progress $A_i(t)$ is also treated as a time-varying accumulable stock variable that evolves according to Eq. (7), thus having the same feature as the stock variable of human capital for energy use efficiency improvement.

[4] In light of the empirical evidence (e.g. Berndt and Wood, 1979; Apostolakis, 1990; Thompson and Taylor, 1995; Frondel and Schmidt, 2002; Koetse et al., 2008), the production function in our model assumes energy and capital substitutability (e.g., CES function) for two reasons. First, our theoretical expositions aim to capture energy technological progress in the long-run BGP, capital and energy is more likely to act as substitutes in the long run. Second, our analysis focuses on energy sectors where the cost share of primary energy inputs is sufficiently large, in this case capital and energy substitutability is more likely to occur.

$\dot{E}_i(t)/E_i(t) \equiv n_i$, and this assumption on the growing trend of primary energy supply is consistent with the empirical evidence as documented in *World Energy Outlook 2012* (IEA, 2012).[5] This model thus represents two generic kinds of energy technologies. One is primary energy-producing technologies (e.g., drilling and extracting primary energy resources) that increase the availability of primary energy supply, which is described by an increase in primary energy supply $\dot{E}_i(t)/E_i(t)$. The other is primary energy-use technologies that improve the efficiency of converting primary energy resources into end-use energy products like electric utility, which is described by an improvement in primary energy use efficiency $\dot{A}_i(t)/A_i(t)$. Moreover, the energy sector in each economy i has a country-specific Solow-type exogenous saving rate s_i for the installment of power-generating equipments and capital assets, and the capital depreciates at a rate δ_i. Based on the above-described model assumptions and specifications, we obtain the following result,

Lemma 1 *In the above-described efficiency-improving vertical model of energy technology progress, the law of motion of the effective capital-energy ratio for each country* $i = 1,2,\ldots,N$ *takes the form:*

$$\dot{k}_i(t) = s_i \cdot f(k_i(t)) - (n_i + g_i(t) + \delta_i) \cdot k_i(t) \quad , \tag{5}$$

where $g_i(t) \equiv \dot{A}_i(t)/A_i(t)$ *is the growth rate of primary energy use efficiency in producing end-use, secondary energy products/services in country* i *at time* t. *The initial condition of this differential equation is given by* $k_i(0) \equiv K_i(0)/(A_i(0) \cdot E_i(0))$ *for each country* $i = 1,2,\ldots,N$.

Proof. Differentiating the effective capital-energy ratio with respect to time and taking into account the law of motion for capital can easily establish the claims in this lemma. ■

Note that, the above-specified Solow-type model just characterizes the economic dynamics for a closed economy, taking no account of cross-country technology interaction in an open economy framework. As the added value of this paper, our multi-country framework provides an endogenous treatment on technological progress by explicitly considering the dual drivers - indigenous innovation

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[5] Taking into account advances in technology and extraction methods, IEA (2012) predicts that for most of world regions aggregate fossil fuel supply will increase at a positive rate between 2010 and 2035 (for details, see Figure 2.9 fossil fuel production in selected regions in pp. 64, *IEA World Energy Outlook 2012*). For crude oil production, most of non-OPEC countries produce at a stable level, OPEC and a handful of non-OPECD countries, notably Brazil, Canada, the U.S., are also responsible for the bulk of the increase in global oil production. Supply in natural gas increases at the fastest rate, both in OECD and non-OECD countries. Coal production at the global level also increases with most of growth occurring in non-OECD countries, and the emerging economies make the biggest contribution to the growth in coal supply. At the aggregate, there is a positive growth of aggregate fossil fuel production and supply. This IEA outlook is also consistent with *BP Energy Outlook 2030*: world primary energy production and supply is projected to grow by 1.6% p.a. over the period 2010 to 2030.

and foreign technology diffusion. Consider that, due to the non-rivalry of knowledge, technological progress in a global framework can be seen as a process in which innovation undertaken by individual countries in the world economy contribute to knowledge accumulation of a global technology pool in a long-run equilibrium, and all innovation in the external world thus adds new knowledge to domestic technology stock (Rosenberg, 1994). Given that innovation in one country can favor innovation in any other countries through cross-country knowledge spillovers, ITD thus becomes a source of benefit for domestic knowledge accumulation and an endogenous driver of technological progress. This view of technological progress was articulated by Gerschenkron (1962) in his seminal essay *Economic Backwardness in Historical Perspective* - individual countries tend to catch up with the world technology frontier at a relatively fast pace by assimilating technology diffusion from the external world.

Accordingly, we consider that the technology level of the world frontier, i.e., the global technology pool, is created by the whole set of individual countries in the world economy,

$$A_{WTF}(t) = \sum_{i=1}^{N} A_i(t) \quad , \tag{6}$$

where $A_{WTF}(t)$ denotes the level of energy use efficiency of the world technology frontier at time t, expressed as a sum of energy use efficiency of individual country $i = 1,2,...,N$ in the world economy. The technology that lies unexplored - technology difference between individual country and the world frontier - would create the potential ITD that spills over to individual countries and become a pulling force that keeps countries growing at a similar rate along the long-run sustained growth.

In this context, for any individual country in the world economy, technological progress benefits from both indigenous innovation and absorption of ITD from the external world. By taking explicit account of the dual drivers of technological progress – indigenous innovation and foreign technology diffusion, we specify the law of motion of country i's energy technology level as:

$$\dot{A}_i(t) = \lambda_i \cdot A_i(t) + \sigma_i \cdot (A_{WTF}(t) - A_i(t)) \quad , \tag{7}$$

where λ_i is the efficiency of undertaking indigenous innovation. The effect of indigenous innovation depends on the existing level of country-specific technology $A_i(t)$, and this is based on the "standing on the shoulders of predecessors" assumption - the higher the current level of technology, the greater the effect of indigenous innovation on improving technology in the next period. σ_i is the capacity of absorbing foreign knowledge diffusion. Both λ_i and σ_i are country-specific, reflecting cross-country differences in innovative capacity determined by some underlying techno-economic factors such as R&D expending, patenting, and intellectual property regimes. Given that $A_{WTF}(t)$ represents the world's maximal level of energy technology, i.e., $A_i(t) < A_{WTF}(t)$ holds for each country i and time t, the technology gap relative to the world frontier $A_{WTF}(t) - A_i(t)$ thus constitutes an international knowledge pool from which foreign technology potentially spills over to individual country i for knowledge absorption. This suggests that *ceteris paribus* an economy that is technologically backward relative to the world frontier can advance its technology level at a faster pace by assimilating more technology diffusion from abroad, this potential advantage thus plays an important role in ensuring a relatively similar growth rate across country in the long-run sustained growth path. However, this does not necessarily mean that backward countries with an access to a larger international knowledge pool can immediately acquire all technologies in the external world and thus reaches the technology level of the world frontier. In fact, the weaker knowledge absorptive capacity inherent in most of the backward countries would become the inhibiting factor that lowers effective absorption of foreign technologies, thus eventually leading to a cross-country divergence in the absolute level of energy technology.

To proceed in a tractable way, we define proportional technology gap, $a_i(t) = A_i(t) / A_{WTF}(t)$, as a measure of country i's technology distance relative to the world frontier at time t. The world frontier increases its energy technology level at a constant rate $g \equiv \dot{A}_{WTF}(t) / A_{WTF}(t)$, and as shown later this growth rate of the world frontier g would be endogenously determined by technological characteristics of individual countries in the world economy. We then obtain the following result.

Lemma 2 *In the above-described efficiency-improving vertical model of energy technology progress, the law of motion of the technology gap for each country* $i = 1,2,...,N$ *takes the form as:*

$$\dot{a}_i(t) = \sigma_i - (\sigma_i + g - \lambda_i) \cdot a_i(t) \quad , \tag{8}$$

where $a_i(t) \equiv A_i(t) / A_{WTF}(t)$ *denotes country* i*'s energy technology gap relative to the world frontier at time* t*, and the initial condition of this differential equation is given by* $a_i(0) \equiv A_i(0) / A_{WTF}(0)$.

Proof. Differentiating the proportional technology gap with respect to time and taking into account the law of motion for energy technology can easily establish the claims in this lemma. ■

Given the above-described model environment, a world equilibrium is defined as an allocation of energy technology gaps $\{[a_i(t)]_{t=0}^{\infty}\}_{i=1}^{N}$ and effective capital-energy ratios $\{[k_i(t)]_{t=0}^{\infty}\}_{i=1}^{N}$, such that starting with initial conditions $[a_i(0), k_i(0)]_{i=1}^{N}$, the world equilibrium allocation $\{[a_i(t), k_i(t)]_{t=0}^{\infty}\}_{i=1}^{N}$ evolves according to the law of motion of technology gap Eq. (8) and the law of motion of effective capital-energy ratios,

$$\dot{k}_i(t) = s_i \cdot f(k_i(t)) - (n_i + g_i(t) + \delta_i) \cdot k_i(t) = s_i \cdot f(k_i(t)) - \left[n_i + \frac{\dot{a}_i(t)}{a_i(t)} + g + \delta_i \right] \cdot k_i(t) \quad , \tag{9}$$

where the growth rate of primary energy use efficiency of country i at time t, $g_i(t)$, is written as:

$$g_i(t)=\frac{\dot{A}_i(t)}{A_i(t)}=\frac{a_i(t)\cdot\dot{A}_{WTF}(t)}{A_i(t)}+\frac{\dot{a}_i(t)\cdot A_{WTF}(t)}{A_i(t)}=\frac{\dot{A}_{WTF}(t)}{A_{WTF}(t)}+\frac{\dot{a}_i(t)}{a_i(t)}=g+\frac{\dot{a}_i(t)}{a_i(t)} .$$

Based on two above-described Lemmas, we obtain the following proposition.

