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Quo Vadis? Energy Consumption and Technological Innovation

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Keywords
Technological Innovation; Energy Consumption; Economic Growth Model.

JEL Classification
Q55; Q58; Q43; Q48; O13; O31; O33; O44; F18.

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Quo Vadis? Energy Consumption and Technological Innovation in China's Economic Growth

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Abstract:

Whether China maintains its business-as-usual energy-intensive growth trajectory or changes to a sustainable development alternative has significant implications for global energy and climate governance. This paper is motivated to theoretically examine China's potential transition from its energy-intensive status quo to an innovation-oriented growth prospect. We develop an economic growth model that incorporates the endogenous mechanism of technological innovation and its interaction with fossil energy use and the environment. We find that from an initial condition with a pristine environment and a small amount of capital installation, the higher dynamic benefits of physical investment will incentivize the investment in physical capital rather than R&D-related innovation. Accumulation of the energy-consuming capital thus leads to an intensive use of fossil energy - an energy-intensive growth pattern. But if the mechanism of R&D-related innovation is introduced into the economy, until the dynamic benefit of R&D is equalized with that of capital investment, the economy embarks on R&D for innovation. As a result, the economy will evolve along an innovation-oriented balanced growth path where consumption, physical capital and technology all grow, fossil energy consumptions decline, and environmental quality improves.

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1. Introduction

In 1992 during his famed Southern Trip, Deng Xiaoping, the chief architect of the Chinese economic reforms, proclaimed that "Development is the only hard truth!". The successive leaders in the post-Deng era have consistently kept the goal of economic growth as China's development priorities. This growth-oriented strategy ignited the astonishing power of China's economic revolution and enabled the achievement of double-digit growth over the past twenty years. However, it is through this search for economic growth that China also adopted another motto – growth at all costs. Two decades later, China is no longer the third world country that Deng lived in, but a main manufacturing powerhouse that has turned a blind eye towards energy resources depletion and environmental degradation that plague all Chinese citizens.

This is clearly demonstrated by China's mammoth appetite for fossil energy use during the past growth periods. Over the years 1990-2012, China's total primary energy consumption grew by 5.1% annually from 910 million tonnes of oil equivalent (Mtoe) to 2721 Mtoe, and the energy-related carbon emissions rise by 6.9% per year from 2244 megatonnes (Mt)) to 9860 Mt (IEA, 2013a). Putting those numbers in a global context, China has overtaken the U.S. to become the world's top energy consumer and carbon emitter (Zhang, 2007a and 2010a,b). In the medium- to long-term, it is expected that this fast-growing economy will drive the world's future growth in energy consumption and account for one quarter of the global total over the period 2020-2030 (IEA, 2013b). As the international community has raised serious concerns about fossil energy use surges and resultant global warming, there is no disagreement that China's business-as-usual growth is highly likely to exacerbate the unsolved global energy/climate problems. To mitigate the environmental externality, China needs to consider replacing its baseline growth pattern by adopting a more sustainable development alternative (Zhang, 2007b and 2010a,b).

In the minds of the leadership in Beijing, one of the keys to achieving long-term green growth and sustainable future is decoupling fossil energy use from economic growth through technological innovation. Indeed, beyond its current role as the global manufacturing engine, China is building the theme of innovation in its economic growth story, which is manifested by the strong growth of R&D investment for innovation. Following the U.S. and Japan, China has become the world's third leading R&D investor - over US$100 billion R&D spending in 2012. R&D expenditure grew notably by 15-20% per year over the last decade, and R&D intensity has doubled as a share of GDP, reaching 2% in 2012 (OECD, 2013). To achieve the long-run target of building an innovation-oriented society, China has set an ambitious plan of strengthening investment in innovation. This is reflected by the government's spending target of 2.5% of GDP on R&D by 2020, which translates into a tripling of R&D investment over the next decade to US$300 billion (OECD, 2012).

In such a context where R&D-related innovation is adopted as a strategic policy to achieve long-term energy-efficient, innovation-led growth prospect, it is particularly vital for the policymakers to have a deep understanding of the interconnected nature of technological innovation, energy use, and economic growth, such that China's energy and innovation policy reforms can be effectively addressed. Therefore, in this paper we contribute to a theoretical model which features an endogenous mechanism of technological innovation and its interactions with fossil energy use and economic growth. Based on this model, we aim to provide deep insights into China's potential transition from its energy-intensive status quo to an innovation-oriented growth prospect.

The model used here is building on the endogenous growth literature, for example, Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992). In addition, our representation of endogenous technological change is closely related to the "stock of knowledge" approach introduced by Goulder and Schneider (1999) and Popp (2004) in energy/climate economic analysis.[1] But difference in modelling approaches is notable. The model used here is a one-sector aggregate framework based on which the underlying mechanism of technological change can be analytically characterized, while most of existing energy/climate policy modelling tend to adopt disaggregated multi-sector frameworks (e.g., CGE-based simulations) for quantitative assessments of policy impacts. In this respect, our study is closely related to several theoretical works analyzing the relationship between economic growth, technological change, and the environment, for example, Selden and Song (1995), Stokey (1998). Bovenberg and Smulders (1995), Grimaud (1999), Reis (2001), Jones and Manuelli (2001), Cassou and Hamilton (2004), Ricci (2007), Cunha-e-sá and Reis (2007), and Rubio et al. (2010).

The rest of this paper is structured as follows. Section 2 sets up the environment of the model. Section 3 provides a social planner solution to characterize the optimal growth path. The balanced growth path (BGP) equilibrium and transitional dynamics are examined in Section 4 and Section 5. Section 6 presents numerical examples. Section 7 concludes.

2. The Model

The Ramsey-Cass-Koopmans growth model is employed as the workhorse for economic analysis. It models the Chinese economy as an infinite-horizon economy in continuous time, and admits a representative household (with measure normalized to unity) which has an instantaneous utility function given by

$$U(C(t),Q(t)) = InC(t) + \sigma \cdot InQ(t) \quad , \tag{1}$$

[1] Several subsequent studies have adopted the "stock of knowledge" method to examine the effect of technological change in energy/climate economics, for example, Nordhaus (2002), Popp (2004), Sue Wing (2006), Bosetti et al. (2011), Otto et al. (2008), Gillingham et al. (2008).

where the household values both environmental quality Q and consumption goods C. Since both environmental and consumption goods are separable, we thus represent the preference by a function of the additively separable form. Logarithmic preferences enable us to simplify the exposition without any loss of generality. (1) is strictly increasing, concave, and twice differentiable for all Q and C in the interior of their domains, and satisfies the Inada conditions. Parameter σ measures the environmental willingness of the household to substitute consumption for environmental goods.

Suppose that, the atmosphere has a fixed amount of environmental carrying capacity (normalized to unity), more energy-related emission pollutants P thus give rise to a lower level of environmental quality Q (environmental quality and energy-related air pollution are inversely related, $Q = P^{-1}$). Meanwhile, consider that one unit of fossil energy use E generates one unit of emission pollutant $E = P$, we thus have $E = E(Q) = Q^{-1}$ and the instantaneous utility function (1) can be rewritten as

$$U(C(t), E(t)) = InC(t) - \sigma \cdot InE(t) \quad , \tag{2}$$

where the environmental pollution (e.g., carbon emissions) caused by the combustion of fossil fuels has a negative externality effect on the household utility. Meanwhile, combustions of fossil fuels and resultant air pollutions have a negative effect on the supply side of the economy, with the production possibilities specified by the aggregate function,

$$Y(t) = Y(K(t), E(t)) = A \cdot K(t)^{\alpha} \cdot P(t)^{-\beta} = A \cdot K(t)^{\alpha} \cdot E(t)^{-\beta}, \tag{3}$$

where Y is the production output of final goods, and K, E, P is physical capital, fossil energy use, and energy-related pollution respectively. $A > 0$ is the total factor productivity (TFP) parameter, and $0 < \alpha, \beta < 1$ denotes the elasticity of Y with respect to K and E. Note that, the specification of (3) captures the negative environmental externality induced by fossil energy uses: environmental pollution due to fossil fuel uses deteriorates capital assets and thus lowers the productivity of physical capital.[2]

