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From Energy-intensive to Innovation-led Growth: On the Transition Dynamics of China's Economy

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Summary
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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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Abstract: Whether China continues its current energy-intensive growth path or adopts a sustainable development prospect has significant implication for energy and climate governance. Building on a Ramsey-Cass-Koopmans growth model incorporating the mechanism of endogenous technological change and its interaction with fossil energy use and economic growth, this paper contributes to an economic exposition of China's potential transition from an energy-intensive to an innovation-led growth path. We find that in China's initial growth period the small amount of capital stock creates higher dynamic benefits of capital investment and incentives of capital stock accumulation rather than R&D-related innovation. Accumulation of energy-consuming capital stock along this non-innovation-led growth path thus leads to an intensive use of fossil energy - an energy-intensive growth pattern. To avoid this undesirable outcome, China's social planner should consider locating a transition point to an innovation-led balanced growth path (BGP). When the growth dynamics reaches that transition point, China's economy would embark on investment in physical capital and R&D simultaneously, and make a transition into the innovation-led BGP along which consumption, capital investment, and R&D have a balanced share. Also in this innovation-led BGP, consumption, physical capital stock, and knowledge stock all grow, fossil energy uses decline.

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1. Introduction

In the last 1970s, with the motto of "development is the only hard truth", Deng Xiaoping, the chief architect of the Chinese economic reforms and opening up, sought to increase its legitimacy of leadership by improving economic growth and the standards of living. The successive leaders in the post-Deng era have consistently kept the goal of economic growth as the top priority of China's development. This growth-oriented strategy ignited the astonishing power of China's economic revolution and enabled the achievement of double-digit fast growth over the past twenty years. However, it is through this search for economic growth and wealth accumulation that China also adopted another motto – growth at all costs. Three 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 uses grew by 5.1% annually from 910 to 2721 million tonnes of oil equivalent, and the energy-related carbon emissions rise by 6.9% per year from 2244 to 9860 megatonnes (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,b; 2010a,b). In the medium- to long-term, it is expected that this fast-growing economy would drive the world's future growth in fossil 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 the resulting global warming, there is no disagreement that China's business-as-usual energy-intensive growth pattern is highly likely to exacerbate the unsolved global energy and climate problems. To mitigate its energy and environmental impacts, China's economic growth needs to consider replacing its baseline pattern by adopting a more sustainable development alternative (Zhang, 2007a,b; 2010a,b).

In the minds of the leadership in Beijing, one of the key strategies to achieve sustainable growth prospect is decoupling fossil energy use from economic growth through technological innovation. Indeed, beyond its current role as the global manufacturing powerhouse, China is building the theme of innovation in its growth story, which is manifested by the remarkable growth of R&D investment for technological 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 past decade, and R&D intensity has doubled as a share of GDP, reaching 2% in 2012 (OECD, 2013). To achieve the goal of building an innovation-oriented society, China has set an ambitious plan of strengthening R&D investment for innovation. This is reflected by the government's budget of spending 2.5% of GDP on R&D by 2020, which translates into a tripling of R&D investment over the next decade to an amount of US$300 billion (OECD, 2012).

In such a context where R&D-related technological innovation is adopted as a strategic response to achieve the long-term energy-efficient, innovation-led growth prospect, it is particularly vital for China's policymakers to have a deep understanding of the interconnected nature of technological innovation, fossil energy use, and economic growth, so that China's policies on economic reform and transition can be appropriately designed. Accordingly, this paper contributes to an economic exposition of the mechanism of technological innovation and its interactions with fossil energy use and economic growth, and by doing that, we aim to give insights into China's potential transition from its current fossil energy-intensive growth pattern to an innovation-led development prospect.

The framework of economic analysis used here is building on the endogenous macroeconomic growth model, for example, Romer (1990), Grossman and Helpman (1991), and Aghion and Howitt (1992). In addition, by treating technology as an accumulated stock of economically useful knowledge asset augmented by R&D investment, 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 and climate economic analysis.[1] But difference in modelling approaches is notable. The model used

[1] Several subsequent studies have adopted the "stock of knowledge" method to examine the effect of

here is an one-sector aggregate framework based on which the underlying mechanism of technological change can be intuitively characterized, while most of existing energy/climate policy models adopt multi-sector disaggregated frameworks (e.g., computable general equilibrium (CGE)-based simulations) for quantitative assessments of policy impacts. In this respect, our study is closely related to several 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 specifies the environment of the model. Section 3 provides a social planner solution as the characterization of the optimal growth path. The long-run innovation-led balanced growth path (BGP) is examined in Section 4, and the energy-intensive status quo and the transitional dynamics to the innovation-led BGP are investigated in Section 5. Section 6 provides numerical examples. Section 7 concludes.

2. Model Specification

Based on the Ramsey-Cass-Koopmans growth model, we model the Chinese economy as an infinite-horizon economy in continuous time, and admit a representative household (with measure normalized to unity) which has an instantaneous utility function,

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

where the household derives utility from consumption of material goods C and environmental goods Q, and both are additively separable. The logarithmic preferences specified in (1) is strictly increasing, concave, and twice differentiable for all C and Q in the interior of their domains, and satisfies the Inada conditions. Exogenous parameter σ measures the household's environmental preference - the willingness to substitute material goods for environmental goods. Consider that, one unit of fossil energy use E

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), and Jin (2012).

produces one unit of energy-related emission pollutant P, that is, $E = P$. Given a fixed amount of environmental carrying capacity, a larger amount of emission pollutants P would reduce the amount of environmental goods available for the household Q, that is, $Q = P^{-1}$. Alternatively, 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 pollution due to the combustion of fossil energy has a negative environmental impact on the household utility.

In the supply side of the economy, with the population normalized to unity, we consider China's current output production is driven by the input uses of physical capital and knowledge, and the long-run growth along an innovation-led BGP requires accumulations of both physical capital and knowledge stock. In this sense, the supply side of China's economy admits a representative firm with the aggregate production function

$$Y(t) = F(K(t), H(t)) = A \cdot K(t)^{\alpha} \cdot H(t)^{\beta}, \tag{3}$$

where Y is the production output of the unique final goods, K, H is the stock of physical capital and knowledge respectively, and A is the total factor productivity (TFP) parameter. $0 < \alpha, \beta < 1$ is the elasticity of Y with respect to K and H, and an innovation-led BGP requires that the neoclassical condition $\alpha + \beta = 1$ holds.[2] Moreover, we suppose that the use of fossil energy is positively related to the deployment of physical capital stock, in the sense that applications of "heavy" physical assets like hardware, equipments, and machines need to be powered by fossil energy combustion. In contrast, we consider technology has an energy-saving effect that can lower the input of fossil energy in production, thus fossil energy use is negatively related with knowledge asset. Combing the energy-consuming effect of physical capital and the energy-saving effect of knowledge asset, we obtain

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

[2] By loglinearizing the equation (3), the condition $\alpha + \beta = 1$ implies the same BGP growth rate of output, physical capital, and knowledge stock $g_Y = g_K = g_H = g^*$, where $g_Y \equiv \dot{Y} / Y, g_K \equiv \dot{K} / K, g_H \equiv \dot{H} / H$.

where $\kappa, \lambda > 0$ denote the elasticity of fossil energy use E with respect to physical capital K and knowledge H, the condition $\lambda > \kappa$ holds in the sense that the energy-saving effect of knowledge is larger than the energy-consuming effect of physical capital. From (4), it is straightforward to find that innovation and knowledge creation, through fossil energy saving, has an ultimate effect that improves environmental goods and benefits the household.