Proposition 1 *In the above-described efficiency-improving vertical model of energy technological progress, there is a balanced growth path (BGP) for the world equilibrium in which both energy technology gap* $a_i(t)$ *and effective capital-energy ratio* $k_i(t)$ *in each country* $i=1,2,...,N$ *are constant* $\dot{a}_i(t)=0$, $\dot{k}_i(t)=0$. *In particular, energy technology gap of country* $i=1,2,...,N$ *relative to the world frontier has a BGP level,*

$$a_i^*=\frac{\sigma_i}{\sigma_i+g-\lambda_i} , \tag{10}$$

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

$$\frac{s_i\cdot f(k_i^*)}{k_i^*}=n_i+g+\delta_i . \tag{11}$$

Moreover, denote the BGP level of country i's technology gap relative to the world frontier by $a_i^*(\sigma_i,\lambda_i,g)$ *and the BGP level of country i's effective capital-energy ratio by* $k_i^*(s_i,n_i,\delta_i,g)$ *when the underlying parameters are* $(\sigma_i,\lambda_i,s_i,n_i,\delta_i,g)$. *Then we have the following comparative statics results,*

$$\begin{array}{llll}\dfrac{\partial a_i^*(\sigma_i,\lambda_i,g)}{\partial\sigma_i}>0, & \dfrac{\partial a_i^*(\sigma_i,\lambda_i,g)}{\partial\lambda_i}>0, & \dfrac{\partial a_i^*(\sigma_i,\lambda_i,g)}{\partial g}<0, & \\ \dfrac{\partial k_i^*(s_i,n_i,\delta_i,g)}{\partial s_i}>0, & \dfrac{\partial k_i^*(s_i,n_i,\delta_i,g)}{\partial n_i}<0, & \dfrac{\partial k_i^*(s_i,n_i,\delta_i,g)}{\partial\delta_i}<0 & \dfrac{\partial k_i^*(s_i,n_i,\delta_i,g)}{\partial g}<0\end{array} . \tag{12}$$

Proof. Imposing the steady-state conditions $\dot{k}_i(t)=0$, $\dot{a}_i(t)=0$ on Eqs. (8)-(9) yields the unique BGP level $a_i^*=\sigma_i/(\sigma_i+g-\lambda_i)$ and k_i^* that satisfies $s_i\cdot f(k_i^*)/k_i^*=n_i+g+\delta_i$. Also simple partial derivative analysis can easily derive the comparative statics results in this proposition. ■

Proposition 1 states that an economy with a stronger capacity of absorbing foreign technology diffusion ($\sigma_i\uparrow$) and a higher efficiency of undertaking indigenous innovation ($\lambda_i\uparrow$) tends to have a lower technology gap relative to the world frontier and thus move upwards along the global ladder of energy technology. It is also indicated that an economy with a lower saving rate for capital accumulation ($s_i\downarrow$) and a higher growth rate of primary energy supply ($n_i\uparrow$) would lower the effective capital-energy ratio, that is, a higher intensity of primary energy inputs used to produce final energy products. Also a higher growth rate of the world energy technology frontier ($g \uparrow$) has an effect to boost energy technological progress in individual countries through ITD, thus this increase in energy input-augmenting efficiency plays a role in lowering the effective capital-energy ratio.[6]

Based on Proposition 1, we continue to show that the rate of energy technological progress of the world frontier g is endogenously determined by technological characteristics of individual countries in the world economy. Dividing both sides of Eq. (6) by $A_{WTF}(t)$ obtains

$$\sum_{i=1}^{N} \frac{A_i(t)}{A_{WTF}(t)} = \sum_{i=1}^{N} a_i(t) = 1 \quad , \tag{13}$$

where $a_i(t) = A_i(t) / A_{WTF}(t)$ is proportional technology gap of each country i relative to the world technology frontier. Given that the potential force in the world economy – working through ITD – pulls individual countries to improve energy technology level, the technology gap of each country would remain constant in the long-run sustained growth path and has a BGP level, $a_i^* = \sigma_i / (\sigma_i + g - \lambda_i)$. (c.f. Proposition 1). Substituting for $a_i(t)$ obtains that in the BGP the world equilibrium must satisfy,

$$\sum_{i=1}^{N} a_i^* = \sum_{i=1}^{N} \frac{\sigma_i}{\sigma_i + g - \lambda_i} = 1 \quad . \tag{14}$$

Given the set of exogenous parameters $[\sigma_i, \lambda_i]_{i=1}^{N}$, the only endogenous variable is the growth rate of energy technology of the world frontier g. Given that the left-hand side is strictly decreasing in g, there is one value of g, say g^*, that satisfies Eq. (14). Hence, there is a BGP world equilibrium in which the growth rate of energy technology of the world frontier g^* is endogenously determined by technological characteristics $[\sigma_i, \lambda_i]_{i=1}^{N}$ of all individual countries $i = 1, \ldots, N$ in the world economy. We then obtain the following result.

Proposition 2 *In the above-described efficiency-improving vertical model of energy technological progress, there is a long-run BGP world equilibrium in which the primary energy use efficiency of individual country* $i = 1, 2, \ldots, N$ *grow at the same rate as the world technology frontier,* $\dot{A}_i^*(t) / A_i^*(t) = \dot{A}_{WTF}^*(t) / A_{WTF}^*(t) = g^*$, *where the growth rate of* g^* *is endogenously determined by Eq. (14). Along the BGP equilibrium, the time path of primary energy use efficiency of country* i *is characterized as*

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[6] This comparative static effect can be alternatively analyzed by normalization for capital stock, that is, the effective capital-energy ratio given in Eq. (4) is rewritten as $k_i \equiv K_i / (A_i \cdot E_i) = 1 / (A_i \cdot E_i / K_i)$. When capital stock K is normalized, the effective capital-energy ratio depends on primary energy supply E and energy technology A, which implies a negative effect of higher growth of primary energy supply and energy technology on the effective capital-energy ratio.

$$A_i^*(t) = A_{WTF}^*(0) \cdot \frac{\sigma_i}{\sigma_i + g - \lambda_i} \cdot \exp(g^* \cdot t) \quad , \tag{15}$$

where $A_{WTF}^*(0)$ *is the initial level of primary energy use efficiency of the world technology frontier in the BGP world equilibrium. The time path of the productivity of energy sector in country* i *takes the form as*

$$y_i^*(t) = A_{WTF}^*(0) \cdot \frac{\sigma_i}{\sigma_i + g - \lambda_i} \cdot f(k_i^*) \cdot \exp(g^* \cdot t) \quad , \tag{16}$$

Both $A_i^*(t)$ *and* $y_i^*(t)$ *are increasing in indigenous innovation efficiency* λ_i *and knowledge absorptive capacity* σ_i.

Proof. Imposing the BGP condition $\dot{a}_i(t) = 0$ on $\dot{a}_i(t) / a_i(t) = \dot{A}_i(t) / A_i(t) - \dot{A}_{WTF}(t) / A_{WTF}(t)$, we obtain $\dot{A}_i^*(t) / A_i^*(t) = \dot{A}_{WTF}^*(t) / A_{WTF}^*(t) = g^*$ for each economy i along the BGP. Taking into account the technology gap of each country relative to the world frontier in the BGP $a_i^* = \sigma_i / (\sigma_i + g - \lambda_i)$, we can establish the first part of this proposition. For the second part, for the energy productivity defined as $y_i(t) = A_i(t) \cdot f(k_i(t))$, we have $\dot{y}_i^*(t) / y_i^*(t) = \dot{A}_i^*(t) / A_i^*(t) = \dot{A}_{WTF}^*(t) / A_{WTF}^*(t) = g^*$ in the BGP. Given the BGP condition $\dot{k}_i^* = 0, \dot{f}(k_i^*) = 0$, we obtain $y_i^*(t) = y_i^*(0) \cdot \exp(g^* \cdot t)$, where $y_i^*(0) = A_{WTF}^*(0) \cdot a_i^* \cdot f(k_i^*)$ denotes the initial level of $y_i^*(t)$ along the BGP. Using the BGP technology gap $a_i^* = \sigma_i / (\sigma_i + g - \lambda_i)$ can establish the second part of the proposition. ■

Proposition 2 provides the following economic implications. First, the rates of energy technological progress tend to converge across countries in the long-run BGP, which is equal to the growth rate of the world technology frontier.[7] Intuitively, there are potential pulling forces in the world economy – here working through ITD - that pull individual countries towards energy technological growth, thus ensuring that energy technology of individual countries grows at the same rate in the long-run

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[7] Note that, the claim that energy productivity grows at the same rate across countries only holds for the long-run BGP, and this does not necessarily hold during the transitional dynamic periods. As shown in the numerical simulation in Appendix B, individual countries improve energy use efficiency at different rates during the transitional dynamics periods, and it is only in the long-run BGP that the growth rates would converge across countries. This long-run convergence in growth rate is consistent with the empirical evidences as documented in *IEA World Energy Outlook 2012*, that is, differences in cross-country growth rate are present during transitional dynamic periods, but there are more limited differences in sustained growth rate in the long-run BGP. For example, countries in the developed world (e.g., US, EU, Japan) have already evolved into the BGP and share a similar rate (1~2% p.a.) of energy efficiency improvement. The developing economies like China and India (still in transitional dynamics to BGP) improve energy use efficiency at a rate of 4~5%, which slightly differ from the growth rate of developed countries, but in the long-run sustained growth path, that rate tends to approach the growth rate of developed countries.

sustained growth path, i.e., cross-country convergence in the growth rate of energy technology. This result is basically consistent with the empirical evidences as documented in *IEA World Energy Outlook 2012* (IEA, 2012): cross-country differences in the growth rate of energy efficiency are potentially present during the transitional dynamic periods, but there are only small cross-country differences in the growth rate of energy efficiency in the long-run BGP.

Second, although the growth rates of energy technology tend to converge across countries in the long-run BGP, the absolute levels of energy technology still feature a diverging trend, primarily due to cross-country differences in indigenous innovation efficiency and knowledge absorptive capacity. In particular, the energy sector in an economy with a stronger capacity of undertaking indigenous innovation and assimilating foreign knowledge diffusion is more likely to create a higher level of primary energy use efficiency, i.e., a more efficient technology of converting primary energy inputs into end-use, secondary energy products/services.