Furthermore, suppose that fossil energy uses positively depend on the deployment of traditional physical capital, which captures the general complementarity between fossil energy use and physical capital. In contrast, innovation has an energy-saving effect in the sense that technology and knowledge assets (e.g., technique know-how, managerial skills) have an notable effect to lower reliance on fossil energy inputs in outputs production, fossil energy use is thus negatively related with knowledge,

$$E(t) = E(K(t), H(t)) = K(t)^{\kappa} \cdot H(t)^{-h}, \tag{4}$$

where H is the knowledge stock, and $\kappa, h > 0$ denote the elasticity of E with respect to K and H. From (3) and (4), it is straightforward to find that innovation and knowledge creation, through fossil

[2] In this respect, we follow the assumption in the literature of environmental pollution on economic growth where the environmental quality is treated as a production factor that can affect the productivity of physical capital (Bovenberg and Smulders, 1995; Cassou and Hamilton, 2004).

energy saving, has a positive effect to improve environmental quality and the productivity of physical capital. The production function (4) is thus alternatively written as

$$Y(t) = F(K(t), H(t)) = A \cdot K(t)^{\alpha - \beta \cdot \kappa} \cdot H(t)^{\beta \cdot h} = A \cdot K(t)^{\bar{\alpha}} \cdot H(t)^{\bar{\beta}}, \tag{5}$$

where $\bar{\alpha} = \alpha - \beta \cdot \kappa$, $\bar{\beta} = \beta \cdot h$ denotes the elasticity of Y with respect to K and H, respectively. To ensure that the economy has a balanced growth path equilibrium, we impose the neoclassical assumption $\bar{\alpha} + \bar{\beta} = \alpha - \beta \cdot \kappa + \beta \cdot h = 1$.[3] Furthermore, given the marginal product of physical capital is decreasing $\alpha < 1$, we have $h > \kappa$, the energy-saving effect of knowledge application is larger than the energy-consuming effect of physical capital deployment.

Given the above-described preference and production technology, the optimal growth problem is equivalent to characterizing the time paths of consumption, R&D, physical capital, and knowledge asset that maximizes the intertemporal utility of the representative household,

$$\max_{[C(t), R(t), K(t), H(t)]_{t=0}^{\infty}} \int_0^{\infty} \exp(-\rho \cdot t) \cdot (InC(t) - \sigma \cdot InE(t)) \cdot dt \quad , \tag{6}$$

subject to

$$\dot{K}(t) = A \cdot K(t)^{\bar{\alpha}} \cdot H(t)^{\bar{\beta}} - C(t) - R(t) \quad , \tag{7}$$

$$\dot{H}(t) = R(t), \tag{8}$$

where there is discounting of future utility streams from the initial period to an infinite future according to the discount rate ρ. The equations (7) and (8) describe the law of motion for physical and knowledge capital given their initial conditions K_0, H_0.[4] Note that, part of the production outputs are used for the innovative activities in terms of R&D investment for knowledge accumulations, which endogenously pins down the dynamics of knowledge creation and technological progress.

3. Characterization of Optimal Growth

To characterize the optimal growth path, we solve the social planner problem by setting up the current-value Hamiltonian which takes the form,[5]

$$\hat{\mathrm{H}}(C, R, K, H, q_K, q_H) = U(C, E(K, H)) + q_K \cdot [F(K, H) - C - R] + q_H \cdot R, \tag{9}$$

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[3] From the loglinearization of (5), the condition $\bar{\alpha} + \bar{\beta}$=1 implies the same constant growth rate of output, capital, and knowledge in the BGP equilibrium $g_Y = g_K = g_H = g^*$, where $g_Y = \dot{Y}/Y, g_K = \dot{K}/K, g_H = \dot{H}/H$.

[4] To simplify the notations, physical capital is assumed not to depreciate.

[5] To economize on notation, we drop the time subscript.

with control variables C, R, state variables K, H, and current-value costate variables q_K, q_H. By applying the maximum principle for infinite-horizon problems, we derive the necessary conditions (an interior solution) that characterize the optimal growth path,

$$\hat{\text{H}}_C = 0 = U_C(C, E(K,H)) - q_K, \tag{10}$$

$$\hat{\text{H}}_R = 0 = -q_K + q_H, \tag{11}$$

$$\hat{\text{H}}_K = \rho \cdot q_K - \dot{q}_K = U_E(C, E(K,H)) \cdot E_K(K,H) + q_K \cdot F_K(K,H) \ , \tag{12}$$

$$\hat{\text{H}}_H = \rho \cdot q_H - \dot{q}_H = U_E(C, E(K,H)) \cdot E_H(K,H) + q_K \cdot F_H(K,H) \ , \tag{13}$$

$$\hat{\text{H}}_{qK} = \dot{K} = F(K,H) - C - R \ , \tag{14}$$

$$\hat{\text{H}}_{qH} = \dot{H} = R. \tag{15}$$

and the transversality conditions,

$$\lim_{t \to +\infty} \exp(-\rho \cdot t) \cdot q_K \cdot K = 0, \quad \lim_{t \to +\infty} \exp(-\rho \cdot t) \cdot q_H \cdot H = 0. \tag{16}$$

From the equations (10)-(13) we derive a more explicit equation that characterizes the static intra-temporal condition of optimal growth,

$$\begin{aligned} &U_E(C, E(K,H)) \cdot E_K(K,H) + U_C(C, E(K,H)) \cdot F_K(K,H) \\ &= U_E(C, E(K,H)) \cdot E_H(K,H) + U_C(C, E(K,H)) \cdot F_H(K,H) \end{aligned}, \tag{17}$$

where investment in both physical and knowledge capital has the same rate of current return (intra-temporal no-arbitrage condition). The LHS is the rate of current return on physical investment, given by its negative effect on the utility through energy-related air pollution $U_E \cdot E_K$, plus its positive effect on the utility via increases in consumption goods $U_C \cdot F_K$. The RHS is the rate of current return on R&D investment, given by its positive effect on the utility via environmental improvements $U_E \cdot E_H$, plus its positive effect on the utility through increases in final consumption goods $U_C \cdot F_H$.

The equations (12)-(13) characterize inter-temporal dynamic no-arbitrage conditions for physical and knowledge capital, respectively. q_K, q_H is the shadow price of physical and knowledge capital respectively (the market value of holding the asset). The product with discount rate ρ is the returns from selling the capital asset. Meanwhile, the returns from holding the asset come from two sources. The first source of returns is intertemporal changes in the value of capital asset that is equal to $\dot{q}_K$. The second is the current returns from capital investment (so-called dividends), which corresponds to the flow payoff in an intra-temporal context given by the RHS of the equations (12)-(13). For the functional forms of the model specified in Section 2, we have the following result.

Lemma 1 *In the above-described endogenous innovation model, the social planner solution yields a static intra-temporal optimality condition that relates consumption-capital ratio to capital-knowledge ratio,*

$$c = \frac{A \cdot [\bar{\alpha} - (1-\bar{\alpha}) \cdot k]}{\sigma \cdot (\kappa \cdot k^{1-\bar{\alpha}} + h \cdot k^{2-\bar{\alpha}})}. \tag{18}$$

where $k \equiv K / H$ *is the capital-knowledge ratio, and* $c \equiv C / K$ *is the consumption-capital ratio. Furthermore, we obtains the growth rate of consumption-capital ratio c as a function of the capital-knowledge ratio k,*

$$\frac{\dot{c}}{c} = \frac{\Delta_1(k)}{\Delta_2(k)} \cdot \frac{\dot{k}}{k}, \tag{19}$$

with the numerator $\Delta_1(k) = h \cdot (1-\bar{\alpha})^2 \cdot k^2 - \bar{\alpha} \cdot [(1-\bar{\alpha}) \cdot \kappa + (2-\bar{\alpha}) \cdot h] \cdot k - \bar{\alpha} \cdot (1-\bar{\alpha}) \cdot \kappa$ *and the denomerator* $\Delta_2(k) = -h \cdot (1-\bar{\alpha}) \cdot k^2 + [\bar{\alpha} \cdot h - (1-\bar{\alpha}) \cdot \kappa] \cdot k + \bar{\alpha} \cdot \kappa$.

Proof. See Appendix A. □

We proceed to characterizing the intertemporal parts of the optimality conditions, which can be summarized by the following result.