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

$$\max_{[C(t),R(t),K(t),H(t)]_{t=0}^{\infty}} \int_0^{\infty} \exp(-\rho \cdot t) \cdot (InC(t) - \sigma \cdot InE(t)) \cdot dt \tag{5}$$

subject to

$$\dot{K}(t) = A \cdot K^{\alpha}(t) \cdot H^{\beta}(t) - C(t) - \quad , \tag{6}$$

$$\dot{H}(t) = R(t), \tag{7}$$

where in this infinite-horizon economy future utility streams are discounted according to the time discount rate ρ. Equations (6) and (7) describe the law of motion for physical capital stock and knowledge stock given their initial conditions K_0, H_0.[3] Note that, part of the produced outputs in the economy is used for spending on R&D-related innovative activities, which thus pins down the endogenous dynamics of knowledge accumulation and technological progress.

3. Characterization of Optimal Growth Path

To characterize the optimal growth path of China's economy, we solve the above-described dynamic programming problem by setting up the current-value Hamiltonian which takes the form,[4]

$$\hat{\mathrm{H}}(C, R, K, H, q_K, q_H) = U(C, E(K, H)) + q_K \cdot [F(K, H) - C - R] + q_H \cdot R, \tag{8}$$

[3] To simplify the notations, we omit the depreciation of physical capital stock.
[4] To economize on notation, we drop the time subscript.

where C, R are control variables, K, H state variables, and q_K, q_H current-value costate variables. The first-order necessary conditions (assumes an interior solution) yield the following equations that characterize the optimal growth path.

$$C: \ U_C(C, E(K,H)) = q_K, \tag{9}$$

$$R: \ q_H = q_K, \tag{10}$$

$$K: \ \rho \cdot q_K = \dot{q}_K + U_E(C, E(K,H)) \cdot E_K(K,H) + q_K \cdot F_K(K,H) \ , \tag{11}$$

$$H: \ \rho \cdot q_H = \dot{q}_H + U_E(C, E(K,H)) \cdot E_H(K,H) + q_K \cdot F_H(K,H) \ , \tag{12}$$

$$q_K: \ \dot{K} = F(K,H) - C - R \ , \tag{13}$$

$$q_H: \ \dot{H} = R. \tag{14}$$

Equations (9)-(10) characterize intra-temporal static optimality conditions for consumption and R&D investment, where the left-hand side is the marginal benefit and the right-hand side is the marginal cost. Moreover, equations (11)-(12) provide the dynamic no-arbitrage optimality conditions for physical capital and knowledge stock where q_K, q_H denote the shadow price of physical capital and knowledge stock (also the market value per unit of physical capital and knowledge asset). The left-hand side corresponds to the marginal cost of holding physical capital and knowledge asset due to the time discount. The right-hand side is the marginal benefit of holding physical capital and knowledge assets which stems from two sources. The first is intertemporal changes in the shadow price of physical capital and knowledge assets $\dot{q}_K, \dot{q}_H$, and the second is the gain of current flow payoff from physical capital and R&D investment. In particular, the current flow payoff from physical capital investment is given by a positive effect on the household utility through increases in consumption of material goods $U_C \cdot F_K$, minus a negative effect on the household utility through fossil energy-related pollution $U_E \cdot E_K$. The flow payoff from R&D investment is given by a positive effect on the utility through increases in consumption of material goods $U_C \cdot F_H$, plus a positive effect on the utility via environmental improvement $U_E \cdot E_H$. Finally, equations

(13)-(14) characterize the law of motion for physical capital and knowledge stock. Characterization of the entire optimal growth path can be summarized by the following result.

Proposition 1 *In the above-described model of China's economy, the social planner maximizes the household utility (5), subject to the law of motion for physical capital and knowledge stock (6)-(7), given their initial conditions* K_0, H_0. *The growth path of the economy is characterized by an intra-temporal static optimality condition which takes the form as*

$$c = \frac{A \cdot [a - (1-a) \cdot k]}{\sigma \cdot (\kappa \cdot k^{1-a} + \lambda \cdot k^{2-a})} \quad , \tag{15}$$

where $c \equiv C / K$ *is the consumption-capital ratio, and* $k \equiv K / H$ *is the capital-knowledge ratio. Moreover, characterization of the optimal growth path also involves inter-temporal dynamic optimality conditions in which the growth rate of consumption-capital ratio is given by*

$$\frac{\dot{c}}{c} = \frac{\dot{C}}{C} - \frac{\dot{K}}{K} = \frac{[a \cdot \lambda + (1-a) \cdot \kappa] \cdot A \cdot k^{a}}{\kappa + \lambda \cdot k} - \rho - g_K \quad , \tag{16}$$

and the growth rate of capital-knowledge ratio is determined by

$$\frac{\dot{k}}{k} = \frac{\dot{K}}{K} - \frac{\dot{H}}{H} = (1+k) \cdot g_K - \frac{A \cdot [(\sigma \cdot \lambda + 1 - a) \cdot k^{a+1} + (\sigma \cdot \kappa - a) \cdot k^{a}]}{\sigma \cdot (\kappa + \lambda \cdot k)} \quad , \tag{17}$$

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

Proof. See Appendix A. ■

4. Innovation-led Growth Prospect

In our analysis, China's innovation-led growth prospect in the long run corresponds to the balanced growth path (BGP), and along this BGP both consumption-capital and capital-knowledge ratios remain constant at some level $c(t) = c^*, k(t) = k^*$, and consumption, physical capital stock, and knowledge stock all grow at a constant rate $g_C(t) = g_K(t) = g_H(t) = g^*$, where the superscript asterisk (*) refers to the corresponding BGP values.

Imposing the BGP conditions $\dot{c}(t)=0, \dot{k}(t)=0$ on the intertemporal dynamic optimality conditions as given in (16)-(17), these two equations can pin down the BGP level of capital-knowledge ratio and consumption-capital ratio, which is summarized by the following result.