Third, it is notable that final-use energy goods output per effective unit of primary energy input remains relatively stable, but that output per physical unit of primary energy input is continuing to grow along the long-run sustained growth path. This trend suggests that, given the long-run physical constraint of the available primary energy resources, energy-augmenting technological progress (in terms of the improvement of primary energy use efficiency) is vital to securing a growing supply of secondary energy products/services for meeting the rising final demands.

3. A variety-expanding horizontal model of energy technological progress

In the aforementioned efficiency-improving vertical innovation model, energy technological progress is described as an improvement in primary energy use efficiency. To give new insight into the mechanism of ITD for energy technological progress, this section offers a complementary perspective where energy technological progress is represented as an expansion of primary energy technology variety – a *so-called* variety-expanding horizontal innovation model. The horizontal pattern of energy innovation is in light of the fact that energy sectors often engage in innovative activities that creates new varieties of differentiated energy technologies. For example, in addition to traditional fossil fuel-based energy technologies like coal, oil, and natural gas, innovation in energy sectors has created a large variety of renewable energy technologies based on nuclear, hydropower, solar, wind, ocean wave, bioenergy, and geothermal etc. The variety-expanding horizontal pattern of energy technological innovation thus provides a new perspective to explore the mechanism of ITD for energy technological progress.[8]

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[8] It is worth mentioning that relative to energy/climate policy modelling based on CGE or IAM models, the theoretical model with an abstract representation of technology (primary energy variety expansion) is not well-suited to measurable real-world variables of technologies. However, it offers a new, complementary perspective that helps theoretically investigate the basic mechanism of ITD for energy

Before turning to the model details, we clarify that the variety-expanding horizontal model is independent of the above-described efficiency-improving vertical model without any overlaps in modelling structure. In this regard, the Solow-type model assumptions and specifications used in previous section no longer exist in the variety-expanding model. In particular, with the target of variety-expanding horizontal innovation, the model presented in this section would focus on the effect on energy technology innovation of energy varieties expansion rather than capital accumulation. Accordingly, based on the Romer's variety-expanding endogenous growth theory (Romer, 1987, 1990), we begin by specifying that end-use, secondary energy products/services are produced competitively in energy sectors in economy $i = 1,2,...,N$ at time t with an aggregate production function

$$Y_i(t) = \frac{1}{1-a} \cdot K_i^{a} \cdot E_i(t)^{1-a} \quad , \tag{17}$$

where the Cobb-Douglas production function exhibits constant returns to scale in capital K and an aggregate energy input composite E in producing end-use energy products/services. Since our variety-expanding horizontal model focuses much more on the variety-expanding effect than it does on capital-accumulation effect on energy technological change, there is thus no specification of capital dynamics and K denotes a constant fixed level of capital deployment for energy goods production. As shown later, the dynamics of the variety-expanding model are characterized by the law of motion of the number of energy technology varieties and intertemporal dynamics in the market value (the innovation incentive) of energy technology suppliers that create each differentiated energy technology variety, Eqs. (20)-(21). The term $1-a$ in the denominator is used for notional simplicity. Using the Dixit-Stiglitz tool, the aggregate energy input composite is a CES aggregator of differentiated varieties of primary energy inputs

$$E_i(t) = \left[\int_0^{N_i(t)} x_i(v,t)^{\frac{\varepsilon-1}{\varepsilon}} dv \right]^{\frac{\varepsilon}{\varepsilon-1}} \quad , \tag{18}$$

where $N_i(t)$ measures the total number of differentiated varieties of primary energy inputs available in energy sectors of country i at time t. $x_i(v,t)$ is the amount of primary energy input of variety $v \in [0, N_i(t)]$ used to produce end-use, secondary energy products in country i at time t. $\varepsilon \equiv 1/a$ is the elasticity of substitution between different primary energy varieties.

In each economy $i = 1,2,...,N$, each differentiated variety of primary energy $v \in [0, N_i(t)]$ is owned and supplied by an energy technology monopolist. With a fully-enforced perpetual intellectual

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technological progress. In this regard, our paper is closely related to and builds on the seminal works of Smulders and de Nooij (2003) and van Zon and Yetkiner (2003) which also apply a variety-expanding model to analyze energy technological innovation.

property right system, this monopolistic energy supplier has the market value of owing each differentiated energy technology variety $v \in [0, N_i(t)]$ as:

$$\begin{aligned} V_i(v,t) &= \int_t^{\infty} \exp\left[-\int_t^{s} r_i(s')\cdot ds'\right]\cdot \pi_i(v,s)\cdot ds \\ s.t.\ \ \pi_i(v,s) &= p_i(v,s)\cdot x_i(v,s) - \psi\cdot x_i(v,s) \end{aligned} \quad , \qquad (19)$$

where the market value $V_i(v,t)$ is expressed as a discounted present value of future profit streams from time t to the infinite future, with market interest rate r_i as the discount factor and $\pi_i(v,t)$ instantaneous flow profit. The monopolistic energy supplier produces each unit of the corresponding primary energy variety at a marginal cost of ψ in units of final energy goods, and $p_i(v,t), x_i(v,t)$ is the profit-maximizing price and quantity choices of this energy technology monopolist. Alternatively, the market value of owing each differentiated primary energy technology $v \in [0, N_i(t)]$ can be rewritten in the Hamilton-Jacobi-Bellman (HJB) form as:

$$r_i(t)\cdot V_i(v,t) = \dot{V}_i(v,t) + \pi_i(v,t) \quad , \qquad (20)$$

where the HJB equation provides an inter-temporal no-arbitrage condition for each monopolistic energy firm. The left-hand side corresponds to the cost of owning primary energy technology due to the loss of market interest rate. The right-hand side is the return from owing each differentiated variety of primary energy technology which stems from two sources - intertemporal changes in the market value and the gain of current flow profit.

As compared to some variety-expanding models in the existing literature, e.g., Smulders and de Nooij (2003), that only consider endogenous technological progress induced by indigenous R&D within a single economy, the added value of our model is to represent the innovation possibility frontier (IPF) as an expansion of energy technology varieties driven by dual drivers - indigenous R&D and ITD,

$$\dot{N}_i(t) = \kappa_i \cdot \left[\frac{N_{WTF}(t)}{N_i(t)}\right]^{\omega_i} \cdot R_i(t) \quad , \qquad (21)$$

where $R_i(t)$ is expenditure on energy R&D for creating new energy technology varieties in country i at time t, and energy R&D expenditure (one category of final energy goods demand in energy market clearing) is taken from the produced output of final energy goods. κ_i is the efficiency of undertaking indigenous R&D, and ω_i is the capacity of absorbing foreign energy technology variety from the external world. κ_i and ω_i are both country-specific in the sense that they reflect cross-country differences in some underlying techno-economic factors that affect innovative capacity

Meanwhile, each country $i = 1, 2, \ldots, N$ in the world economy benefits from positive externality of ITD by assimilating the unexplored technology varieties available in the external world according to its gap relative to the world technology frontier, $N_{WTF}(t) / N_i(t)$. This specification suggests that a larger technology gap relative to the external knowledge pool is likely to create a larger number of technology varieties that potentially spill over to domestic countries, and *ceteris paribus* a higher level of foreign technology spillover translates into a higher level of domestic technology absorption. This is consistent with the view of technological progress put forward by Gerschenkron (1962) in his famous essay *Economic Backwardness in Historical Perspective*: other things being equal, backward countries can catch up with the world technology frontier at a relatively fast pace due to its access to a larger international knowledge pool that remains to be assimilated.[9] Accordingly, innovation possibility frontier given in Eq. (21) reflects the basic process of endogenous technological change for an open economy: technological progress (here in terms of technology variety expansion) for a particular country in the world economy is driven by both indigenous innovation and absorption of foreign technologies.

We continue to specify the free entry condition (FEC) of undertaking R&D in energy sectors. In explicit, once spending one unit of R&D expenditure, energy firms in each economy $i = 1, 2, \ldots, N$ can create a flow rate $\kappa_i \cdot [N_{WTF}(t) / N_i(t)]^{\omega_i}$ of new energy technology varieties according to the IPF given in Eq. (21), with each differentiated variety of technology having a market value given by Eq. (19). Thus, the FEC of energy technology research (with positive R&D spending) takes the form as

$$\kappa_i \cdot \left[\frac{N_{WTF}(t)}{N_i(t)} \right]^{\omega_i} \cdot V_i(v, t) = \tau_i \quad , \tag{22}$$

where this optimality condition requires an equalization between marginal benefit and marginal cost of undertaking energy R&D. The left-hand side is the marginal benefit of R&D - one unit of R&D spending generates $\kappa_i \cdot [N_{WTF}(t) / N_i(t)]^{\omega_i}$ units of new energy technology varieties, and each variety v creates a market value of $V_i(v, t)$. τ_i in the right-hand side is the marginal cost of R&D specific to country i, reflecting country-specific differences in the marginal cost of undertaking R&D activities.

Finally, the energy sectors in each country $i = 1, 2, \ldots, N$ at each point in time t should satisfy the following market clearing condition

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[9] Note that, this does not necessarily mean that technologically backward countries with an access to a larger pool of foreign technology can acquire all these technologies from abroad, because the weak knowledge absorptive capacities of the backward countries would become an inhibiting factor that slows effective absorption of foreign technologies. In general, a country with a larger technology gap relative to the world frontier usually has a weaker capacity of absorbing foreign technology diffusion. Accordingly, for a country with a larger gap relative to the world frontier, its weak knowledge absorptive capacity will inhibit effective absorption of ITD, even if the backward country has an access to a larger pool of foreign technologies available in the external world.

$$X_i(t)+R_i(t)+C_i(t)=Y_i(t) \quad , \tag{23}$$

where $X_i(t)$ is the spending on intermediate production inputs of primary energy used to produce end-use, secondary energy products. Given that each primary energy technology supplier produces its corresponding variety of primary energy input at a marginal cost of ψ (in unit of final energy goods), we thus obtain

$$X_i(t)=\int_0^{N_i(t)} \psi \cdot x_i(v,t)\cdot dv \quad , \tag{24}$$

as the aggregate spending on intermediate inputs over the set of all primary energy varieties. $R_i(t)$ is expenditure on energy R&D investment for creating new energy technology variety according to the innovation possibility frontier given in Eq. (21). $C_i(t)$ is household's consumption of end-use energy products, of which the time path can be characterized by the Euler equation for consumption,[10]

$$\frac{\dot{C}_i(t)}{C_i(t)}=\frac{1}{\theta}\cdot(r_i(t)-\rho) \quad , \tag{25}$$

where θ denotes the coefficient of relative risk aversion for a CRRA household preference, ρ is time discount rate, and $r_i(t)$ is market interest rate in economy i at time t. The energy market clearing condition requires that the three categories of demand for final energy products $X_i(t), R_i(t), C_i(t)$ should add up to the total output supply $Y_i(t)$ in each country i at each point in time t.