Lemma 2. *In the above-described endogenous innovation model, the social planner solution yields inter-temporal dynamic optimality conditions which characterize the growth rate of consumption-capital ratio,*

$$\frac{\dot{c}}{c} = \frac{\dot{C}}{C} - \frac{\dot{K}}{K} = \frac{[\bar{\alpha} \cdot h + (1-\bar{\alpha}) \cdot \kappa] \cdot A \cdot k^{\bar{\alpha}}}{\kappa + h \cdot k} - \rho - g_K, \tag{20}$$

and the growth rate of capital-knowledge ratio,

$$\frac{\dot{k}}{k} = \frac{\dot{K}}{K} - \frac{\dot{H}}{H} = (1+k) \cdot g_K - \frac{A \cdot [(\sigma \cdot h + 1 - \bar{\alpha}) \cdot k^{\bar{\alpha}+1} + (\sigma \cdot \kappa - \bar{\alpha}) \cdot k^{\bar{\alpha}}]}{\sigma \cdot (\kappa + h \cdot k)}. \tag{21}$$

where g_K *is the growth rate of physical capital,* $g_K \equiv \dot{K} / K$.

Proof. See Appendix B. □

The system of equations (19), (20), and (21) can be used to pin down the analytical solutions of $\dot{k}/k$, $\dot{c}/c$, and g_K, which are summarized by the following result.

Lemma 3 *In the above-described endogenous innovation model, the social planner maximizes the intertemporal utility of the household (6), subject to the law of motion for physical and knowledge capital (7)-(8), given the initial conditions* $H(0) > 0, K(0) > 0$. *The social planner solution yields the optimality conditions which determine the growth rate of capital-knowledge ratio as*

$$\begin{aligned} \frac{\dot{k}}{k} = & \frac{[1+\sigma \cdot (h-\kappa)] \cdot [\bar{\alpha} - (1-\bar{\alpha}) \cdot k] \cdot A \cdot k^{\bar{\alpha}}}{\sigma \cdot (\kappa + h \cdot k) \cdot [(1+k) \cdot \Delta_1(k) + \Delta_2(k)]} \cdot \Delta_2(k) \\ & - \frac{\sigma \cdot \rho \cdot [\kappa + (\kappa + h) \cdot k + h \cdot k^2]}{\sigma \cdot (\kappa + h \cdot k) \cdot [(1+k) \cdot \Delta_1(k) + \Delta_2(k)]} \cdot \Delta_2(k) \end{aligned}, \tag{22}$$

the growth rate of consumption-capital ratio as,

$$\frac{\dot{c}}{c}=\frac{\Delta_1(k)}{\Delta_2(k)}\cdot\left\{\frac{[1+\sigma\cdot(h-\kappa)]\cdot[\bar{\alpha}-(1-\bar{\alpha})\cdot k]\cdot A\cdot k^{\bar{\alpha}}}{\sigma\cdot(\kappa+h\cdot k)\cdot[(1+k)\cdot\Delta_1(k)+\Delta_2(k)]}\cdot\Delta_2(k)\right. \\ \left. -\frac{\sigma\cdot\rho\cdot[\kappa+(\kappa+h)\cdot k+h\cdot k^2]}{\sigma\cdot(\kappa+h\cdot k)\cdot[(1+k)\cdot\Delta_1(k)+\Delta_2(k)]}\cdot\Delta_2(k)\right\}, \quad (23)$$

and the growth rate of physical capital as

$$g_K\equiv\dot{K}/K=\frac{(\sigma\cdot h+1-\bar{\alpha})\cdot A\cdot k^{1+\bar{\alpha}}+(\sigma\cdot\kappa-\bar{\alpha})\cdot A\cdot k^{\bar{\alpha}}}{\sigma\cdot(\kappa+h\cdot k)\cdot[(1+k)\cdot\Delta_1(k)+\Delta_2(k)]}\cdot\Delta_1(k) \\ +\frac{\sigma\cdot[\bar{\alpha}\cdot h+(1-\bar{\alpha})\cdot\kappa]\cdot A\cdot k^{\bar{\alpha}}-\sigma\cdot\rho\cdot(\kappa+h\cdot k)}{\sigma\cdot(\kappa+h\cdot k)\cdot[(1+k)\cdot\Delta_1(k)+\Delta_2(k)]}\cdot\Delta_2(k). \quad (24)$$

Given $\dot{k}/k$, $\dot{c}/c$, *and* g_K, *the growth rate of consumption is determined by* $g_C\equiv\dot{C}/C=\dot{c}/c+g_K$, *and the rate of technological progress (knowledge accumulation) is determined by* $g_H\equiv\dot{H}/H=g_K-\dot{k}/k$.

Proof. See Appendix C. □

The entire time path of the optimal growth of the economy can thus be computed as follows. Given the initial condition $k(0)\equiv K(0)/H(0)$ and the differential equation (22), we solve for the time path of $[k(t)]_{t>0}$. Once $[k(t)]_{t\geq 0}$ is determined, we use (18) and (24) to compute the time paths of $[c(t)]_{t\geq 0}$, $[g_K(t)]_{t\geq 0}$, and $[g_H(t)]_{t\geq 0}$. Given the initial condition $[K(0),H(0)]$ and $[g_K(t),g_H(t)]_{t\geq 0}$, we compute the time path of $[K(t),H(t)]_{t\geq 0}$. Finally, given $[c(t)]_{t\geq 0},[K(t)]_{t\geq 0}$, we calculate the time path of $[C(t)]_{t\geq 0}$.

4. Balanced Growth Path

The BGP equilibrium is defined as an allocation (k^*,c^*,g^*) such that both the consumption-capital and capital-knowledge ratios are constant $c(t)=c^*, k(t)=k^*$, and the consumption, physical capital, and knowledge capital all grow at a constant rate $g_C(t)=g_K(t)=g_H(t)=g^*$. The stationary condition $\dot{k}(t)=0$ on (22) yields the BGP equilibrium level of the capital-knowledge ratio k^* that satisfies

$$[1+\sigma\cdot(h-\kappa)]\cdot[\bar{\alpha}-(1-\bar{\alpha})\cdot k^*]\cdot A\cdot k^{*\bar{\alpha}}=\sigma\cdot\rho\cdot[\kappa+(\kappa+h)\cdot k^*+h\cdot k^{*2}]. \quad (25)$$

We thus obtain the result that characterizes the existence and uniqueness of the BGP equilibrium.

Proposition 1 *In the above-described model with exogenous parameters* A, σ, ρ, κ, h, *and* $\bar{\alpha}$, *denote* $k^*_U(\sigma,\rho,\kappa,h,\bar{\alpha})$ *as the unique BGP level of capital-knowledge ratio, and* $A^*_U(\sigma,\rho,\kappa,h,\bar{\alpha})$ *as the TFP parameter that supports this unique BGP equilibrium.* $k^*_U(\sigma,\rho,\kappa,h,\bar{\alpha})$, $A^*_U(\sigma,\rho,\kappa,h,\bar{\alpha})$ *are endogenously* *determined by the equilibrium condition,*

$$[1+\sigma\cdot(h-\kappa)]\cdot[\bar{\alpha}-(1-\bar{\alpha})\cdot k_U^*]\cdot A_U^*\cdot k_U^{*\bar{\alpha}}=\sigma\cdot\rho\cdot[\kappa+(\kappa+h)\cdot k_U^*+h\cdot k_U^{*2}], \tag{26}$$

and the tangency condition,

$$[1+\sigma\cdot(h-\kappa)]\cdot[\bar{\alpha}^2-(1-\bar{\alpha}^2)\cdot k_U^*]\cdot A_U^*\cdot k_U^{*\bar{\alpha}-1}=\sigma\cdot\rho\cdot[\kappa+h+2\cdot h\cdot k_U^*]. \tag{27}$$

If an exogenously given TFP parameter is larger than the endogenously determined parameter that supports the unique BGP equilibrium, $A>A_U^*$, then there exist two different BGP equilibria k_1^* and k_2^*, where $0<k_1^*<k_U^*<k_2^*<\bar{\alpha}/(1-\bar{\alpha})$. If $A=A_U^*$, then there exists a unique BGP equilibrium k_U^*. If $A<A_U^*$, there exists no BGP equilibrium.

Proof. See Appendix D. □

We focus on an economically relevant case where the TFP parameter A is sufficiently high, and Proposition 1 implies that there exist two BGP equilibria. One is associated with a higher capital-knowledge ratio k_2^* and a lower consumption-capital ratio c_2^*. The other is characterized by a lower k_1^* and a higher c_1^*. In this case, the former equilibrium with k_2^* and c_2^* will have a positive growth rate of consumption, physical capital, and technology, and the fossil energy use will decrease at a constant rate along this BGP equilibrium. This can be summarized by the following result.