Proposition 2 *In the above-described model of China's economy, the social planner maximizes the utility function (5), subject to the law of motion for physical capital and knowledge stock (6)-(7). An innovation-led balanced growth path (BGP) of China's economy is characterized as an allocation* (k^*, c^*, g^*) *in which the BGP level of capital-knowledge ratio* k^* *is determined by*

$$[1+\sigma\cdot(\lambda-\kappa)]\cdot[a-(1-a)\cdot k^*]\cdot A\cdot k^{*a}=\sigma\cdot\rho\cdot[\kappa+(\kappa+\lambda)\cdot k^*+\lambda\cdot k^{*2}] \quad . \tag{18}$$

Given the BGP level of capital-knowledge ratio k^*, *the BGP level of consumption-capital ratio* c^* *is given by*

$$c^*=\frac{A\cdot[a-(1-a)\cdot k^*]}{\sigma\cdot(\kappa\cdot k^{*1-a}+\lambda\cdot k^{*2-a})} \quad , \tag{19}$$

and the BGP growth rate of consumption, physical capital stock, and knowledge stock g^* *is given by*

$$g^*=\frac{[a\cdot\lambda+(1-a)\cdot\kappa]\cdot A\cdot k^{*a}}{\kappa+\lambda\cdot k^*}-\rho \quad . \tag{20}$$

Proof. Imposing the BGP conditions $\dot{c}(t)=0, \dot{k}(t)=0$ on the dynamic optimality conditions (16)-(17) derives a two-equation system with two unknown variables k and g_K. Substituting out g_K obtains equation (18) that endogenously determines the BGP level of capital-knowledge ratio k^*. Given k^*, the static intra-temporal optimality condition (15) pins down the BGP level of consumption-capital ratio c^*, and the BGP growth rate g^* is determined by equation (16). ■

Proposition 2 characterizes the relative levels and growth rates of consumption, physical capital stock, and knowledge stock along the innovation-led BGP. Based on this proposition, we obtain the following result that characterizes the existence of BGP.

Proposition 3 *Consider that China's economy is represented by the above-described model with a set of exogenous parameters* $[A,\sigma,\rho,\kappa,\lambda,a]$, *we denote* $k_U^*(\sigma,\rho,\kappa,\lambda,a)$ *as the capital-knowledge ratio in a unique BGP, and*

$A_U^*(\sigma,\rho,\kappa,\lambda,a)$ as the TFP that supports this unique BGP, where the subscript "U" refers to the unique BGP. The value of k_U^* in this unique BGP is endogenously determined by

$$\frac{a-(1-a)\cdot k_U^*}{a^2-(1-a^2)\cdot k_U^*}=\frac{\kappa+(\kappa+\lambda)\cdot k_U^*+\lambda\cdot k_U^{*2}}{(\kappa+\lambda)\cdot k_U^*+2\lambda\cdot k_U^{*2}} \quad , \tag{21}$$

and given k_U^*, the TFP A_U^* that supports this unique BGP is given by

$$A_U^*=\frac{\sigma\cdot\rho\cdot[\kappa+(\kappa+\lambda)\cdot k_U^*+\lambda\cdot k_U^{*2}]}{[1+\sigma\cdot(\lambda-\kappa)]\cdot[a-(1-a)\cdot k_U^*]\cdot k_U^{*a}} \quad . \tag{22}$$

If the exogenous TFP parameter A is larger than A_U^* as given in (22), $A>A_U^*$, then there exists two different BGP equilibria k_1^* and k_2^*, where $0<k_1^*<k_U^*<k_2^*$. If $A=A_U^*$, then there is a unique BGP k_U^*. If $A<A_U^*$, there exists no BGP. In particular, if the TFP parameter is sufficiently high, then there is at least one BGP in which consumption, physical capital, and technology grows at a positive rate of $g^*>0$, and fossil energy use declines at a rate of $g_E^*=(\kappa-\lambda)\cdot g^*<0$.

Proof. See Appendix B. ■

Based on the above-described propositions, we establish the following comparative static results that show how the BGP changes with the underlying parameters.

Corollary 1 *Consider the economically relevant case where China's economy has a long-run BGP with a positive growth rate, denote the BGP level of capital-knowledge ratio by k^* when the underlying exogenous parameters are $(A,\sigma,\rho,\kappa,\lambda,a)$. Then the comparative statics are*

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

$$\frac{\partial k^*(A,\sigma,\rho,\kappa,\lambda,a)}{\partial \kappa}<0,\quad \frac{\partial k^*(A,\sigma,\rho,\kappa,\lambda,a)}{\partial a}>0,\quad \frac{\partial k^*(A,\sigma,\rho,\kappa,\lambda,a)}{\partial \lambda} \text{ is undetermined.}$$

In particular, denote the economic growth rate along this innovation-led BGP by g^*, then the household preference towards environmental preservation would lead to restructuring of China's economy with a higher knowledge-capital ratio $\partial k^*/\partial\sigma<0$, and lowers the economic growth rate, $dg^*/d\sigma<0$.

Proof. The first part of corollary can be proved schematically. As Fig. 1(a) shows, we focus on the larger level of the BGP k_2^*. A rise in A shifts upwards the curve associated with the LHS of the equation (18), 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 a shifts upwards the LHS curve and thus raises k_2^*. A rise in λ shifts upwards both LHS and RHS curves simultaneously, thus the net effect on k_2^* is undetermined. For the second part, given that $\partial k^* / \partial\sigma < 0$, it is possible that an improvement in environmental preference would reduce the BGP level of ca1pital-knowledge ratio so that $k^* < a \cdot \kappa / [(1-a) \cdot \lambda]$. In this case, the effect on the BGP growth rate can be shown by taking derivative of the growth rate g with respect to k evaluated at the BGP k^*,

$$\frac{dg^*}{dk^*} = \left.\frac{dg}{dk}\right|_{k^*} = \frac{[a \cdot \lambda + (1-a) \cdot \kappa] \cdot A \cdot k^{*a}}{(\kappa + \lambda \cdot k^*)^2} \cdot \frac{a \cdot \kappa - (1-a) \cdot \lambda \cdot k^*}{k^*} > 0 .$$

Given that consumers' environmental attitudes (σ rises) decrease k^*, $dk^* / d\sigma < 0$, it is thus possible that an increase in σ would lower the BGP level of k^* so that $k^* < a \cdot \kappa / [(1-a) \cdot \lambda]$ and thus $dg^* / dk^* > 0$. Accordingly, household preference towards environmental goods and green economy would lower the growth rate along the BGP equilibrium, $dg^* / d\sigma < 0$. ■

5. Energy-intensive Growth and Transitional dynamics

The fossil energy-intensive status quo of China's economy is due primarily to its unbalanced portfolio of investment with massive investment in physical capital stock and insufficient R&D investment for technological innovation. Without accumulation of the energy-saving knowledge stock, deployment of energy-consuming physical capital would lead to an intensive use of fossil energy input, thus creating China's current energy-intensive, non-innovation-led growth pattern. This section provides a detailed exposition on China's fossil energy-intensive status quo and its potential transition dynamics to the above-described innovation-led BGP.