For the above-described variety-expanding model of energy technological progress, the world equilibrium is defined as an allocation in which in each country $i=1,2,\ldots,N$ each primary energy firm chooses price and quantity $[p_i(v,t), x_i(v,t)]_{v\in[0,N_i(t)],t=0}^{\infty}$ to maximize the market value Eq. (19), the evolution of the market value $[V_i(v,t)]_{v\in[0,N_i(t)],t=0}^{\infty}$ is determined by the Hamilton-Jacobi-Bellman Eq. (20), the number of energy technology variety $[N_i(t)]_{t=0}^{\infty}$ evolves according to the innovation possibility frontier Eq. (21) and free entry condition of R&D Eq. (22), the evolution of energy consumption $[C_i(t)]_{t=0}^{\infty}$, spending on intermediate primary energy input $[X_i(t)]_{t=0}^{\infty}$, energy R&D expenditure $[R_i(t)]_{t=0}^{\infty}$, and outputs of final energy products $[Y_i(t)]_{t=0}^{\infty}$ is consistent with energy

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[10] We consider an infinite-horizon economy admitting a representative household with a CRRA preference. The Euler equation for consumption is derived by solving the representative household's problem - maximizing intertemporal utility $\int_0^{\infty}\exp(-\rho t)\cdot[C_i(t)^{1-\theta}-1]/(1-\theta)\cdot dt$, subject to a budget constraint $\dot{H}_i(t)=r_i(t)\cdot H_i(t)+W_i(t)-C_i(t)$, where $H_i(t), W_i(t), C_i(t)$ denotes asset holdings, income earnings, and consumption of the household, respectively.

market clearing condition in each economy i at time t as given in Eq. (23).

The balanced growth path world equilibrium is defined as the steady state of the above-described world equilibrium, that is, an equilibrium path where in each country $i = 1,2,...,N$, energy consumption $[C_i(t)]_{t=0}^{\infty}$, spending on intermediate primary energy input $[X_i(t)]_{t=0}^{\infty}$, energy R&D expenditure $[R_i(t)]_{t=0}^{\infty}$, output of final energy products $[Y_i(t)]_{t=0}^{\infty}$, and the number of energy technology varieties $[N_i(t)]_{t=0}^{\infty}$ all grow at the same rate g^*. Along this BGP equilibrium, both market interest rate and instantaneous flow profits remain constant at some level $r_i(t) = r_i^*$, $\pi_i(v,t) = \pi_i^*$, and the market value of owning each differentiated variety of primary energy technology is equal to $V_i^* = \pi_i^* / r_i^*$, where the asterisk (*) refers to the corresponding BGP values. Based on this definition, we then obtain the following result that characterizes the BGP world equilibrium.

Proposition 3 *In the above-described variety-expanding horizontal model of energy technological progress, there exists a BGP world equilibrium where the gap of country* i*'s energy technology variety relative to the world technology frontier is given by,*

$$\frac{N_i^*}{N_{WTF}^*} = \left[\frac{\kappa_i \cdot V_i^*}{\tau_i}\right]^{1/\omega_i} = \left[\frac{\kappa_i \cdot a \cdot K_i}{\tau_i \cdot r_i^*}\right]^{1/\omega_i} , \qquad (26)$$

where the BGP market value of owning each differentiated energy technology variety remains constant at some level $V_i^* = \pi_i^* / r_i^* = a \cdot K_i / r_i^*$. *In particular, a country with a higher* κ_i, ω_i, K_i *or a lower* τ_i, r_i *would have a lower technology variety gap relative to the world frontier. Given that the technology variety gap remains constant in the BGP, the number of energy technology variety owned by each economy* $i = 1,2,...,N$ *in the world economy would grow at the same rate as the world technology frontier* g^*,

$$\frac{\dot{N}_i^*}{N_i^*} = \frac{\dot{N}_{WTF}^*}{N_{WTF}^*} = g^* \quad . \qquad (27)$$

Moreover, an economy with a greater number of energy technology varieties tends to have a higher productivity of using primary energy resources to produce end-use, secondary energy products/services.

Proof. See Appendix C. ■

Proposition 3 states that the position of individual country in the global technology ladder (as measured by the technology variety gap relative to the world frontier) depends mainly on four factors: efficiency of indigenous research κ_i,[11] capacity of absorbing foreign knowledge spillovers ω_i,[12]

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[11] In general, indigenous R&D efficiency is related to uncertainty effect. In an R&D context, uncertainty can be thought of as the micro-level probability of research success for individual labs. This is

marginal cost of R&D τ_i,[13] and the market value of innovation V_i^*.[14] These four factors then correspond to two interconnected stages of technological progress: 1) Technology research where the intangible ideas/blueprints of new technology variety are invented; and 2) Product development where specific tangible market-oriented products embodying the blueprint of intangible technologies are produced and deployed in the marketplace for pursuing economic opportunities.

Intuitively, efficiency of undertaking indigenous research, capacity of absorbing international knowledge spillovers, and R&D cost are closely related to the stage of technology research, while the market value of innovation is a determinant to the stage of product development. In particular, an economy with a higher efficiency of indigenous research, a stronger capacity of absorbing ITD, and a lower cost of R&D would create more varieties of technology blueprints in the stage of technology research. Later in the stage of product development, as the amount of capital available for product development (that converts technology blueprints into market-oriented products) is larger, and the cost of holding technology assets due to the loss of market interest rate is lower, the market value of innovation (i.e., creating and holding new differentiated technology assets) would be higher, thus stimulating the incentive to create new technology varieties for pursuing economic benefits.

Moreover, Proposition 3 argues that a country with a larger number of energy technology variety is likely to be more efficient in converting primary energy resource into end-use, secondary energy products. Intuitively, thanks to the love-for-variety effect embedded in the Dixit-Stiglitz production technology, a new variety of primary energy technology would create a pecuniary externality effect

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equivalent to the macro-level efficiency of innovation for the R&D sector including a large number of research labs (based on the law of large number). For uncertainty, see Baker and Shittu (2008), Bosetti and Tavoni (2009), Held et al. (2009), Pizer (1999), Popp (2013).

[12] In general, knowledge absorptive capacity is related to spillover effect (an economy with a stronger capacity of knowledge absorption better enjoys the beneficial spillover effect by assimilating more foreign technology spillovers), and vested interest effect (domestic incumbents are often in favor of certain distortionary policies that limit the market entry of new technologies from abroad, thus lowering the absorption of foreign technology). For spillover effect, see Popp (2006), Clarke (2008), Popp and Newell (2012). For energy technological “lock-in” due to political vested interests, see Cowan (1990), Cowan and Hulten (1996), Unruh (2002, 2002), Jin and Zhang (2014).

[13] In general, R&D cost is related to irreversibility effect (irreversible R&D investment incurs large adjustment costs and sunk costs which raise the costs of R&D for knowledge capital accumulation) and learning-by-doing effect (in an innovation context learning-by-doing can be thought of as a decrease in unit cost of R&D investment as a function of cumulative knowledge assets). For irreversibility, see Arrow and Fisher (1974), Ulph and Ulph (1997), Pindyck (2002, 2007), Kolstad (2006a,b), Fisher and Narain (2003); For learning-by-doing effect, see van der Zwann et al. (2002), Gerlagh and van der Zwann (2003), Manne and Richels (2004).

[14] That is, the higher market value of innovation would stimulate a stronger incentive to create new technology for pursuing economic benefits. This is consistent with the market-driven view on innovation. As articulated in the seminal works of Schmookler (1966), Griliches (1957), and Griliches and Schmookler (1963), technological innovation and adoption is largely an economic activity which, like other economic activities, is pursued by profit-maximizing firms for economic opportunities.

that improves the productivity of existing varieties of primary energy inputs, thus a larger number of varieties would increase the productivity of using each primary energy variety to produce end-use energy products.

As shown by Eq. (27) in Proposition 3, along the BGP world equilibrium, the number of energy technology varieties owned by each economy $i = 1, 2, ..., N$ would grow at the same rate as the world technology frontier g^*. Intuitively, this is primarily due to the potential pulling forces in the world economy – working through ITD - that keeps individual countries growing at a similar growth rate along the long-run sustained growth. We now further the analysis by endogenously characterizing this technology growth rate to which individual countries converge.