Proposition 2 *Consider the above-described model, in the case where the TFP parameter has a sufficiently high value, there exist two BGP equilibira, and at least one of them has a positive growth rate of consumption, capital, and technology $g^*>0$. Moreover, along this BGP equilibrium fossil energy consumption would fall at a rate of $g_E^*=(\kappa-h)\cdot g^*<0$.*

Proof. See Appendix E. □

There are also several straightforward comparative static results that show the BGP equilibrium changes with the underlying parameters. For this reason, we establish the following result.

Corollary 1 *Consider the case where the TFP parameter has a sufficiently high value and there exists a BGP equilibrium with a positive growth rate, denote the capital-knowledge ratio along this BGP equilibrium by $k^*(A,\sigma,\rho,\kappa,h,\bar{\alpha})$ when the underlying parameters are $A,\sigma,\rho,\kappa,h,\bar{\alpha}$. Then*

$$\frac{\partial k^*(A,\sigma,\rho,\kappa,h,\bar{\alpha})}{\partial A}>0,\quad \frac{\partial k^*(A,\sigma,\rho,\kappa,h,\bar{\alpha})}{\partial \sigma}<0,\quad \frac{\partial k^*(A,\sigma,\rho,\kappa,h,\bar{\alpha})}{\partial \rho}<0$$

$$\frac{\partial k^*(A,\sigma,\rho,\kappa,h,\bar{\alpha})}{\partial \kappa}<0,\quad \frac{\partial k^*(A,\sigma,\rho,\kappa,h,\bar{\alpha})}{\partial \bar{\alpha}}>0,\quad \frac{\partial k^*(A,\sigma,\rho,\kappa,h,\bar{\alpha})}{\partial h}\ \textit{is undetermined}$$

Proof. See Appendix F. □

This result implies that an improvement in consumer's environmental awareness (an increase in

σ) would reduce the BGP level of the capital-knowledge ratio k^*. Moreover, household preference towards environmental goods has an effect on the long-run growth rate. This can be shown by taking derivative of the growth rate g with respect to k evaluated at the BGP k^*,[6]

$$\frac{dg^*}{dk^*} = \left.\frac{dg}{dk}\right|_{k^*} = \frac{[\bar{\alpha}\cdot h + (1-\bar{\alpha})\cdot\kappa]\cdot A\cdot k^{*\bar{\alpha}}}{[\kappa + h\cdot k^*]^2}\cdot\frac{\bar{\alpha}\cdot\kappa - (1-\bar{\alpha})\cdot h\cdot k^*}{k^*}. \tag{28}$$

Given that consumers' environmental attitudes (σ rises) decrease k^*, $dk^*/d\sigma < 0$, it is thus possible that a sufficiently high level of σ would lower the BGP level of k^* so that $k^* < \bar{\alpha}\cdot\kappa/[(1-\bar{\alpha})\cdot h]$ and thus $dg^*/dk^* > 0$. In this case, household preference towards environmental goods and green economy would lower the growth rate along the BGP equilibrium, $dg^*/d\sigma < 0$.

5. Transitional Dynamics

This section turns to transitional dynamics from initial conditions to the BGP equilibrium. Consider that given the initial levels of capital and knowledge, K_0, H_0, if their ratio is equal to the BGP level, $K_0/H_0 = k^*$, then there is no transitional dynamics. That is, starting from the initial condition $K_0 > 0, H_0 > 0$, the economy will immediately jump into the BGP equilibrium along which both capital-knowledge and consumption-capital ratios remain constant $k(t) = k^*, c(t) = c^*$, and consumption, capital, and technology all grow at a constant rate $g_C(t) = g_K(t) = g_H(t) = g^*$ for all t.

However, if the initial level of capital accumulation is lower so that $K_0/H_0 < k^*$, then there is transitional dynamics from the initial condition to the BGP equilibrium. In this case, the lower level of capital implies that the dynamic benefit (as measured by the shadow price) of capital investment is higher than that of R&D, $q_K > q_H$, thus economic resources will be allocated to capital investment instead of R&D-related innovation. This is shown by the value function q_K,[7]

$$\begin{aligned}\rho\cdot q_K &= \dot{q}_K + U_E(C,E)\cdot E_K(K,H) + U_C(C,E)\cdot F_K(K,H)\\ &= \dot{q}_K + \left[\underbrace{-\frac{\sigma\cdot\kappa}{Q}\cdot K^{-\kappa-1}\cdot H^h}_{(1)} + \underbrace{\frac{1}{C}\cdot\bar{\alpha}\cdot A\cdot\left[\frac{K}{H}\right]^{\bar{\alpha}-1}}_{(2)}\right].\end{aligned} \tag{29}$$

[6] The equation (28) follows from the equation (20) where the BGP growth rate of the economy can be represented as $g = [\bar{\alpha}\cdot h + (1-\bar{\alpha})\cdot\kappa]\cdot A\cdot k^{\bar{\alpha}}/(\kappa + h\cdot k) - \rho$.

[7] It follows from the equation (12) and is the Hamilton-Jacobi-Bellman (HJB) equation for physical asset values. Given the inverse relationship between environmental quality and fossil energy use $E = E(Q) = Q^{-1}$, we have $U_E(C,E)\cdot E_K(K,H) = (-\sigma\cdot E^{-1})\cdot(-Q^{-2})\cdot(-\kappa\cdot K^{-\kappa-1}\cdot H^h) = -\sigma\cdot\kappa\cdot Q^{-1}\cdot K^{-\kappa-1}\cdot H^h$.

In the initial condition, there is a sufficiently high level of environmental quality $Q \to +\infty$ due to the lowest amount of fossil energy use, the negative effect of capital investment on the utility through energy-related air pollution (the RHS term (1)) is sufficiently small, thus the positive effect on the utility through increases in consumption goods (the RHS term (2)) dominates the net effect. As the latter effect is inversely related to capital, (29) implies that the lower the level of capital K, the higher the shadow price of capital q_K.[8]

In this case, as the level of physical capital is lower during transitional periods, the shadow price of capital q_K is higher than that of knowledge q_H, the social planner thus has an incentive to invest in physical capital instead of R&D.[9] Thus the FOC necessary condition (11) (assumes an interior solution) should be rewritten as the complementary slackness condition (a boundary solution) for R&D R,

$$\hat{\mathrm{H}}_R(C,R,K,H,q_K,q_H) = -q_K + q_H \le 0, \quad R \ge 0, \quad (-q_K + q_H)\cdot R = 0.$$

It suggests that during the transitional periods the shadow price of knowledge is lower than that of physical capital, $q_H < q_K$, thus economic resources are only used to invest in physical capital and there is no R&D for innovation $R = 0$. As a result, the knowledge stock remains at its initial lowest level H_0, and the transitional dynamics of the economy are characterized by two differential equations:[10]

$$\dot{C} = -\sigma\cdot\kappa\cdot\frac{C^2}{K} + \bar{\alpha}\cdot A\cdot\left[\frac{H_0}{K}\right]^{1-\bar{\alpha}}\cdot C - \rho\cdot C, \tag{30}$$

$$\dot{K} = F(K,H_0) - C = A\cdot H_0^{1-\bar{\alpha}}\cdot K^{\bar{\alpha}} - C. \tag{31}$$

With H_0 as the initial level of knowledge stock available during the transitional stage, the differential equations (30)-(31) characterize the dynamic paths of consumption and physical capital without knowledge accumulation and technological progress. The stationary conditions $\dot{C} = 0, \dot{K} = 0$ thus give the unique steady-state solution to the system of differential equations (30)-(31),

$$K_{SS} = [A\cdot(\bar{\alpha} - \sigma\cdot\kappa)\cdot\rho^{-1}]^{\frac{1}{1-\bar{\alpha}}}\cdot H_0, \tag{32}$$

$$C_{SS} = A^{\frac{1}{1-\bar{\alpha}}}\cdot[(\bar{\alpha} - \sigma\cdot\kappa)\cdot\rho^{-1}]^{\frac{\bar{\alpha}}{1-\bar{\alpha}}}\cdot H_0, \tag{33}$$

where K_{SS}, C_{SS} is the steady-state level of capital and consumption, respectively. We examine the local stability of the transitional dynamics around the steady state, and establish the following result.

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[8] The equation (29) is rewritten as $\rho q_K - \dot{q}_K = D$, where D is the current flow payoff from capital investment. Integration yields the explicit function of the shadow price $q_K(t) = \int_t^{+\infty} D(s)\cdot\exp(-\rho(s-t))\cdot ds$. Since the flow payoff D is higher when the level of capital K is lower, the shadow price of capital q_K would be higher.