Recall that the Hamilton-Jacobi-Bellman (HJB) equation (11) provides the dynamic no-arbitrage condition for physical capital investment. Substituting the functional forms of the model specified in Section 2, this HJB equation takes the form,[5]

$$\begin{aligned}\rho \cdot q_K &= \dot{q}_K + U_E(C,E)\cdot E_K(K,H) + U_C(C,E)\cdot F_K(K,H) \\ &= \dot{q}_K + \left[\underbrace{-\frac{\sigma\cdot\kappa}{Q}\cdot K^{-\kappa-1}\cdot H^{\lambda}}_{(1)} + \underbrace{\frac{1}{C}\cdot a\cdot A\cdot\left[\frac{K}{H}\right]^{a-1}}_{(2)}\right] \quad . \end{aligned} \tag{23}$$

Consider that when China embarks on its economic reform and development, the amount of physical capital stock initially deployed for output production is sufficiently small. As a result, the level of fossil energy use is lower, and the pristine environment implies that the level of environmental goods Q available in the economy is sufficiently high, thus the negative impact of energy-consuming physical capital on the household utility through fossil energy-related pollution - term (1) in (23) - is sufficiently small. The positive effect on the household utility through increases in consumption of material goods - term (2) in (23) - dominates the net effect. As the latter effect is inversely related to physical capital stock, the lower the level of physical capital stock K, the higher the shadow price of physical capital q_K.[6]

Accordingly, during China's transitional dynamics period, the dynamic benefit (as measured by the shadow price) of physical capital is much higher than that of knowledge, and the social planner thus only has an incentive to invest in physical capital stock rather than R&D-related innovation.[7] Alternatively, the first-order necessary condition (10) (assumes an interior solution) should be rewritten as the complementary slackness condition (a boundary solution) for R&D,

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[5] It follows from the Hamilton-Jacobi-Bellman (HJB) equation (11) for the market value of physical capital stock. Given the inverse relationship between environmental goods and fossil energy use $E = E(Q) = Q^{-1}$, we have $U_E \cdot E_K = (-\sigma\cdot E^{-1})\cdot(-Q^{-2})\cdot(-\kappa\cdot K^{-\kappa-1}\cdot H^{\lambda}) = -\sigma\cdot\kappa\cdot Q^{-1}\cdot K^{-\kappa-1}\cdot H^{\lambda}$.

[6] Rewriting (11) as $\rho q_K - \dot{q}_K = D_K$, with D_K denoting the flow payoff from capital investment. Integration yields the explicit form of the shadow price of capital $q_K(t) = \int_t^{+\infty} \exp(-\rho(s-t))\cdot D_K(s)\cdot ds$. As the flow payoff D_K is higher when the level of K is lower, the shadow price q_K is higher.

[7] We denote the market value of the capital stock of K by $V(K)$, the shadow price of capital measures the increments to the market value from investing an extra unit of capital, $q_K = V'(K)$.

$$-q_K + q_H \leq 0, \quad R \geq 0, \quad (-q_K + q_H) \cdot R = 0 . \tag{24}$$

This suggests that during China's initial growth period, the dynamic benefit of physical capital investment is much higher than that of R&D investment, $q_K > q_H$, thus the social planner only spends on investment in physical capital stock rather than technology and knowledge asset. As a result, there is massive investment in physical capital, while R&D investment for technological innovation is lacking. Without the energy-saving effect of knowledge accumulation and technological progress, accumulation of energy-consuming physical capital leads to an intensive use of fossil energy, thus creating the current energy-intensive, non-innovation-led growth pattern.

Without R&D-induced knowledge accumulation during this initial growth period, the knowledge stock available remains at its initial level. The intertemporal dynamics of China's economy thus feature a non-innovation-led growth path which can be represented by the following differential equations: [8]

$$\dot{C} = -\sigma \cdot \kappa \cdot \frac{C^2}{K} + a \cdot A \cdot \left[\frac{H_0}{K}\right]^{1-a} \cdot C - \rho \cdot C , \tag{25}$$

$$\dot{K} = A \cdot H_0^{1-a} \cdot K^a - C . \tag{26}$$

With H_0 denoting the initial stock of knowledge available along this non-innovation-led growth path, the system of differential equations (25)-(26) thus characterizes the dynamic paths of consumption and physical capital stock along China's current non-innovation-led growth pattern. Imposing stationary conditions $\dot{C} = 0, \dot{K} = 0$ on equations (25)-(26) derives the unique steady-state level of consumption and physical capital stock along this non-innovation-led growth path:

$$C_{SS} = A^{\frac{1}{1-a}} \cdot [(a - \sigma \cdot \kappa) \cdot \rho^{-1}]^{\frac{a}{1-a}} \cdot H_0 , \tag{27}$$

$$K_{SS} = [A \cdot (a - \sigma \cdot \kappa) \cdot \rho^{-1}]^{\frac{1}{1-a}} \cdot H_0 . \tag{28}$$

The following results summarize the characteristics of the non-innovation-led growth path.

Proposition 4 *During China's initial growth period the dynamic benefit of physical capital investment is much*

[8] Equation (25) follows from equations (9) and (11), and equation (26) follows from equation (13).

higher than that of R&D investment, the social planner only has an incentive to spend on investment in physical capital stock rather than technology stock. As a result, R&D investment for knowledge accumulation is lacking and there is only investment in physical capital stock, thus generating a non-innovation-led growth path in which the dynamics of consumption and physical capital stock are characterized by the differential equations (25)-(26). In particular, this non-innovation-led growth path has a saddle-path stability. That is, there is an one-dimensional stable equilibrium path, such that starting from an initial capital-consumption pair (K_0, C_0)*, physical capital stock and consumption would evolve along the path of dynamics equations (25)-(26) and converge to the steady state* (K_{SS}, C_{SS}) *given by (27)-(28).*

Proof. See Appendix C. ■

The phase diagram associated with the non-innovation-led growth path is plotted in Fig. 1(c). The curve that corresponds to $\dot{K} = 0$ is upward sloping. Above the curve, $\dot{K} < 0$, and below the curve, $\dot{K} > 0$. The locus of points where $\dot{C} = 0$ have a bell shaped curve. Above the curve, $\dot{C} < 0$, and below the curve, $\dot{C} > 0$. The interaction of these two loci defines the steady state (K_{SS}, C_{SS}). We complete the rest of the phase diagram by looking at the direction of motion. Given these directions of movements, it is straightforward to verify that there exists a unique one-dimensional stable. For any given initial stock of physical capital K_0, there is an initial level of consumption C_0 that is uniquely determined in this stable arm. Then starting with this initial capital-consumption pair (K_0, C_0), the economy follows the path of the dynamic equations (25)-(26) and converges to the steady state (K_{SS}, C_{SS}).