Based on the view of technological progress put forward by Gerschenkron (1962) and Rosenberg (1994), we consider that technological progress n the world economy can be seen as a process in which innovation undertaken by individual countries can contribute to knowledge accumulation of a global technology pool in a long-run equilibrium, and all technology varieties in the external world thus add new knowledge to the domestic stock of technology varieties. By assimilating foreign technology diffusion from the external knowledge pool, individual countries tend to catch up with the world frontier at a fast pace. Accordingly, the whole set of countries in the world economy contributes to the stock of technology varieties of the world frontier,

$$N_{WTF}(t) = \sum_{i=1}^{N} N_i(t) \quad , \tag{28}$$

where $N_{WTF}(t)$ is the stock of energy technology variety of the world technology frontier at time t, as a sum of energy technology variety owned by individual country $i = 1, 2, ..., N$ in the world economy. Dividing both sides of Eq. (28) by $N_{WTF}(t)$ obtains

$$\sum_{i=1}^{N} \frac{N_i(t)}{N_{WTF}(t)} = 1 \quad , \tag{29}$$

where $N_i(t) / N_{WTF}(t)$ is the energy technology variety gap of each country i relative to the world frontier. Since individual countries tend to catch up with the world frontier by taking advantage of assimilating foreign technology variety diffused from abroad, the variety gap of each country relative to the world frontier would remain constant in the long-run sustained growth path, and has a BGP value given in Eq. (26). Substituting Eq. (26) into Eq. (29) obtains that the BGP equilibrium must satisfy,

$$\sum_{i=1}^{N} \frac{N_i^*}{N_{WTF}^*} = \sum_{i=1}^{N} \left[\frac{\kappa_i \cdot a \cdot K_i}{\tau_i \cdot r_i^*} \right]^{1/\omega_i} = 1 \quad . \tag{30}$$

where the asterisk (*) refers to the corresponding BGP values.

Furthermore, according to the Euler equation Eq. (25) that characterizes the dynamic path of consumption, the BGP equilibrium market interest rate in economy i must satisfy

$$r_i^* = \theta \cdot g_{C_i}{}^* + \rho \quad , \tag{31}$$

where $g_{C_i}{}^* \equiv \dot{C}_i^* / C_i^*$ denotes the BGP growth rate of household consumption of final energy products in economy i. Differentiating the energy market clearing condition Eq. (23) with respect to time t obtains

$$\frac{C_i(t)}{Y_i(t)} \cdot g_{C_i}(t) + \frac{X_i(t)}{Y_i(t)} \cdot g_{X_i}(t) + \frac{R_i(t)}{Y_i(t)} \cdot g_{R_i}(t) = g_{Y_i}(t), \tag{32}$$

where $g_{C_i}(t) \equiv \dot{C}_i(t) / C_i(t)$, $g_{X_i}(t) \equiv \dot{X}_i(t) / X_i(t)$, $g_{R_i} \equiv \dot{R}_i(t) / R_i(t)$, $g_{Y_i} \equiv \dot{Y}_i(t) / Y_i(t)$ denotes the growth rate of C_i, X_i, R_i, and Y_i in economy i at time t, respectively. Meanwhile, solving the variety-expanding model derives the outputs of final energy products (for details, see Appendix C)

$$Y_i(t) = \frac{1}{1-a} \cdot \left[\int_0^{N_i(t)} x_i(v,t)^{1-a} dv \right] \cdot K_i^a = \frac{1}{1-a} \cdot K_i \cdot N_i(t) \quad , \tag{33}$$

where it is suggested that the growth rate of final energy product outputs $g_{Y_i} \equiv \dot{Y}_i(t) / Y_i(t)$ should be equal to the growth rate of energy technology variety $g_{N_i} \equiv \dot{N}_i(t) / N_i(t)$. Eq. (32) thus implies that for each country i household energy consumption, spending on intermediate primary energy inputs, energy R&D expenditure, final energy goods outputs, and energy technology varieties should grow at the same rate g_i^* in the BGP,

$$g_{Ci}{}^* = g_{Xi}{}^* = g_{Ri}{}^* = g_{Yi}{}^* = g_{Ni}{}^* = g_i^* \quad , \tag{34}$$

where the asterisk (*) refers to the BGP values. Finally, according to Eq. (27) in Proposition 3, in the BGP energy technology varieties owned by each country $i = 1, 2, ..., N$ in the world economy would grow at the same rate as the world technology frontier g^*, that is,

$$g_i^* = g^* \qquad \text{for all countries } i = 1, 2, ..., N \quad . \tag{35}$$

Substituting Eq. (31), (34), and (35) into (30), we have

$$\sum_{i=1}^{N} \left[\frac{\kappa_i \cdot a \cdot K_i}{\tau_i \cdot (\theta \cdot g^* + \rho)} \right]^{\frac{1}{\omega_i}} = 1 \quad . \tag{36}$$

The only unknown variable is the growth rate of energy technology variety of the world frontier g^*. Given the left-hand side of Eq. (36) is strictly decreasing in g^*, there is one value of g^* that satisfies this equation. Hence, there is a BGP world equilibrium in which the growth rate of energy technology variety of the world frontier g^* is endogenously determined by techno-economic characteristics $[\kappa_i, \omega_i, \tau_i, K_i]_{i=1}^N$ of all individual countries $i = 1,\ldots,N$ in the world economy. This result can be summarized in this following proposition.

Proposition 4 *In the above-described variety-expanding horizontal model of energy technological progress, there exists a unique BGP world equilibrium where the growth rate of energy technology variety of the world technology frontier is given by* g^* *and energy technology variety of individual country* $i = 1,\ldots,N$ *in the world economy grows at this common rate, i.e., cross-country convergence in the growth rate of energy technology variety . This growth rate is endogenously determined by technological and economic characteristics* $[\kappa_i, \omega_i, \tau_i, K_i]_{i=1}^N$ *of all individual countries in the world economy as give in Eq. (36). In particular, for a world economy in which its individual countries* $i = 1,\ldots,N$ *have a higher level of* $[\kappa_i, \omega_i, K_i]_{i=1}^N$ *or a lower level of* $[\tau_i, r_i]_{i=1}^N$*, there would be a larger growth rate of energy technology variety in the BGP world equilibrium.*

Proof. The preceding discussion establishes all the claims in this proposition. ■

Proposition 4 implies that a higher level of indigenous R&D efficiency κ_i, knowledge absorptive capacity ω_i, and capital available for product development K_i, or a lower level of R&D cost τ_i and market interest rate r_i would lead to a larger endogenous growth rate of energy technology variety in the long-run BGP g^*. Intuitively, for a world economy where all its member countries have stronger innovative capacities (indigenous R&D efficiency and ITD absorptive capacity) and lower R&D costs, technological progress achieved by individual countries would be faster, thus leading to a fast pace of technological progress at the world level due to cross-country technological diffusion. In the mean time, when all individual countries have an access to a larger amount of capital and a lower market interest rate in the stage of new product development, the innovative incentive induced by higher market values and economic opportunities would stimulate the creation of new energy technology variety at a faster pace at the world level.

4. Concluding remarks

As cross-country technological interdependence and interaction have important implications for global energy and climate governance, a detailed study of the mechanism of ITD for energy technological progress has been placed high upon research agenda. However, most of the existing studies on energy technology diffusion are large-scale CGE/IAM–based modelling, and it is often ambiguous to capture and understand the fundamental mechanism of ITD for energy and carbon savings within a complex "black box" modelling framework. Therefore, as a helpful methodological complement, this paper contributes to transparent analytical models for an economically intuitive exposition of the basic mechanism of ITD for energy technological progress.

We first develop an efficiency-improving vertical innovation model where energy technological progress is represented by an improvement in energy use efficiency driven by indigenous innovation and foreign technology diffusion. We find that the growth rates of energy use efficiency are the same across countries in the long-run BGP world equilibrium, which are equal to the growth rate of energy use efficiency of a world technology frontier that is determined by technological characteristics of all individual countries in the world economy. The reason is that there are potential forces in the world economy – working through ITD - that pull individual countries towards energy technological progress, ensuring that energy use efficiency of individual countries grows at a relatively similar rate in the long-run sustained growth path. However, cross-country differences in the efficiency of undertaking indigenous research and the capacity of absorbing foreign knowledge spillovers lead to cross-country divergence in the absolute levels of energy technology. An economy with a stronger capacity of ITD absorption and indigenous research tends to have a more advanced level of energy technology.

To give complementary insight into the mechanism of ITD for energy technological progress, we further present a variety-expanding horizontal innovation model where energy technological progress is represented by an expansion of energy technology varieties driven by indigenous R&D and foreign technology variety spillover. We show that in the BGP world equilibrium each country's gap of energy technology varieties relative to the world frontier depends on four key factors: efficiency of indigenous research, capacity of absorbing foreign knowledge spillovers, marginal cost of R&D investment, and the market value of innovation. A particular country with a higher efficiency in indigenous research, a stronger capacity of absorbing ITD, a lower marginal cost of R&D, and a higher market value of innovation would create more energy technology varieties in the long-run sustained growth path. Moreover, an economy with a greater number of energy technology varieties tends to have a higher productivity of using primary energy resources to produce end-use, secondary energy products.

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Appendix

Appendix A: An Extended Efficiency-improving Innovation Model with Human Capital

Given that human capital is explicitly considered as one of the production factor inputs, the production function can be specified as

$$Y_i(t) = F(K_i(t), H_i(t), A_i(t)\cdot E_i(t)) \quad , \tag{A1}$$

where $H_i(t)$ denotes human capital in economy $i = 1, 2, \ldots, N$ at time t, and the other variables have the same as the model developed in Section 2. Using the constant returns to scale feature, the secondary energy product outputs per effective unit of primary energy input can be written as,

$$\tilde{y}_i(t) \equiv \frac{Y_i(t)}{A_i(t)\cdot E_i(t)} = F\left[\frac{K_i(t)}{A_i(t)\cdot E_i(t)}, \frac{H_i(t)}{A_i(t)\cdot E_i(t)}, 1\right] \equiv f(k_i(t), h_i(t)) \quad , \tag{A2}$$

where the effective physical capital-energy ratio and effective human capital-energy ratio are given by

$$k_i(t) \equiv \frac{K_i(t)}{A_i(t)\cdot E_i(t)} \quad \text{and} \quad h_i(t) \equiv \frac{H_i(t)}{A_i(t)\cdot E_i(t)} . \tag{A3}$$