[9] We denote the market value when it starts with a capital stock of K by $V(K)$, thus the shadow price of capital q_K measures the increments to the market value from investing an extra unit of capital, $V'(K) = q_K$.

[10] It follows from (10) and (12) $\dot{C}/C = -\dot{U}_C/U_C = -\dot{q}_K/q_K = (U_E/U_C)\cdot E_K + F_K - \rho$.

Lemma 4. *The dynamic equations (30)-(31) characterizes the time paths of consumption and physical capital without innovation and technological progress. This non-innovation-led growth path has a saddle-path stability: there is a unique equilibrium path represented by a one-dimensional stable arm, such that starting from an initial capital-consumption pair* (K_0, C_0) *along this stable arm, the system of differential equations (30)-(31) leads to convergence to the unique steady state* (K_{SS}, C_{SS}) *given by (32)-(33).*

Proof. See Appendix G. □

As Fig. 1(c) shows, the dynamic equations (30)-(31) are plotted in the $K-C$ phase diagram. The curve corresponding to $\dot{K}=0$ is upward sloping. Above the curve, $\dot{K}<0$. Below the curve, $\dot{K}>0$. On the other hand, the locus of points where $\dot{C}=0$ has a bell shaped curve. Above the curve, $\dot{C}<0$. Below the curve, $\dot{C}>0$. The interaction of these two loci defines the steady state (K_{SS}, C_{SS}). Once these two loci are drawn, the rest of the phase diagram can be completed by looking at the direction of motion according to the differential equations (30)-(31). Given these directions of movements, it is straightforward to verify that there exists a unique one-dimensional stable arm converging to the steady state. This implies that for a given initial level of capital $K_0>0$, there exists an initial level of consumption $C_0>0$ that is uniquely determined so that the economy starts along this stable arm. Then starting with this initial capital-consumption pair (K_0, C_0), the economy then follows the path of the differential equations (30)-(31) and converges to the steady state (K_{SS}, C_{SS}).

However, this transitional dynamics corresponds to the non-innovation-led growth path (there is no R&D and knowledge stock remains at the lowest level H_0). As investment augments the capital to its steady state level K_{SS}, fossil energy use will monotonically increase and peak at a level of $E_{SS}=K_{SS}^{\kappa}\cdot H_0^{-h}$, resulting in deterioration of environmental quality. However, if the social planner allocates resources to R&D for innovation, then an innovation-led growth scenario will emerge in the sense that starting with the initial capital-consumption pair (K_0, C_0), the economy tends towards the BGP equilibrium where consumption, capital, and technology all grow at a rate g^*, rather than the steady state (K_{SS}, C_{SS}). For this reason, we establish the following result.

Proposition 3. *In the above-described model, define the transition point to the BGP as the capital-consumption pair* (K_T, C_T) *that satisfies* $K_T=k^*\cdot H_0, C_T=c^*\cdot K_T$*, with* H_0 *as the initial level of knowledge and* (k^*, c^*) *as the BGP level of capital-knowledge and consumption-capital ratio. To makes a transition to an innovation-led BGP rather than the non-innovation-led steady state* (K_{SS}, C_{SS})*, the transition point* (K_T, C_T) *should be located within the domain where both consumption and capital are increasing and* $K_0<K_T<K_{SS}, C_0<C_T<C_{SS}$.

This proposition states that starting with the initial condition (K_0, C_0), the economy evolves along the non-innovation-led growth path (according to the equations (30)-(31)) and tends towards the steady state (K_{SS}, C_{SS}). Since the shadow price of capital is higher than that of knowledge during this transitional period, there is only investment in capital. Accordingly, consumption, capital, and fossil energy use will increase monotonically without technological progress. This dynamic process proceeds until the economy reaches the transition point (K_T, C_T) that is located in front of the steady state (K_{SS}, C_{SS}). Once the transition point is reached, the shadow prices of physical capital and knowledge are equalized, and the economy embarks on R&D investment for technological innovation. As an outcome, the economy would immediately jump to the innovation-led BGP equilibrium along which consumption, capital, and technology all grow at a constant rate $g_C = g_K = g_H = g^* > 0$, and fossil energy uses decline at the rate of $g_E^* = (\kappa - h) \cdot g^* < 0$.

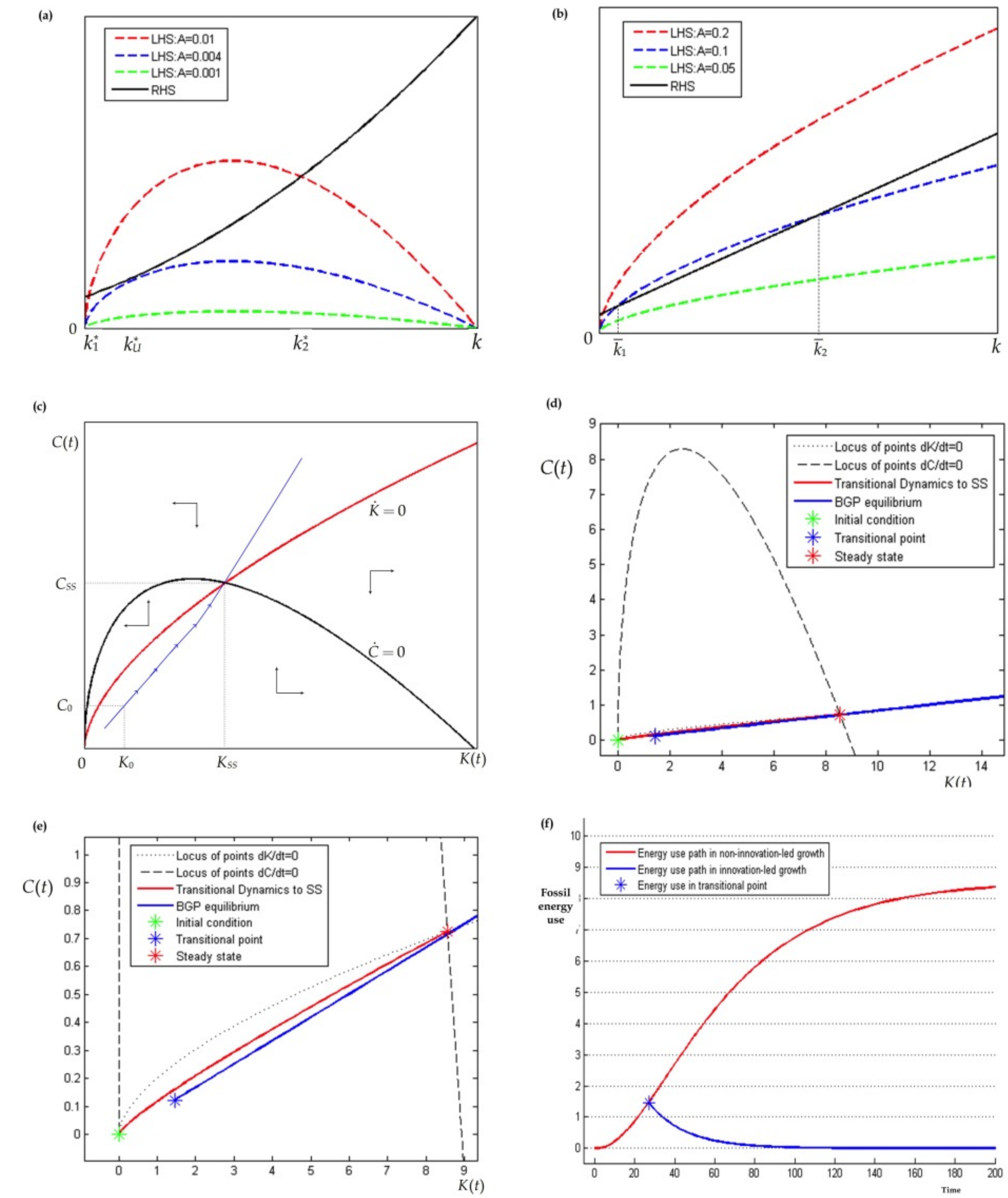

Figure 1(a). Existence and multiplicity of the BGP when the TFP parameter A has different values.
(b). Economic growth rate when the TFP parameter A has different values.
(c). The phase diagram associated with the system of differential equations (30)-(31).
(d) Overview of the transitional dynamics to the steady state and the BGP;
(e) Zoon in the transitional dynamics to the steady state and the BGP.
(f) Energy use trends in non-innovation-led and innovation-led growth paths.