With regard to the energy consequence of this non-innovation-led growth pattern, the lack of R&D makes the stock of knowledge asset remain at the initial level H_0, and investment augments the stock of energy-consuming physical capital to its steady state level K_{SS}. As a result, there is a monotonic increase in fossil energy use that peaks at a level of $E_{SS} = K_{SS}{}^{\kappa} \cdot H_0{}^{-\lambda}$, featuring an energy-intensive pattern of economic growth. To avoid this undesirable growth scenario and achieve a sustainable one in the long run, China's economy needs making a transition from the energy-intensive status quo to an innovation-led growth prospect, in the sense that the economy should be directed to tend towards the innovation-led BGP where consumption, physical capital stock, and knowledge stock all grow at a rate g^*, rather than converges to the steady state (K_{SS}, C_{SS}) along the non-innovation-led growth path. For this reason, we establish the following result.

Proposition 5. *In the above-described transitional dynamics, to ensure that China's economy can have a transition to an innovation-led BGP rather than converge to the non-innovation-led steady state* (K_{SS}, C_{SS})*, the social planner should locate a transition point* (K_T, C_T) *within the domain where both consumption and capital are increasing and* $K_0 < K_T < K_{SS}, C_0 < C_T < C_{SS}$*, where the transition point to the innovation-led BGP is a capital-consumption pair* (K_T, C_T) *that satisfies* $K_T = k^* \cdot H_0, C_T = c^* \cdot K_T$*, with* H_0 *the initial stock of knowledge and* (k^*, c^*) *the BGP level of capital-knowledge and consumption-capital ratio.*

This proposition states that starting with the initial condition (K_0, C_0), China's economy would evolve along a non-innovation-led growth path (according to (25)-(26)) and tends towards the steady state (K_{SS}, C_{SS}). This is because the dynamic benefit of physical capital investment is much higher than that of knowledge accumulation during this growth period, and there is only investment in physical capital without R&D investment. Accordingly, accumulation of energy-consuming physical capital shapes a monotonic increase in fossil energy use, resulting in an energy-intensive pattern of growth. To avoid this undesirable outcome, China's social planner should consider locating a transition point to the innovation-led BGP (K_T, C_T) in front of the non-innovation-led steady state (K_{SS}, C_{SS}). By doing that, when China's economy grows and reaches that transition point, the dynamic benefit of knowledge accumulation would be equalized with that of physical capital investment, the economy then embarks on R&D investment for technological innovation. As an outcome, China's economy would evolve along the innovation-led BGP in which consumption, physical capital stock, and knowledge stock all grow at a rate of $g_C = g_K = g_H = g^* > 0$. With the energy-saving effect of knowledge stock accumulation and technology progress, fossil energy uses would decline at the rate of $g_E^* = (\kappa - \lambda) \cdot g^* < 0$.

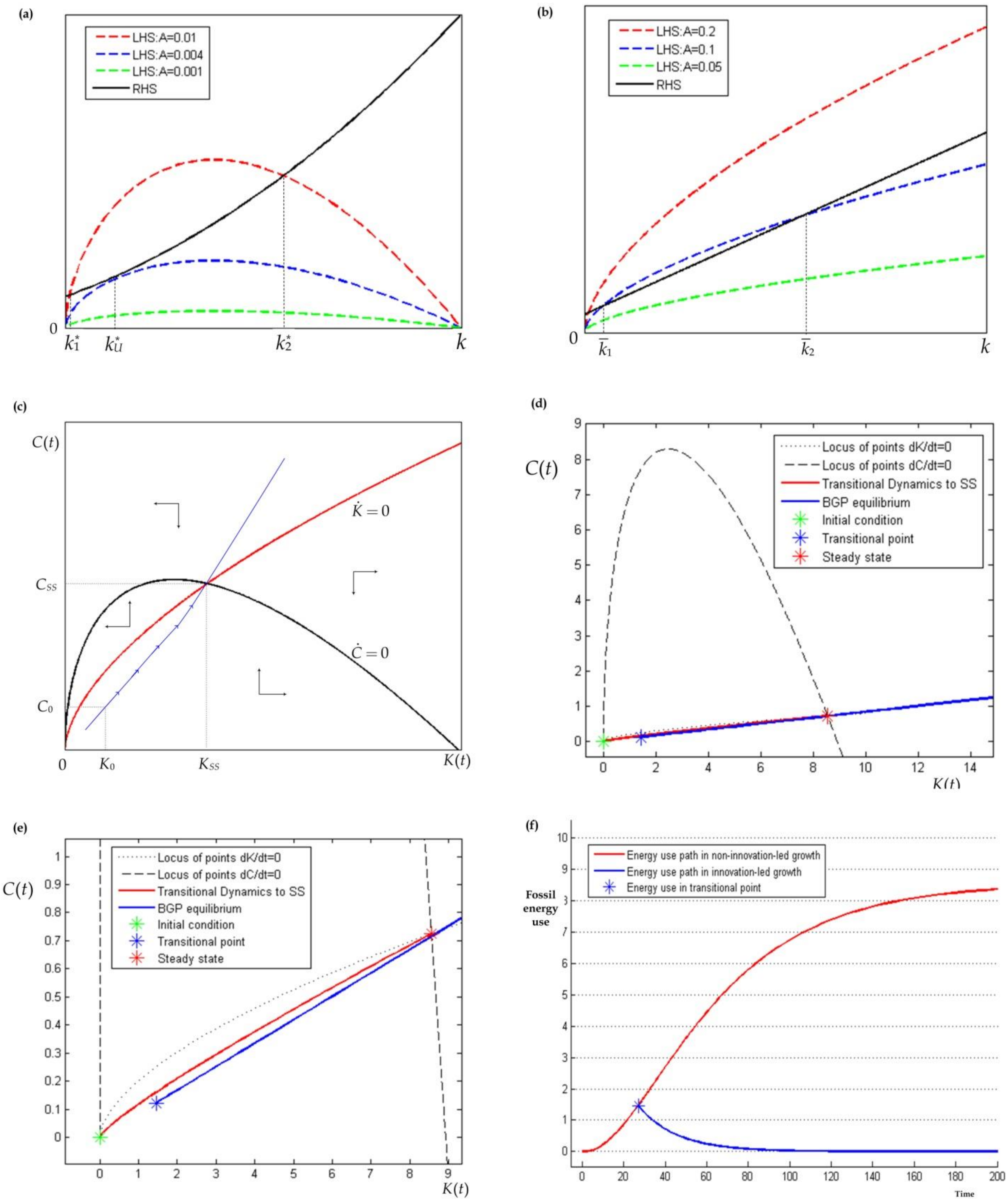

Figure 1(a). Existence and multiplicity of the BGP when the TFP parameter has different values.
(b). Economic growth rate when the TFP parameter has different values.
(c). The phase diagram associated with the non-innovation-led growth path.
(d). Overview of the transitional dynamics to the innovation-led BGP.
(e). Zoon in the transitional dynamics to the innovation-led BGP.
(f). Intertemporal dynamics of fossil energy use in both non-innovation-led and innovation-led growth paths.