As in the work of Mankiw, Romer and Weil (1992), investments in human capital take a similar form to investments in physical capital: households save a fraction of s_{ki} of their income to invest in physical capital and a faction s_{hi} to invest in human capital. Denote the depreciation rates of physical and human capital by δ_{ki} and δ_{hi}, respectively. With these notations, the dynamics of the model with human capital is characterized by the law of motion of effective physical capital-energy $\{[k_i(t)]_{t=0}^{\infty}\}_{i=1}^{N}$, effective human capital-energy ratio $\{[h_i(t)]_{t=0}^{\infty}\}_{i=1}^{N}$, and energy technology $\{[a_i(t)]_{t=0}^{\infty}\}_{i=1}^{N}$,

$$\begin{aligned} \dot{k}_i(t) &= s_{ki}\cdot f(k_i(t), h_i(t)) - \left[n_i + (\dot{a}_i(t)/a_i(t)) + g + \delta_{ki}\right]\cdot k_i(t) \\ \dot{h}_i(t) &= s_{hi}\cdot f(k_i(t), h_i(t)) - \left[n_i + (\dot{a}_i(t)/a_i(t)) + g + \delta_{hi}\right]\cdot h_i(t) \\ \dot{a}_i(t) &= \sigma_i - (\sigma_i + g - \lambda_i)\cdot a_i(t) \end{aligned} \quad , \tag{A4}$$

we thus pin down the BGP world equilibrium defined by the allocation $[a_i^*, k_i^*, h_i^*]$ that satisfies the following system of equations,

$$\begin{aligned} & s_{ki} \cdot f(k_i^*, h_i^*) - \left[n_i + g + \delta_{ki} \right] \cdot k_i^* = 0 \\ & s_{hi} \cdot f(k_i^*, h_i^*) - \left[n_i + g + \delta_{hi} \right] \cdot h_i^* = 0 \\ & \sigma_i - (\sigma_i + g - \lambda_i) \cdot a_i^* = 0 \end{aligned} \tag{A5}$$

In contrast, for the benchmark model without human capital as given in Section 2, the dynamics of the model is characterized by the law of motion of effective physical capital-energy ratio $\{[k_i(t)]_{t=0}^{\infty}\}_{i=1}^{N}$ and energy technology $\{[a_i(t)]_{t=0}^{\infty}\}_{i=1}^{N}$

$$\begin{aligned} & \dot{k}_i(t) = s_{ki} \cdot f(k_i(t)) - \left[n_i + (\dot{a}_i(t) / a_i(t)) + g + \delta_{ki} \right] \cdot k_i(t) \\ & \dot{a}_i(t) = \sigma_i - (\sigma_i + g - \lambda_i) \cdot a_i(t) \end{aligned} , \tag{A6}$$

the BGP world equilibrium defined by the allocation $[a_i^*, k_i^*]$ is determined by the following system of equations,

$$\begin{aligned} & s_{ki} \cdot f(k_i^*) - \left[n_i + g + \delta_{ki} \right] \cdot k_i^* = 0 \\ & \sigma_i - (\sigma_i + g - \lambda_i) \cdot a_i^* = 0 \end{aligned} \tag{A7}$$

Comparing both models, it is straightforward to obtain that whether human capital is included in or excluded from the model makes no difference to the main results, i.e., there is a potential force in the world economy – working through ITD - that leads to cross-county convergence to a similar rate of energy technological progress in the long-run BGP world equilibrium. To show this result, notice that in both models the technology gap of each individual country relative to the world frontier is equal to zero $\dot{a}_i(t) = 0$ in the BGP, the level of energy use efficiency thus grows at the same rate as the world frontier, $\dot{A}_i^* / A_i^* = \dot{A}_{WTF}^* / A_{WTF}^* = g$. For the model that explicitly considers the input of human capital, we have energy productivity defined as $y_i(t) = A_i(t) \cdot f(k_i(t), h_i(t))$, and given the BGP conditions $\dot{k}_i^* = 0, \dot{h}_i^* = 0, \dot{f}(k_i^*, h_i^*) = 0$, we obtain that energy productivity of each country should grow at the same rate as the world frontier along the BGP world equilibrium, $\dot{y}_i^* / y_i^* = \dot{A}_i^* / A_i^* = g$ - thus making no difference to the main results derived from the model without human capital as given in Section 2.

Appendix B: A Numerical Example of the Efficiency-improving Innovation Model

This Appendix provides a numerical example to illustrate the transitional dynamics of the efficiency-improving innovation model presented in Section 2. We consider three hypothetical countries with different technological characteristics, and compute the transitional dynamics of the model as follows.

First, given exogenous parameters $[\lambda_i, \sigma_i]_{i=1}^N$ indicating indigenous innovation efficiency and knowledge absorptive capacity in Tab. 1, we use Eq. (14) to determine the endogenous rate of energy technological progress of the world frontier and obtain g = 0.034. Second, given the exogenous parameters $[\lambda_i, \sigma_i]_{i=1}^N$, the growth rate of the world frontier g, and initial conditions $[a_i(0)]_{i=1}^N$, we use the differential equation Eq. (8) to compute the time paths of technology gaps of each country relative to the world frontier $\{[a_i(t)]_{t=0}^\infty\}_{i=1}^N$. Third, given the time paths $\{[a_i(t)]_{t=0}^\infty\}_{i=1}^N$ and exogenous parameters in Tab. 2, we use the differential equation Eq. (9) to solve for the time paths of effective capital-energy ratios $\{[k_i(t)]_{t=0}^\infty\}_{i=1}^N$. Finally, given the time paths $\{[k_i(t)]_{t=0}^\infty\}_{i=1}^N$, we use Eq. (3) to compute the output per effective unit of primary energy input $\{[\tilde{y}_i(t)]_{t=0}^\infty\}_{i=1}^N$ and Eq. (2) to compute the output per physical unit of primary energy input $\{[y_i(t)]_{t=0}^\infty\}_{i=1}^N$.

Figs (1)-(2) provide the simulation results of the numerical example. As Fig. 1(a) shows, in the long-run BGP country A would have the lowest gap relative to the world technology frontier with a value of 0.5. Country B follows, with its technology gap around 0.35 relative to the world frontier. The technology gap of country C reaches a BGP level of 0.15 – the most backward position in the global technology ladder. Country A has the strongest capacity in indigenous innovation and ITD absorption, and is thus located in the top of the global technology ladder with the lowest gap relative to the frontier. In contrast, country C with the weakest indigenous innovation and knowledge absorptive capacity tends to be located in the bottom of the global technology ladder with the largest gap as compared to the frontier. It is also notable that over the time frame the technology gap of advanced country A declines from its initial level of 0.8 to the BGP level of 0.5, while the technology gap of backward country B improves from its initial level of 0.15 to the BGP level of 0.35 and C from 0.05 to 0.15. This result suggests a shifting geography of technology distribution: while the advanced country still contributes to most of the technology available in the world and thus has the lowest gap relative to the frontier, their shares in global technology distribution are anticipated to decline which is largely offset by backward countries' share gains. This is primarily because the potential force in the world economy – working through ITD – pulls individual countries to advance energy technology, and an economy that is technologically backward relative to the world frontier can advance technology level at a faster pace by assimilating more technology diffused from abroad.

Fig. 1(b) shows the time paths of primary energy use efficiency of the world technology frontier and three individual countries. Over the transitional dynamics periods, the world frontier improves its primary energy use efficiency at a rate of 3.45% and that growth rate for country A, B, and C averages to 2.96%, 4.31%, and 4.67%, respectively. In the long-run BGP, the growth rates of primary energy use efficiency in three countries all converge to 3.45% - the same growth rate as the world technology frontier, because the potential force– here working through ITD – would pull individual countries toward the world technology frontier, ensuring that individual country experiences the same rate of energy efficiency improvement in the long-run sustained growth. Meanwhile, it is also notable that albeit cross-country convergence in the growth rates, the absolute levels of energy use efficiency diverge across countries due to cross-country differences in indigenous innovation efficiency and knowledge absorptive capacity. Relative to country B and C, country A with a stronger capacity of undertaking indigenous innovation and absorbing foreign knowledge spillover tends to have a higher level of primary energy use efficiency.

Fig. 2(a) shows that the effective capital-energy ratio achieves the highest BGP level in country A, followed by country B, and finally country C. Since country A has the highest saving rate for capital investment and the lowest growth rate of primary energy supply, primary energy inputs thus have the lowest contribution to the production of end-use energy products in country A. In contrast, production of secondary energy products in countries B and C requires an intensive use of primary energy input, due to the fact that they have a lower saving rate of capital investment and a higher growth rate of primary energy supply. Moreover, a comparison between Fig. 2(b) and Fig. 2(c) shows that for each country, secondary energy products output per effective units of primary energy input remains constant, but that output per physical unit of primary energy input is growing in the BGP. This trend suggests that primary energy-augmenting technological progress, i.e., improvement in primary energy use efficiency, is vital to securing the supply of end-use, secondary energy products for meeting the growing final demands, given the long-run availability constraint of primary energy resources.

Appendix C: Proof of Proposition 3

We first solve the problem of secondary energy firms that maximizes the instantaneous flow profits,

$$\max \ \frac{1}{1-a}\cdot\left[\int_0^{N_i(t)} x_i(v,t)^{1-a}\cdot dv\right]\cdot K_i^a-\int_0^{N_i(t)} p_i(v,t)\cdot x_i(v,t)\cdot dv-r_i(t)\cdot K_i \quad , \tag{C1}$$

where the flow profits are obtained by subtracting the costs of renting capitals and using primary energy inputs from produced output. The F.O.C. w.r.t. $x_i(v,t)$ for each variety $v\in[0,N_i(t)]$ yields the demands for each primary energy input variety, $x_i(v,t)=p_i(v,t)^{-1/a}\cdot K_i$.