6. Numerical Examples

This section provides numerical examples to illustrate the dynamics of energy use and technological innovation in China's economic growth. Tab. 1 summarizes the values of the model parameters ($A, \sigma, \rho, \kappa, h, \alpha, \beta, \overline{\alpha}, \overline{\beta}$) for numerical simulations.

Table 1
Parameterization in numerical simulation

A	σ	ρ	κ	h	α	β	$\overline{\alpha}$	$\overline{\beta}$
0.2	0.01	0.05	1	2	0.8	0.2	0.6	0.4

A : Total factor productivity parameter
σ : Consumer preference towards environmental goods
ρ : The time discount rate
κ : Elasticity of fossil energy use with respect to energy-consuming physical capital
h : Elasticity of fossil energy use with respect to energy-saving knowledge
α: Elasticity of production outputs with respect to the input of physical capital
β : Elasticity of production outputs with respect to the input of fossil energy
$\overline{\alpha}$: Elasticity of production outputs with respect to fossil energy input when the negative environmental externality of energy-related air pollution is internalized
$\overline{\beta}$: Elasticity of production outputs with respect to knowledge capital.

In terms of the household utility, σ =0.01 (preference towards environmental goods), and ρ =0.05 (discount rate). In the production function, α=0.8 β=0.2 (elasticity of output with respect to capital and fossil energy input), h =2 κ =1 (elasticity of fossil energy use with respect to energy-saving knowledge and energy-consuming physical capital). These values thus yield $\overline{\alpha} = \alpha - \beta \cdot \kappa$=0.6 and $\overline{\beta} = \beta \cdot h$=0.4 (elasticity of output with respect to physical capital and knowledge). Note that, the negative externality effect of energy-related pollution on production reduces the standard value of capital elasticity α=0.8 by $\beta \cdot \kappa$=0.2 to an adjusted level of $\overline{\alpha}$=0.6. The energy-saving technology has a positive effect to offset the negative environmental externality and thus favors output production as indicated by $\overline{\beta}$ =0.4. The condition $\overline{\alpha} + \overline{\beta}$=1 holds such that the economy can reach a BGP equilibrium. Moreover, given the values of $(\sigma, \rho, \kappa, h, \overline{\alpha})$, we use (26) and (27) to calculate the value of the TFP parameter that supports a unique BGP equilibrium and obtain A_U^*=0.004, thus we impose a value of A =0.2 to ensure the existence of the BGP equilibrium.

Given $(\sigma, \rho, \kappa, h, \overline{\alpha}, A)$, we use (25) and (18) to compute the BGP levels of capital-knowledge and consumption-capital ratio and obtain k^* =1.4526, c^* =0.0836. The equation (20) calculates the growth rate along the BGP equilibrium and obtain g^* =0.0525. Therefore, the BGP equilibrium is characterized by a constant capital-knowledge and consumption-capital ratio k^* =1.4526, c^* =0.0836, and the consumption, physical capital, and technology all grow at a constant rate g^* =0.0525.

Turn to the transitional dynamics to the BGP. Given an initial low level of capital K_0 =0.0001, the shadow price of capital is higher than that of knowledge, thus there is only investment in physical capital without R&D, resulting in a non-innovation-led growth path. In this case, given the values of $(\sigma, \rho, \kappa, h, \bar{\alpha}, A)$ and the initial normalized level of knowledge H_0 =1, the non-innovation-led growth path is characterized by the system of differential equations,

$$\dot{C} = -0.01 * \frac{C^2}{K} + 0.12 * K^{-0.4} \cdot C - 0.05 * C, \tag{34}$$

$$\dot{K} = 0.2 * K^{0.6} - C \quad . \tag{35}$$

The phase diagram associated with (34)-(35) is plotted in Fig. 1(d). The dashed black curve corresponds to $\dot{C} = 0$ and the dash-dot black curve to $\dot{K} = 0$. We adopt the relaxation algorithm to numerically solve the transitional dynamics associated with the two-point boundary value problem (Trimborn et al., 2008). Computations yield two real eigenvalues, one positive ξ_1 = 0.0732, and one negative ξ_2 = -0.0232. This implies that there is a one-dimensional stable arm: starting with the initial condition (green star in Fig. 1(e)), the economy evolves along the non-innovation-led growth path (red line in Fig. 1(e)) and tend towards the steady state K_{SS} =8.5562, C_{SS} =0.7251 (red star in Fig. 1(e)). Due to the accumulation of energy-consuming capital, fossil energy use will increase monotonically in the non-innovation-led growth path and peak at a level of $E_{SS} = K_{SS}^{\kappa} \cdot H_0^{-h}$ =8.5562 (red line in Fig. 1(f)).

As shown by the blue line in Fig. 1(e), the other growth alternative is making a transition to the BGP where investments in both capital and R&D occur simultaneously. That is, until the economy follows the non-innovation-led growth path and augments its capital to a level of $K_T = k^* \cdot H_0$ =1.4526 which corresponds to the transition point (blue star in Fig. 1(e)), the dynamic benefits of physical capital and knowledge become equalized, thus the planner embarks on allocating part of economic resources to R&D for innovation. This results in reductions in consumption for a given level of capital accumulation, thus the economy will immediately jump downwards to the transitional point (K_T, C_T) where the consumption falls to a level of $C_T = c^* \cdot K_T$ =0.1214. When this transitional point is reached, the economy will enter the innovation-led BGP along which consumption, physical capital, and knowledge all grow at a constant positive rate g^* =0.0525 over the long-term period, without stagnation in the steady state in the non-innovation-led growth path. Moreover, as shown in the blue line in Fig. 1(f), from the transitional point where the economy embarks on R&D for innovation, fossil energy use will decline at a rate of g_E^* =-0.0525 along the innovation-led growth path.

7. Conclusion

Whether China continues its business-as-usual energy-intensive growth track or adopts a sustainable development alternative has significant implications for global energy/climate governance. This paper is motivated to provide a theoretical exposition on the possibility of China's transition from its current energy-intensive growth pattern to an innovation-oriented development prospect.

We develop an endogenous growth model that incorporates the mechanism of technological innovation and its interaction with fossil energy use. We find that from an initial condition with a pristine environment and a small amount of capital installation, the lower marginal cost (through energy-related air pollution) and the higher marginal benefit on the utility (via consumption goods increase) create higher dynamic benefits for capital investment, which incentivize investment in capital rather than R&D-related innovation. As a result, the non-innovation-led growth through capital accumulation will lead to fossil energy use surge and environmental degradation. However, as physical investment augments the capital stocks, the marginal costs increase and the marginal benefits fall, leading to a decline in the net benefit of capital investment. Therefore, if the mechanism of R&D-related innovation is introduced into the economy, then until the dynamic benefit of R&D is equalized with that of capital investment, the Chinese economy will embark on R&D for innovation. As a result, the economy will evolve along an innovation-led BGP where consumption, physical capital and technology all grow, fossil energy consumptions decline, and environmental quality improves.

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References

Aghion, P., Howitt, P., (1992). "A model of growth through creative destruction." *Econometrica*, 110, 323-351.

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.

Bovenberg, A., Smulders, S., (1995). "Environmental quality and pollution-augmenting technological change in a two-sector endogenous growth model." *Journal of Public Economics* 57, 369-91.

Cassou, S., Hamilton, S., (2004). "The transition from dirty to clean industries: optimal fiscal policy and the environmental Kuznets curve." *Journal of Environmental Economics and Management* 48, 1050-77.

Cassou, S., Hamilton, S., (2004). "The transition from dirty to clean industries: optimal fiscal policy and the environmental Kuznets curve." *Journal of Environmental Economics and Management* 48: 1050-77.

Cunha-e-sá, M., Reis, A., (2007). "The optimal timing of adoption of a green technology." *Environmental and Resource Economics* 36, 35-55.

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

Goulder, L., Schneider, S., (1999). "Induced technological change and the attractiveness of CO2 abatement policies." *Resource and Energy Economics* 21, 211-253.

Grimaud, A., (1999). "Pollution permits and sustainable growth in a Schumpeterian model." *Journal of Environmental Economics and Management* 38: 249-266.

Grossman, G., Helpman, E., (1991). "Quality ladders in the theory of growth." *Review of Economic Studies* 68, 43–61.