6. Numerical Examples

To accompany the analytical results presented in previous sections, this section provides a numerical example to illustrate China's transitional dynamics from energy-intensive to innovation-led growth. Tab. 1 summarizes the values of the model parameters ($A, \sigma, \rho, \kappa, \lambda, a, \beta$) for numerical simulations.

Table 1
Parameterization in numerical simulation

A	σ	ρ	κ	λ	a	β
0.2	0.01	0.05	1	2	0.6	0.4

A : Total factor productivity parameter
σ : Consumer preference towards the environmental goods
ρ : Time discount rate
κ : Elasticity of fossil energy use with respect to energy-consuming physical capital stock
λ : Elasticity of fossil energy use with respect to energy-saving knowledge stock
a : Elasticity of output production with respect to the input of physical capital stock
β : Elasticity of output production with respect to the input of knowledge stock.

In the demand side of China's economy, we impose σ =0.01 for the household's preference towards environmental goods, and ρ =0.05 for the time discount rate. In the supply side, the elasticity of output production with respect to the input of physical capital and knowledge is equal to a =0.6 β =0.4, respectively. These values satisfy the neoclassical condition $a+\beta$ =1 such that the economy can have an innovation-led BGP in the long run. For the impact on fossil energy, the elasticity of fossil energy use with respect to energy-saving knowledge stock and energy-consuming physical capital is equal to λ =2 κ =1, respectively. Moreover, given the values for the set of parameters $(\sigma, \rho, \kappa, \lambda, a, \beta)$, equations (21)-(22) are used to pin down the value of TFP that supports a unique BGP A_U^* =0.004, and to ensure the existence of a BGP in which consumption, physical capital stock, and knowledge stock grows at a positive rate, we impose a sufficiently higher value of TFP parameter, A =0.2.

Given the set of exogenous parameters $(A, \sigma, \rho, \kappa, \lambda, a, \beta)$, we use equations (18)-(19) to pin down the BGP levels of capital-knowledge and consumption-capital ratios k^* =1.4526, c^* =0.0836. Then the equation

(20) determines the BGP growth rate of consumption, capital, and technology g^* =0.0525. Therefore, China's long-run innovation-led BGP is characterized by a constant capital-knowledge and consumption-capital ratio k^* =1.4526, c^* =0.0836. Moreover, in this innovation-led BGP, consumption, physical capital, and knowledge stock in China's economy all grow at a constant rate of g^* =0.0525.

We now simulate China's transitional dynamics from energy-intensive status quo to the long-run innovation-led BGP. According to the HJB equation (23), to create a shadow price of physical capital that is relatively higher than that of knowledge, we need to impose a sufficient low level on the initial stock of physical capital K_0 =0.0001. In this case, China's social planner only has an incentive to spend on physical capital investment without R&D expenditure and knowledge accumulation, thus creating a non-innovation-led growth path during the transitional dynamics periods. Given the set of parameter values $(A,\sigma,\rho,\kappa,\lambda,a,\beta)$ and the initial stock of knowledge H_0 =1 (normalization), China's non-innovation-led growth path during the transitional dynamics periods is characterized by a system of differential equations,

$$\dot{C} = -0.01 * \frac{C^2}{K} + 0.12 * K^{-0.4} \cdot C - 0.05 * C, \tag{29}$$

$$\dot{K} = 0.2 * K^{0.6} - C \quad . \tag{30}$$

The phase diagram associated with the equation system (29)-(30) is plotted in Fig. 1(d)-(e). The dashed black curve corresponds to $\dot{C} = 0$ and the dash-dot black curve represents $\dot{K} = 0$. Following the procedure as documented in Appendix C, we compute the Jacobian matrix of the equation systems at the steady state and yield two real eigenvalues, one positive ξ_1 = 0.0732, and one negative ξ_2 = -0.0232, implying that there exists a one-dimensional stable arm. We then apply the relaxation algorithm to numerically simulate the transitional dynamics associated with the two-point boundary value problem (Trimborn et al., 2008). That is, starting with the initial condition (green star in Fig. 1(e)), consumption and physical capital stock of China's economy would evolves along a non-innovation-led growth path (red line in Fig. 1(e)) and tend towards the steady state C_{SS} = 0.7251, K_{SS} = 8.5562 (red star in Fig. 1(e)). Without knowledge accumulation in this non-innovation-led growth path, accumulation of the energy-consuming physical capital stock leads to an monotonic increase in fossil energy use with a peak level of $E_{SS} = K_{SS}^{\kappa} \cdot H_0^{-\lambda}$ = 8.5562 (red line in Fig. 1(f)).

As compared to tending towards the steady state in the non-innovation-led growth path, the blue line in Fig. 1(e) illustrates an alternative growth path along which China make a transition to an innovation-led BGP where consumption, physical capital, and technology all grow simultaneously. To achieve that transition, the social planner should locate a transition point (K_T, C_T) in front of the non-innovation-led growth steady state (K_{SS}, C_{SS}), where the level of physical capital stock and consumption at this transition point is equal to $K_T = k^* \cdot H_0$ =1.4526, $C_T = c^* \cdot K_T$ =0.1214. By doing that, when China's economy follows the energy-intensive, non-innovation-led growth path and augments its physical capital stock to a level of K_T =1.4526 which corresponds to the transition point (blue star in Fig. 1(e)), the dynamic benefit of knowledge accumulation would be equalized with that of physical capital investment, the social planner then has an incentive to invest in physical capital and R&D simultaneously. As a result, China's economy will immediately jump into the transitional point (K_T, C_T) by adjusting its consumption to a level of C_T =0.1214. When this transition point is reached, China's economy would be placed in the innovation-led BGP along which consumption, physical capital, and technology all grow at a positive rate of g^* =0.0525, thus avoiding the possibility of stagnation in the steady state along the non-innovation-led growth path. As shown in the blue line in Fig. 1(f), when China's economy reaches the transition point where the social planner embarks on R&D-related innovation for accumulating energy-saving knowledge stock, fossil energy use would decline at a rate of g_E^* = - 0.0525 along the innovation-led growth path.