Next we consider the problem of primary energy firms that produce and supply each variety of primary energy, maximization of the intertemporal profit streams Eq. (19) is equivalent to maximizing the instantaneous profit for each time point,

$$\pi_i(v,t)=[p_i(v,t)-\psi]\cdot x_i(c,t)=[p_i(v,t)-\psi]\cdot p_i(v,t)^{-1/a}\cdot K_i \quad , \tag{C2}$$

where each primary energy firm sets a profit-maximizing pricing rule ($\psi\equiv 1-a$ for normalization),

$$p_i(v,t)=\frac{\psi}{1-a}=1=p_i \qquad \text{for all } v\in[0,N_i(t)] \text{ and } t \;, \tag{C3}$$

and supplies the same quantity of each primary energy input variety,

$$x_i(v,t)=p_i(v,t)^{-1/a}\cdot K_i=K_i=x_i(t) \qquad \text{for all } v\in[0,N_i(t)] \text{ and } t \;. \tag{C4}$$

This gives the profit possessed by the monopolistic firm owing each primary energy variety,

$$\pi_i(v,t)=[p_i(v,t)-\psi]\cdot x_i(v,t)=a\cdot K_i=\pi_i \qquad \text{for all } v\in[0,N_i(t)] \text{ and } t \;. \tag{C5}$$

Based on the HJB equation of the market value, Eq. (20), we thus obtain that the BGP market value of the energy firm supplying each primary energy variety is equal to $V_i^*=\pi_i^*/r_i^*=a\cdot K_i/r_i^*$, given that the interest rate and flow profits remain constant at some level $r_i(t)=r_i^*, \pi_i(v,t)=\pi_i^*$ along the BGP equilibrium. Substituting $V_i^*=a\cdot K_i/r_i^*$ into the free entry condition of R&D, Eq. (22), we can derive Eq. (26) and complete the proof of the first part of Proposition 3.

For the second part of Proposition 3, given the right-hand side of Eq. (26) is constant, the technology gap of each country relative to the world frontier N_i^*/N_{WTF}^* remains constant in the BGP, we thus obtain Eq. (27), implying that the technology variety of each country i should grow at the same rate as the world frontier in the BGP, $\dot{N}_i^*/N_i^*=\dot{N}_{WTF}^*/N_{WTF}^*=g^*$.

For the final part of Proposition 3, we consider the effect of technology variety expansion on the efficiency of converting each primary energy input into secondary energy products. As shown above, energy technology monopolist supplies the same quantity of primary energy inputs to the secondary energy producers $x_i(v,t)=K_i=x_i$, for all $v\in[0,N_i(t)]$. Production function of the secondary energy producers can thus be rewritten as,

$$Y_i(t)=\frac{1}{1-a}\cdot\left[\int_0^{N_i(t)}x_i(v,t)^{1-a}dv\right]\cdot K_i^a=\frac{1}{1-a}\cdot\left[N_i(t)\cdot x_i(t)^{1-a}\right]\cdot x_i(t)^a=\frac{1}{1-a}\cdot x_i\cdot N_i(t) \;. \tag{C6}$$

It shows that an expansion of energy technology varieties $N_i(t)$ raises the efficiency of converting each primary energy input variety x_i into end-use, secondary energy products $Y_i(t)$. Given that the number of primary energy input variety $N_i(t)$ increases at a rate g^* in the BGP, the productivity of using primary energy input to generate secondary energy products also grows at a rate g^*. ■

References

Acemoglu, D., 2009. Introduction to modern economic growth. Princeton University Press, Princeton, NJ, USA.

Apostolakis, B., 1990. Energy-capital substitutability/complementarity: the dichotomy. Energy Economics 12: 48-58.

Arrow, K. J., Fisher, A. C. 1974. Environmental preservation, uncertainty, and irreversibility. Quarterly Journal of Economics 88(2), 312-319

Baker, E., Shittu, E., 2008. Uncertainty and endogenous technical change in climate policy models. Energy Economics 30 (6), 2817–2828.

Becker, G., Murphy, K., Tamura, R., 1990. Human capital, fertility, and economic growth. Journal of Political Economy 98, S12-S37.

Becker, G., 1965. A theory of the allocation of time. Economic Journal 75, 493-517.

Ben-Porath, Y., 1967. The Production of human capital and the life cycle of earnings. Journal of Political Economy 75, 352-365.

Berndt, E. R., Wood, D., 1979. Engineering and econometric interpretations of energy-capital complementarity. American Economic Review 69, 342-354.

Bosetti, V., Carraro, C., Duval, R., Tavoni, M., 2011. What should we expect from innovation? A mode-based assessment of the environmental and mitigation cost implications of climate-related R&D. Energy Economics 33, 1313-1320.

Bosetti, V., Carraro, C., Massetti, E., Tavoni, M., 2008. International energy spillovers and the economics of green house gas atmospheric stabilization. Energy Economics 30, 2912-2929.

Bosetti, V., Tavoni, M., 2009. Uncertain R&D, backstop technology and GHG stabilization. Energy Economics 31, S18-S26.

Buonanno, P., Carraro, C., Galeotti, M., 2003. Endogenous induced technical change and the costs of Kyoto. Resource and Energy Economics 25, 11–34.

Clarke, L., Weyant, J., Edmonds, J., 2008. On the sources of technological advance: what do the models assume? Energy Economics 30 (2), 409–424.

Cowan, R., 1990. Nuclear power reactors: a study in technological lock-in. The Journal of Economic History 50 (3), 541–567.

Cowan, R., Hulten, S., 1996. Escaping lock-in: the case of the electric vehicle. Technological Forecasting and Social Change 53 (1), 61–79.

De Cian, E., Tavoni, M., 2012. Do technology externalities justify restrictions on emission permit trading?. Resource and Energy Economics 34(4), 624-646.

Dechezleprêtre, A., Glachant, M., Meniere, Y., 2008. The Clean Development Mechanism and the international diffusion of technologies: An empirical study. Energy Policy 36, 1273–1283.

Fisher, A.C., Narain, U., 2003. Global warm, endogenous risk, and irreversibility. Environmental and Resource Economics 25, 395-416 .

Frondel, M., Schmidt, C., 2002. The capital-energy controversy: An artifact of cost shares? The Energy Journal 23(3), 53-79.

Gerlagh, R., Kuik, O., 2007. Carbon leakage with international technology spillovers. FEEM Working Paper No. 33.2007.

Gerlagh, R., van der Zwann, B., 2003. Gross world product and consumption in a global warming model with endogenous technological change. Resource and Energy Economics 25 (1), 35-37.

Gerschenkron, A., 1962. Economic Backwardness in Historical Perspective. Harvard University Press, Cambridge, MA, USA.

Gillingham, K., Newell, R., Pizer, W., 2008. Modeling endogenous technological change for climate policy analysis. Energy Economics 30, 2734–2753.

Griliches, Z, Schmookler, J., 1963. Inventing and maximizing. American Economic Review 53, 725-729.

Griliches, Z., 1957. Hybrid corn: an exploration in the economics of technological change. Econometrica 25, 501-522.

Grubb, M., Hope, C., Fouquet, R., 2002. Climatic implications of the Kyoto Protocol: The contribution of international spillover. Climatic Change 54, 11–28.

Hall, B.H., Helmers, C. 2013. Innovation and diffusion of clean/green technology: Can patent commons help? Journal of Environmental Economics and Management 66, 33-51.

Held, H., Kriegler, E., Lessmann, K., Edenhofer, E., 2009. Efficient climate policies under technology and climate uncertainty. Energy Economics S50-S61.

Hübler, M., 2011. Technology diffusion under contraction and convergence: A CGE analysis of China, Energy Economics 33, 131-142.

International Energy Agency (IEA), 2012. World Energy Outlook 2012. OECD, Paris.

Jaffe, A.B., Newell, R.G., Stavins, R.N., 2005. A tale of two market failures: technology and environmental policy. Ecological Economics 54, 164–174.

Jin, W., Zhang, Z.X., 2014. Explaining the slow pace of energy technological innovation: Why market conditions matter? FEEM Working Paper Series, No. 18. 2014

Johnstone, N., Hascic, I., Popp, D., 2010. Renewable energy policies and technological innovation: evidence based on patent counts. Environmental and Resource Economics 45, 133-155.

Keller, W., 2004. International technology diffusion. Journal of Economic Literature 42, 752–782.

Koetse, M., de Groot, H., Florax, R., 2008. Capital-energy substitution and shifts in factor demand: A meta-analysis. Energy Economics 30, 2236–2251

Kolstad, C.D. 1996a. Fundamental irreversibilities in stock externalities. Journal of Public Economics 60, 221-233.

Kolstad, C. D. 1996b, Learning and stock effects in environmental regulations: the case of greenhouse gas emissions. Journal of Public Economics 60(2), 221-233

Lanjouw, J.O., Mody, A., 1996. Innovation and the international diffusion of environmentally responsive technology. Research Policy 25, 549–571.

Leimbach, M., Baumstark, L., 2010. The impact of capital trade and technological spillovers on climate policies. Ecological Economics 69, 2341–2355.

Leimbach, M., Edenhofer, O., 2007. Technological spillovers within multi-region models: Intertemporal optimization beyond the Negishi approach. Economic Modelling 24, 272–294.

Leimbach, M., Eisenack, K., 2009. A trade algorithm for multi-region models subject to spillover externalities. Computational Economics 33, 107–130.

Löschel, A., Otto, V., 2009. Technological uncertainty and cost effectiveness of CO2 emission reduction. Energy Economics 31, S4-S17

Lovely, M., Popp, D., 2011. Trade, technology and the environment: Does access to technology promote environmental regulation? Journal of Environmental Economics and Management 61, 16–35.

Manne, A., Richels, R., 2004. The impact of learning-by-doing on the timing and costs of CO2 abatement. Energy Economics 26, 603–619.

Mincer, J., 1974. Schooling, Experience, and Earnings. New York: National Bureau of Economic Research.

Narayanan, B., Walmsley, T., 2008. Global Trade, Assistance, and Production: The GTAP 7 Data Base. Center for Global Trade Analysis, Purdue University.

Nelson, R., Phelps, E.S., 1966. Investment in humans, technological diffusion, and economic growth. American Economic Review 56, 69-75.

Parrado, R., De Cian, E., 2014. Technology spillovers embodied in international trade: Intertemporal, regional and sectoral effects in a global CGE framework. Energy Economics 41, 76-89

Philibert, C., 2004. International Energy Technology Collaboration and Climate Change Mitigation. OECD Environment Directorate and International Energy Agency, Paris.

Pindyck, R. S., 2002. Optimal timing problems in environmental economics. Journal of Economic Dynamics & Control 26, 1677-1697.