International Energy Agency (IEA), 2013a. *World Energy Statistics*. OECD, Paris.

International Energy Agency (IEA), 2013b, *World Energy Outlook*. OECD/WEO. Paris

Jones, L., Manuelli, R., (2001). "Endogenous policy choice: the case of pollution and growth." *Review of Economic Dynamics* 4: 369-405.

Nordhaus, W., (2002). Modeling induced innovation in climate change policy. In: Grubler, A., Nakicenovic, N., Nordhaus, W. Eds., *Technological Change and the Environment*. Resources for the Future Press, Washington, DC.

OECD, (2012). *OECD Science, Technology and Industry Outlook 2012*. OECD, Paris.

OECD, (2013). *Main Science and Technology Indicators*, Volume 2013/2. OECD, Paris

Otto, V., Löschel, A., Reilly, J., (2008). "Directed technical change and differentiation of climate policy." *Energy Economics* 30, 2855-2878.

Popp, D., (2004). "ENTICE: endogenous technological change in the DICE model of global warming." *Journal of Environmental Economics and Management* 48, 742–768.

Reis, A., (2001). "Endogenous growth and the possibility of eliminating pollution." *Journal of Environmental Economics and Management* 42, 360-73.

Ricci, F., (2007). "Environmentally policy and growth when inputs are differentiated in pollution intensity." *Environmental and Resource Economics* 38, 285-310

Romer, P., (1990). "Endogenous technological change." *Journal of Political Economy* 98, S71-S102.

Rubio, S., Garcia, J., Hueso J., (2010). "Neoclassical Growth, Environment and Technological Change: The Environmental Kuznets Curve." FEEM Working Paper No. 125.2009

Selden, T., Song, D., (1995). "Neoclassical growth, the J curve for abatement, and the inverted U curve for pollution." *Journal of Environmental Economics and Management* 29: 162-68.

Stokey, N., (1998). "Are there limits to growth?" *International Economic Review* 39, 1-31.

Sue Wing, I., (2006). "Representing induced technological change in models for climate policy analysis." *Energy Economics* 28, 539–562.

Trimborn, T., Koch, K., Steger, T., (2008). "Multi-dimensional transitional dynamics: A simple numerical procedure." *Macroeconomic Dynamics* 12, 1-19.

Zhang, Z.X., (2007a). "Why has China not embraced a global cap-and-trade regime?". *Climate Policy* 7, 166-170.

Zhang, Z.X., (2007b). "China is moving away the pattern of `develop first and then treat the pollution'." *Energy Policy* 35, 3547-3549.

Zhang, Z.X., (2010a). "Is it fair to treat China as a Christmas tree to hang everybody's complaints? Putting its own energy saving into perspective". *Energy Economics* 32, S47-S56.

Zhang, Z.X., (2010b). "China in the transition to a low-carbon economy". *Energy Policy* 38, 6638-6653.

Appendix A. Proof of Lemma 1

Substituting the functional forms of the model into the equation (17), we obtain

$$-\frac{\sigma\cdot\kappa}{K}+\bar{\alpha}\cdot A\cdot\frac{1}{C}\cdot\left[\frac{K}{H}\right]^{\bar{\alpha}-1}=\frac{\sigma\cdot h}{H}+(1-\bar{\alpha})\cdot A\cdot\frac{1}{C}\cdot\left[\frac{K}{H}\right]^{\bar{\alpha}}, \tag{A1}$$

and (A1) can be rewritten as,

$$-\sigma\cdot\kappa\cdot c+\bar{\alpha}\cdot A\cdot k^{\bar{\alpha}-1}=\sigma\cdot h\cdot c\cdot k+(1-\bar{\alpha})\cdot A\cdot k^{\bar{\alpha}} \tag{A2}$$

Rearranging (A2) yields (18).

Using the tilde symbol "~" to denote the growth rate, e.g., $\tilde{x}=\dot{x}/x$, we loglinearize the equation (18) to obtain (19)

$$\begin{aligned}
\tilde{c} &= -\frac{(1-\bar{\alpha})\cdot k}{\bar{\alpha}-(1-\bar{\alpha})\cdot k}\cdot\tilde{k}+\frac{\kappa\cdot(1-\bar{\alpha})\cdot k^{1-\bar{\alpha}}}{\kappa\cdot k^{1-\bar{\alpha}}+h\cdot k^{2-\bar{\alpha}}}\cdot\tilde{k}+\frac{h\cdot(2-\bar{\alpha})\cdot k^{2-\bar{\alpha}}}{\kappa\cdot k^{1-\bar{\alpha}}+h\cdot k^{2-\bar{\alpha}}}\cdot\tilde{k}\\
&= -\left[\frac{-h\cdot(1-\bar{\alpha})^2\cdot k^2+\bar{\alpha}\cdot[(1-\bar{\alpha})\cdot\kappa+(2-\bar{\alpha})\cdot h]\cdot k+\bar{\alpha}\cdot(1-\bar{\alpha})\cdot\kappa}{-h\cdot(1-\bar{\alpha})\cdot k^2+[\bar{\alpha}\cdot h-(1-\bar{\alpha})\cdot\kappa]\cdot k+\bar{\alpha}\cdot\kappa}\right]\cdot\tilde{k}\\
\Rightarrow \frac{\dot{c}}{c} &= \left[\frac{h\cdot(1-\bar{\alpha})^2\cdot k^2-\bar{\alpha}\cdot[(1-\bar{\alpha})\cdot\kappa+(2-\bar{\alpha})\cdot h]\cdot k-\bar{\alpha}\cdot(1-\bar{\alpha})\cdot\kappa}{-h\cdot(1-\bar{\alpha})\cdot k^2+[\bar{\alpha}\cdot h-(1-\bar{\alpha})\cdot\kappa]\cdot k+\bar{\alpha}\cdot\kappa}\right]\cdot\frac{\dot{k}}{k}=\frac{\Delta_1(k)}{\Delta_2(k)}\cdot\frac{\dot{k}}{k}\ . \quad \square
\end{aligned}$$

Appendix B. Proof of Lemma 2

The growth rate of consumption is derived as follows:

$$\frac{\dot{C}}{C}=-\frac{\dot{U}_C}{U_C}=-\frac{\dot{q}_K}{q_K}=\frac{U_E\cdot E_K}{U_C}+F_K-\rho=\frac{[\bar{\alpha}\cdot h+(1-\bar{\alpha})\cdot\kappa]\cdot A\cdot k^{\bar{\alpha}}}{\kappa+h\cdot k}-\rho, \tag{B1}$$

where the first equality comes from the logarithmic utility (1), the second and third follow from the optimality conditions (10) and (12) respectively. The final gives an explicit characterization for the functional equations of the model. Then from (B1) and the definition of consumption-capital ratio, $c\equiv C/K$, we obtain the equation (20). From the optimality conditions (14)-(15), we obtain the resource constraint of the economy, $A\cdot K^{\bar{\alpha}}\cdot H^{\bar{\beta}}-C-\dot{K}-\dot{H}=0$, and the growth rate of knowledge as,

$$\begin{aligned} g_H \equiv \frac{\dot{H}}{H} &= \frac{A\cdot K^{\bar{\alpha}}\cdot H^{\bar{\beta}} - C - \dot{K}}{H} = A\cdot k^{\bar{\alpha}} - c\cdot k - g_K\cdot k \\ &= \frac{A\cdot[(\sigma\cdot h + 1 - \bar{\alpha})\cdot k^{\bar{\alpha}+1} + (\sigma\cdot\kappa - \bar{\alpha})\cdot k^{\bar{\alpha}}]}{\sigma\cdot(\kappa + h\cdot k)} - g_K\cdot k \end{aligned}, \tag{B2}$$

where we substitute for c and obtain the growth rate of knowledge as a function of k. Then from (B2) and the definition of capital-knowledge ratio, $k \equiv K/H$, we obtain the equation (21). □

Appendix C. Proof of Lemma 3

By equaling (19) to (20), we eliminate $\dot{c}/c$ and derive $\dot{k}/k$ as a function of g_K

$$\frac{\dot{k}}{k} = \left\{\frac{[\bar{\alpha}\cdot h + (1-\bar{\alpha})\cdot\kappa]\cdot A\cdot k^{\bar{\alpha}}}{\kappa + h\cdot k} - \rho - g_K\right\}\cdot\frac{\Delta_2(k)}{\Delta_1(k)} . \tag{C1}$$

Then equaling (C1) to (21), we eliminate $\dot{k}/k$ to derive (24) for $g_K = \dot{K}/K$. Using (24) to substitute for g_K in (C1), we obtain (22) for $\dot{k}/k$. Given $\dot{k}/k$, we use (19) to derive (23) for $\dot{c}/c$. □

Appendix D. Proof of Proposition 1

This proposition can be prove schematically. As Fig. 1(a) shows, the curve associated with the RHS in (25) is a quadratic function and monotonically increases in the domain $k > 0$ provided that $\kappa > 0, h > 0$. The LHS is a bell-shaped function of k, first increases and then decreases as k progresses from null to the maximal $\bar{\alpha}/(1-\bar{\alpha})$. There is only one equilibrium point when both curves intersect at the unique point k_U^* where the LHS is equal to the RHS as shown by (26). Also the uniqueness of this equilibrium requires both curves are tangent to each other at this point k_U^* (the slopes of both functions are the same), which is characterized by (27).