Moreover, it is worth noting that the above-described simulation results offer useful insights into China's potential transition from its current fossil energy-intensive growth pattern to an innovation-led development prospect. First, our simulation results show that China's long-run innovation-led growth prospect would have two features. (1) A constant capital-knowledge and consumption-capital ratio

$k^* = K^* / H^*$ = 1.4526, $c^* = C^* / K^*$ = 0.0836, and (2) consumption C^*, physical capital stock K^*, and knowledge stock H^* grow simultaneously at a rate of g^* = 0.0525. Given that the physical capital K^* is an accumulable stock augmented by capital investment I^*, that is, $\dot{K}^* = I^*$, and the physical capital stock K^* grow at a rate of $\dot{K}^* / K^* = g^*$ = 0.0525, we obtain that the BGP level of capital investment would satisfy $I^* \equiv \dot{K}^* = 0.0525K^*$. As compared to the BGP level of consumption $C^* = 0.0836K^*$, in the BGP the relative ratio between consumption and investment is $C^* : I^*$ =0.0836:0.0525. Moreover, given $k^* = K^* / H^*$ =1.4526, we have H^* / K^* =0.6884 and $H^* = 0.6884K^*$. Given $\dot{H}^* / H^* = g^*$ = 0.0525, the BGP level of R&D investment would satisfy $R^* \equiv \dot{H}^* = 0.0525H^* = 0.0525 \times 0.6884\text{K}=0.0361\text{K}$. Therefore, in the long-run BGP of China's economy, consumption, physical capital investment, and R&D spending for technological progress would have a balanced share $C^* : I^* : R^*$ = 0.0836:0.0525:0.0361= 5: 3:2, with consumption, physical capital, and technology growing at a balanced rate of 5%.

Second, for the transitional dynamics of China's economy, the simulation results show that investment will augment the stock of physical capital from the initial low level K_0 =0.0001 to a level of K_T =1.4526 that corresponds to the transition point, which translates into an increase of about 14526 folds. Basically, this result is empirically consistent with China's economic growth trend. Over the past 35-year rapid growth (1978-2013), China has experienced massive investment in physical capital with annual growth rates of 20-30%. Therefore, with a 25% annual average growth rate of physical capital investment, economic growth over a 35-year time frame would bring about 12321-fold increases in the stock of physical capital, which is basically consistent with our numerical simulation results.

7. Conclusions

Whether China continues its business-as-usual energy-intensive growth path or adopts a sustainable innovation-led growth alternative has significant implications for energy and climate governance. Building on a Ramsey-Cass-Koopmans growth model incorporating the mechanism of endogenous technological change and its interaction with fossil energy use and macroeconomic growth, this paper contributes to an economic exposition on China's potential transition from an energy-intensive growth pattern to an innovation-oriented development prospect.

We show that during the initial period of China's economic growth, the small amount of capital stock creates higher dynamic benefits of capital investment, the social planner only has an incentive to augment physical capital stock rather than undertake R&D investment for technological innovation, thus creating a non-innovation-led growth path. As a result, starting with the initial condition, China's economy would evolve along a non-innovation-led growth path and tend towards the steady state where the stock of physical capital augments by about 855662 folds. This non-innovation-led path gives rise to China's energy-intensive growth pattern, in the sense that without knowledge accumulation and the energy-saving effect of technological progress, sole accumulation of energy-consuming physical capital would lead to monotonic increases in fossil energy use by 855662 folds at the steady state.

To avoid the undesirable stagnation in the steady state, the social planner of China's economy should consider locating a transition point to the innovation-led BGP in front of the non-innovation-led growth steady state. The growth dynamics would reach that transition point when China's economy follows the non-innovation-led path and the stock of physical capital is augmented by about 14526 folds over a 35-year time frame (1978-2013) with the average growth rate of capital investment by about 25% annually. Once the transition point is reached, the dynamic benefit of knowledge accumulation would be equalized with that of physical capital investment, the social planner thus embarks on investment in physical capital and R&D simultaneously. As a result, China's economy would be placed in an innovation-led BGP in which consumption, physical capital investment, and R&D investment have a balanced share of 5:3:2. Meanwhile, along this innovation-led BGP, consumption, physical capital stock, and knowledge stock all grow at a rate of 5% annually. With the energy-saving effect of knowledge accumulation and technology progress, fossil energy uses would decline at the rate of 5% annually along the innovation-led BGP.

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Appendix A. Proof of Proposition 1

Substituting (9)-(10) into (11)-(12) derives the intra-temporal no-arbitrage condition between physical capital and knowledge capital investment.

$$\begin{aligned} &U_E(C,E(K,H))\cdot E_K(K,H)+U_C(C,E(K,H))\cdot F_K(K,H) \\ &=U_E(C,E(K,H))\cdot E_H(K,H)+U_C(C,E(K,H))\cdot F_H(K,H) \end{aligned} \quad , \tag{A1}$$

Substituting the functional forms of the model into (A1) obtains

$$-\frac{\sigma\cdot\kappa}{K}+a\cdot A\cdot\frac{1}{C}\cdot\left[\frac{K}{H}\right]^{a-1}=\frac{\sigma\cdot\lambda}{H}+(1-a)\cdot A\cdot\frac{1}{C}\cdot\left[\frac{K}{H}\right]^{a} \quad , \tag{A2}$$

Denote $c\equiv C/K$ and $k\equiv K/H$, (A2) can be rewritten as,

$$-\sigma\cdot\kappa\cdot c+a\cdot A\cdot k^{a-1}=\sigma\cdot\lambda\cdot c\cdot k+(1-a)\cdot A\cdot k^{a} \quad , \tag{A3}$$

Rearranging (A3) yields (15).

For inter-temporal dynamic optimality conditions, the growth rate of consumption is derived as:

$$\frac{\dot{C}}{C}=-\frac{\dot{U}_C}{U_C}=-\frac{\dot{q}_K}{q_K}=\frac{U_E\cdot E_K}{U_C}+F_K-\rho=\frac{[a\cdot\lambda+(1-a)\cdot\kappa]\cdot A\cdot k^{a}}{\kappa+\lambda\cdot k}-\rho , \tag{A4}$$

where the first equality comes from the logarithmic utility function, the second and third follow from the optimality conditions (9) and (11), and the final equality gives the explicit characterization for the model. From (A4) and the definition of consumption-capital ratio, $c \equiv C/K$, we obtain the equation (16). Based on the optimality conditions (13)-(14), the aggregate resource constraint of the economy is written as $A \cdot K^{a} \cdot H^{\beta} - C - \dot{K} - \dot{H} = 0$, and the growth rate of knowledge stock is determined by,

$$\begin{aligned} g_H \equiv \frac{\dot{H}}{H} &= \frac{A \cdot K^{a} \cdot H^{\beta} - C - \dot{K}}{H} = A \cdot k^{a} - c \cdot k - g_K \cdot k \\ &= \frac{A \cdot [(\sigma \cdot \lambda + 1 - a) \cdot k^{a+1} + (\sigma \cdot \kappa - a) \cdot k^{a}]}{\sigma \cdot (\kappa + \lambda \cdot k)} - g_K \cdot k \end{aligned}, \tag{A5}$$

where we substitute for c and obtain the growth rate of knowledge as a function of k. Then from (A5) and the definition of capital-knowledge ratio, $k \equiv K/H$, we obtain the equation (17). ■