Pindyck, R. S., 2007. Uncertainty in environmental economics. NBER working paper 12752.

Pizer, W., 1999. The optimal choice of climate change policy in the presences of uncertainty. Resource and Energy Economics 21 (3-4), 255-287.

Popp, D., 2006. Innovation in climate policy models: implementing lessons from the economics of R&D. Energy Economics 28 (56), 596-609.

Popp, D., 2006a. Innovation in climate policy models: Implementing lessons from the economics of R&D. Energy Economics 28, 596-609.

Popp, D., 2006b. International innovation and diffusion of air pollution control technologies: The effects of NO_X and SO_2 regulation in the U.S., Japan, and Germany. Journal of Environmental Economics and Management 51, 46–71.

Popp, D., 2011. International technology transfer, climate change, and the clean development mechanism. Review of Environmental Economics and Policy 5, 131-152.

Popp, D., Hascic, I., Medhi, N., 2010b. Technology and the diffusion of renewable energy. Energy Economics 33, 648-662.

Popp, D., Newell, R., 2012. Where Does Energy R&D Come From? Examining Crowding out from energy R&D. Energy Economics 34(4), 980-991.

Popp, D., Newell, R., Jaffe, A., 2010a. Energy, the environment, and technological change. In: Hall, B., Rosenberg, N. (Eds.), Handbook of the Economics of Innovation. Academic Press.

Popp, D., Santen, N., Fisher-Vanden, K., Webster, M., 2013. Technology variation vs. R&D uncertainty: What matters most for energy patent success? Resources and Energy Economics 35(4), 505-533.

Romer, P., 1986. Increasing Returns and Long-Run Growth. Journal of Political Economy 94, 1002–1037.

Romer, P., 1990. Endogenous Technological Change. Journal of Political Economy 98, S71–S102.

Rosenberg, N., 1994. Exploring the Black Box: Technology, Economics, and History. Cambridge University Press, Cambridge

Schmookler, J., 1966. Invention and economic growth. Harvard University Press. Cambridge, MA

Smulders, S., de Nooij, M., 2003. The impact of energy conservation on technology and economic growth. Resource and Energy Economics 25 (1), 59-79.

Thompson, P., Taylor, T.G., 1995. The capital-energy substitutability debate: A new look. The Review of Economics and Statistics 77: 565-569.

Ulph, A., Ulph, D., 1997, Global warming, irreversibility and learning. Economic Journal 107(442), 636-650

Unruh, G., 2000. Understanding carbon lock-in. Energy Policy 28, 817–830.

Unruh, G., 2002. Escaping carbon lock-in. Energy Policy 30, 317–325.

van der Zwann, B., Gerlagh, R., Klaassen, G., Schrattenholzer, L., 2002. Endogenous technological change in climate change modeling. Energy Economics 24, 1-9.

van Zon, A., Yetkiner, I.H., 2003. An endogenous growth model with embodied energy-saving technical change. Resource and Energy Economics 25 (1), 81-103.

Verdolini, E., Galeotti, M. 2011. At home and abroad: An empirical analysis of innovation and diffusion in energy technologies. Journal of Environmental Economics and Management 61, 119-134.

World Bank. 2008. Global Economic Prospects: Technology Diffusion in the Developing World. Washington, DC: World Bank.

Table 1
Parameter values for solving for the time paths of proportional technology gaps of three countries (A, B, and C) relative to the world technology frontier $\{[a_i(t)]_{t=0}^{\infty}\}_{i=1}^{N}$

	σ_i	λ_i	$a_i(0)$
A	0.015	0.018	0.8
B	0.010	0.015	0.15
C	0.005	0.008	0.05

λ_i : country i's efficiency of undertaking indigenous innovation, and the values are based on the fact that the proportional technology gap of each country i relative to the world frontier is less than unity, $\sigma_i / (\sigma_i + g - \lambda_i) < 1$, which translates into $\lambda_i < g$. The ex ante value of the technological growth rate of the world frontier g is based on the fact that the highest rate of energy efficiency improvement achieved among advanced countries in recent decades averages to 2-3%. The ex post value of g is endogenously determined by technological characteristics $[\sigma_i, \lambda_i]_{i=1}^{N}$ of all individual countries in the world economy.

σ_i : country i's capacity of absorbing foreign knowledge diffusion from the external world, and this setting reflects no "free riding" in innovation - domestic countries should undertake indigenous innovation commitment and not solely free ride on foreign knowledge diffusion. Indigenous innovation is of primary importance to fostering domestic technological progress, and absorption of ITD is secondarily important: $\sigma_i < \lambda_i$.

$a_i(0)$: the initial values of country i's proportional technology gap relative to the world technology frontier, and the setting of these parameter values is based on the ratio of country i's R&D spending relative to the global R&D total.

Table 2
Parameter values used in solving for the time paths of effective capital-energy ratios of three countries (A, B, and C) $\{[k_i(t)]_{t=0}^{\infty}\}_{i=1}^{N}$

	s_i	a_i	n_i	δ_i	$k_i(0)$
A	0.3	0.7	0.02	0.1	2.33
B	0.28	0.65	0.025	0.1	1.86
C	0.25	0.6	0.03	0.1	1.5

s_i : country i's exogenous saving rate for capital investment.
a_i : country i's output elasticity of capital (the input cost share of capital in production output) for a Cobb-Douglas production function.
n_i : country i's growth rate of primary energy resource supply.
δ_i : country i's depreciation rate of physical capital.
$k_i(0)$: the initial value of country i's effective capital-energy ratio, measured as the ratio of input shares between capital and primary energy input: $k_i(0) = a_i / (1 - a_i)$.

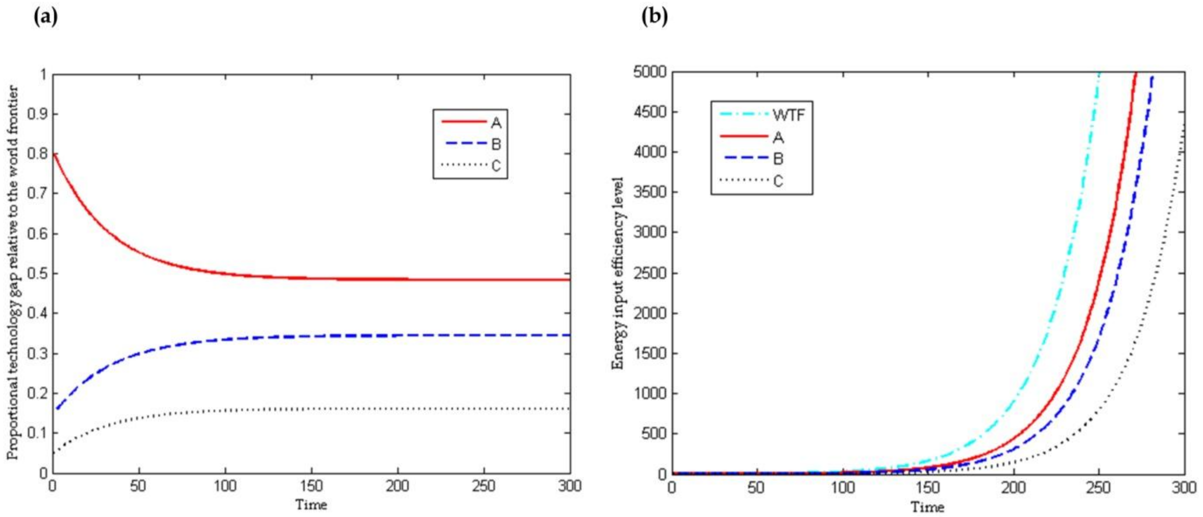

Figure 1: (a) The time paths of proportional technology gap of three hypothetical countries (A, B, and C) relative to the world technology frontier (WTF). The values in the Y axis lie within the range [0, 1], the value of null implies that the specific country has the largest gap relative to the world frontier, and the value of unity means the specific country has a technology level that is the same as the world frontier. Time in the X axis denotes years.
(b) The time paths of primary energy use efficiency for the world technology frontier (WTF) and three individual countries (A, B, and C). The unit of the Y axis is the benchmark initial year's energy use efficiency of the world technology frontier. Time in the X axis denotes years.

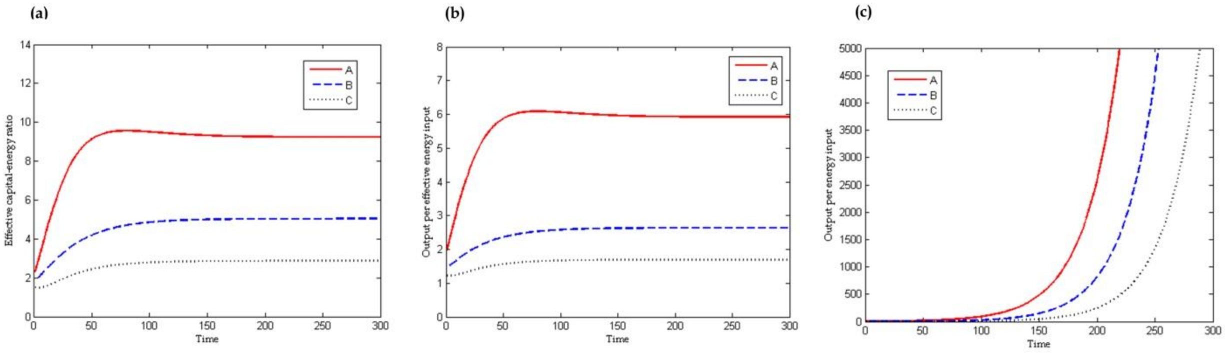

Figure 2: (a) The time paths of effective capital-energy ratios for three countries (A, B, and C), where the effective capital-energy ratio is defined by Eq. (4);
(b) The time paths of output per effective primary energy input for three countries (A, B, and C), where the output per effective unit of energy input is defined by Eq. (3);
(c) The time paths of output per physical primary energy input for three countries (A, B, and C), where the output per physical unit of energy input is defined by Eq. (2).