If the given TFP parameter is larger than the endogenously determined parameter that supports the unique BGP equilibrium, $A > A_U^*$, then the LHS will move upwards and create two intersection points with the RHS curve, and the intersection points correspond to the two different equilibria k_1^*, k_2^*, where $0 < k_1^* < k_U^* < k_2^* < \bar{\alpha}/(1-\bar{\alpha})$. If $A = A_U^*$, then both curves intersect at the unique point k_U^* which corresponds to a unique BGP equilibrium. If $A < A_U^*$, there is no intersection between both curves and thus no BGP equilibrium. □

Appendix E. Proof of Proposition 2

The BGP growth rate of consumption, capital and knowledge all grow at the same rate given by (B1), from which we compute the bound values $\bar{k}$ that support a positive growth rate as,

$$[\bar{\alpha}\cdot h+(1-\bar{\alpha})\cdot\kappa]\cdot A\cdot\bar{k}^{\bar{\alpha}}=\rho\cdot(\kappa+h\cdot\bar{k}). \tag{E1}$$

As Fig. 1(b) shows, the RHS is a linear function of k, and the LHS is a power function. When A has a sufficiently high value, both curves intersect at two points $\bar{k}_1, \bar{k}_2$, and any given value of k within the interval $k\in(\bar{k}_1,\bar{k}_2)$ would lead to a positive growth rate g. It is clear that $\bar{k}_1$ decreases and $\bar{k}_2$ increases when there is an increase in A that shifts the LHS upwards. We focus on the larger BGP level of capital-knowledge ratio k_2^*. Since an increase in A shifts the LHS of (25) upwards, and k_2^* increases with A whereas $\bar{k}_1$ decreases with A, we thus expect that for an high enough value of A, there is $k_2^* > \bar{k}_1$. Given that k_2^*, $\bar{k}_2$ increase with A, and $\lim_{A\to+\infty}\bar{k}_2=+\infty$, $\lim_{A\to+\infty}k_2^*=\bar{\alpha}/(1-\bar{\alpha})$, we thus expect that for a high enough value of A, there exists $k_2^* < \bar{k}_2$. Hence, we obtain $\bar{k}_1 < k_2^* < \bar{k}_2$, and the growth rate associated with k_2^* is positive $g_2^* > 0$. From the equation (4), $E = K^{\kappa} \cdot H^{-h}$, we have $g_E=\kappa\cdot g_K-h\cdot g_H$. In the BGP equilibrium, $g_K = g_H = g^*$, we obtain $g_E^*=(\kappa-h)\cdot g^*$. Given the condition $h > \kappa$, the BGP level of fossil energy uses falls at the rate of $g_E^*=(\kappa-h)\cdot g^*<0$. □

Appendix F. Proof of Corollary 1

This corollary can be proved schematically. Let's focus on the larger level of the BGP equilibrium k_2^*. A rise in A shifts upwards the curve associated with the LHS of the equation (25), thus k_2^* will increase. A rise in σ shifts downwards the LHS curve and thus lowers k_2^*. An increase in ρ shifts upwards the RHS curve and thus lowers k_2^*. A rise in κ shifts upwards the RHS curve and downward the LHS curve simultaneously and thus lowers k_2^*. An increase in $\bar{\alpha}$ shifts upwards the LHS curve and thus raises k_2^*. A rise in h shifts upwards both the LHS and RHS curves simultaneously, thus the net effect on k_2^* is undetermined. □

Appendix G. Proof of Lemma 4

To analyze the local stability of the transitional dynamics around the steady state, we calculate their partial derivatives of the system of differential equations (30)-(31) at the steady state (K_{SS}, C_{SS}):

$$\left.\frac{\partial\dot{C}}{\partial C}\right|_{K_{SS},C_{SS}}=\bar{\alpha}\cdot A\cdot\left(\frac{H_0}{K_{SS}}\right)^{1-\bar{\alpha}}-2\sigma\cdot\kappa\cdot\frac{C_{SS}}{K_{SS}}-\rho=-\sigma\cdot\kappa\cdot\frac{C_{SS}}{K_{SS}} \tag{G1}$$

$$\left.\frac{\partial\dot{C}}{\partial K}\right|_{K_{SS},C_{SS}}=\frac{C_{SS}}{K_{SS}}\cdot\left[A\cdot(\bar{\alpha}^2-\bar{\alpha})\cdot\left(\frac{H_0}{K_{SS}}\right)^{1-\bar{\alpha}}+\sigma\cdot\kappa\cdot\frac{C_{SS}}{K_{SS}}\right]=\frac{C_{SS}}{K_{SS}}\cdot\left[A\cdot\bar{\alpha}^2\cdot\left(\frac{H_0}{K_{SS}}\right)^{1-\bar{\alpha}}-\rho\right] \tag{G2}$$

$$\left.\frac{\partial\dot{K}}{\partial C}\right|_{K_{SS},C_{SS}}=-1 \tag{G3}$$

$$\left.\frac{\partial \dot{K}}{\partial K}\right|_{K_{SS},C_{SS}} = \bar{\alpha}\cdot A\cdot\left(\frac{H_0}{K_{SS}}\right)^{1-\bar{\alpha}} \tag{G4}$$

where (G1)-(G2) are simplified by the stationary conditions $\dot{C}_{SS}=0, \dot{K}_{SS}=0$. Given the steady-state levels K_{SS}, C_{SS} given by (32)-(33), we obtain the Jacobian of the equation systems at the steady state,

$$\begin{pmatrix} \left.\frac{\partial \dot{C}}{\partial C}\right|_{K_{SS},C_{SS}} & \left.\frac{\partial \dot{C}}{\partial K}\right|_{K_{SS},C_{SS}} \\ \left.\frac{\partial \dot{K}}{\partial C}\right|_{K_{SS},C_{SS}} & \left.\frac{\partial \dot{K}}{\partial K}\right|_{K_{SS},C_{SS}} \end{pmatrix} = \begin{pmatrix} -\sigma\cdot\kappa\cdot\frac{\rho}{\bar{\alpha}-\sigma\cdot\kappa} & \frac{\rho}{\bar{\alpha}-\sigma\cdot\kappa}\cdot\left(\frac{\bar{\alpha}^2\cdot\rho}{\bar{\alpha}-\sigma\cdot\kappa}-\rho\right) \\ -1 & \frac{\bar{\alpha}\cdot\rho}{\bar{\alpha}-\sigma\cdot\kappa} \end{pmatrix}. \tag{G5}$$

The eigenvalues are given by the value of ξ that solves the following quadratic form:

$$\det\begin{pmatrix} -\sigma\cdot\kappa\cdot\frac{\rho}{\bar{\alpha}-\sigma\cdot\kappa}-\xi & \frac{\rho}{\bar{\alpha}-\sigma\cdot\kappa}\cdot\left(\frac{\bar{\alpha}^2\cdot\rho}{\bar{\alpha}-\sigma\cdot\kappa}-\rho\right) \\ -1 & \frac{\bar{\alpha}\cdot\rho}{\bar{\alpha}-\sigma\cdot\kappa}-\xi \end{pmatrix} = -\frac{\rho^2\cdot(1-\bar{\alpha})}{\bar{\alpha}-\sigma\cdot\kappa}-\rho\cdot\xi+\xi^2. \tag{G6}$$

Provided that $\bar{\alpha}-\sigma\cdot\kappa>0$, there are two real eigenvalues, one negative and one positive. This condition thus establishes the local saddle-path stability. □