Appendix B. Proof of Proposition 3

Schematically, as Fig. 1(a) shows, the curve associated with the RHS in (18) is a quadratic function and monotonically increases in the domain $k > 0$ provided that $\kappa > 0, \lambda > 0$. The LHS is a bell-shaped function of k, first increases and then decreases as k progresses from null to the maximal $a/(1-a)$. There is a unique equilibrium when both curves intersect at the unique point k_U^*, and the equilibrium condition requires that the LHS is equal to the RHS,

$$[1 + \sigma \cdot (\lambda - \kappa)] \cdot [a - (1-a) \cdot k_U^*] \cdot A_U^* \cdot k_U^{*a} = \sigma \cdot \rho \cdot [\kappa + (\kappa + \lambda) \cdot k_U^* + \lambda \cdot k_U^{*2}], \tag{B1}$$

and the uniqueness of this equilibrium also requires both curves are tangent to each other at this point k_U^* (the slopes of both functions are the same), which satisfies the tangency condition,

$$[1 + \sigma \cdot (\lambda - \kappa)] \cdot [a^2 - (1-a^2) \cdot k_U^*] \cdot A_U^* \cdot k_U^{*a-1} = \sigma \cdot \rho \cdot [\kappa + \lambda + 2\lambda \cdot k_U^*]. \tag{B2}$$

Dividing (B1) by (B2), we obtain the equation (21) that k_U^* should satisfy. Given the value of k_U^*, we use (B1) to calculate the value of TFP that supports the unique BGP A_U^* as given in (22). As Fig. 1(a) shows, if the exogenous TFP parameter is larger than the value of TFP that supports the unique BGP, $A > A_U^*$, then the LHS curve moves upwards and create two points that intersect with the RHS curve, and the intersection points correspond to two different BGP k_1^*, k_2^*, where $0 < k_1^* < k_U^* < k_2^* < a/(1-a)$.

Moreover, based on the equation (20) that characterizes the BGP growth rate, the BGP value of capital-knowledge ratio $\bar{k}$ that support a positive BGP growth rate is determined by,

$$[a\cdot\lambda+(1-a)\cdot\kappa]\cdot A\cdot\bar{k}^{a}=\rho\cdot(\kappa+\lambda\cdot\bar{k}). \tag{B3}$$

As Fig. 1(b) shows, the RHS is a linear function of k, and the LHS is a power function. When the TFP A is sufficiently high and both curves intersect at two points $\bar{k}_1, \bar{k}_2$, any value of $\bar{k}$ that lies within the interval $\bar{k} \in (\bar{k}_1, \bar{k}_2)$ leads to a positive BGP growth rate $g^* > 0$, and as an increase in A shifts the LHS upwards, $\bar{k}_1$ decreases and $\bar{k}_2$ increases, with $\lim_{A\to+\infty} \bar{k}_1 = 0$ and $\lim_{A\to+\infty} \bar{k}_2 = +\infty$. Meanwhile, Fig. 1(a) shows that the BGP capital-knowledge ratio k_2^* increases with A, yet the limit is bounded with $\lim_{A\to+\infty} k_2^* = a/(1-a)$. We thus expect that for the TFP with a sufficiently high level, we would have $\bar{k}_1 < k_2^* < \bar{k}_2$, and the BGP growth rate associated with k_2^* is positive $g^* > 0$. Moreover, given that $g_K = g_H = g^*$, we obtain $g_E^* = (\kappa - \lambda)\cdot g^*$, and given $\lambda > \kappa$, fossil energy uses falls at the rate of $g_E^* = (\kappa-\lambda)\cdot g^* < 0$ in the BGP. ■

Appendix C. Proof of Proposition 4

The preceding discussion in Section 5 can establish the claims in the first part of this proposition. For the second part, we analyze the saddle path stability by deriving the partial derivatives of the system of differential equations (25)-(26) evaluated at the steady state (K_{SS}, C_{SS}):

$$\left.\frac{\partial \dot{C}}{\partial C}\right|_{K_{SS},C_{SS}} = a\cdot A\cdot\left(\frac{H_0}{K_{SS}}\right)^{1-a} - 2\sigma\cdot\kappa\cdot\frac{C_{SS}}{K_{SS}} - \rho = -\sigma\cdot\kappa\cdot\frac{C_{SS}}{K_{SS}} \tag{C1}$$

$$\left.\frac{\partial \dot{C}}{\partial K}\right|_{K_{SS},C_{SS}} = \frac{C_{SS}}{K_{SS}}\cdot\left[A\cdot(a^2-a)\cdot\left(\frac{H_0}{K_{SS}}\right)^{1-a} + \sigma\cdot\kappa\cdot\frac{C_{SS}}{K_{SS}}\right] = \frac{C_{SS}}{K_{SS}}\cdot\left[A\cdot a^2\cdot\left(\frac{H_0}{K_{SS}}\right)^{1-a} - \rho\right] \tag{C2}$$

$$\left.\frac{\partial \dot{K}}{\partial C}\right|_{K_{SS},C_{SS}} = -1 \tag{C3}$$

$$\left.\frac{\partial \dot{K}}{\partial K}\right|_{K_{SS},C_{SS}} = a\cdot A\cdot\left(\frac{H_0}{K_{SS}}\right)^{1-a} \tag{C4}$$

where (C1)-(C2) 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 (27)-(28), we obtain the Jacobian of the equation systems at the steady state,

$$\begin{pmatrix} \left.\frac{\partial \dot{C}}{\partial C}\right|_{K_{SS},C_{SS}} & \left.\frac{\partial \dot{C}}{\partial K}\right|_{K_{SS},C_{SS}} \\ \left.\frac{\partial \dot{K}}{\partial C}\right|_{K_{SS},C_{SS}} & \left.\frac{\partial \dot{K}}{\partial K}\right|_{K_{SS},C_{SS}} \end{pmatrix} = \begin{pmatrix} -\sigma\cdot\kappa\cdot\frac{\rho}{a-\sigma\cdot\kappa} & \frac{\rho}{a-\sigma\cdot\kappa}\cdot\left(\frac{a^2\cdot\rho}{a-\sigma\cdot\kappa}-\rho\right) \\ -1 & \frac{a\cdot\rho}{a-\sigma\cdot\kappa} \end{pmatrix}. \tag{C5}$$

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

$$\det\begin{pmatrix} -\sigma\cdot\kappa\cdot\frac{\rho}{a-\sigma\cdot\kappa}-\xi & \frac{\rho}{a-\sigma\cdot\kappa}\cdot\left(\frac{a^2\cdot\rho}{a-\sigma\cdot\kappa}-\rho\right) \\ -1 & \frac{a\cdot\rho}{a-\sigma\cdot\kappa}-\xi \end{pmatrix} = -\frac{\rho^2\cdot(1-a)}{a-\sigma\cdot\kappa}-\rho\cdot\xi+\xi^2 . \tag{C6}$$

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

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