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Product Homogeneity, Knowledge Spillovers, and Innovation: Why Energy Sector is Perplexed by a Slow Pace of Technological Progress

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Abstract

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Keywords

Energy Technological Innovation; Product Homogeneity; Knowledge Spillovers; Love-for-variety Effect

JEL Classification

Q55; Q58; Q41; Q43; Q48; O31.

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Product Homogeneity, Knowledge Spillovers, and Innovation:

Why Energy Sector is Perplexed by a Slow Pace of Technological Progress

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Abstract: There is a growing body of literature mentioning the slow pace of energy technological progress as compared to other technologies like information technology (IT), but the reasons why energy sector is perplexed by slow innovation remain unexplained. Based on a variety-expanding endogenous technological change model, this paper provides a rigorous economic exposition of the mechanism that underlies the slow progress of energy technological innovation. We show that in decentralized market equilibrium the growth rate of energy technology variety is lower than that of IT variety. This stems from both market fundamentals where the homogeneity of end-use energy goods is less likely to harness the pecuniary externality embedded in the household's love-for-variety preference, and technology fundamentals where the capital-intensiveness of energy technology inhibits the non-pecuniary technological externality due to knowledge spillovers. We further show that a social planner solution can promote energy technological progress, yet still cannot achieve an outcome in which energy technology variety grows faster than IT variety. By targeting subsidies on energy technology R&D and the use of intermediate primary energy inputs by secondary energy producers, the decentralized market equilibrium can achieve an outcome in which energy technology grows faster than IT.

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1. Introduction

In 1969, the Apollo mission succeeded in achieving the goal of landing the first human on the Moon. This greatest achievement in human history not only created profound economic, political, and cultural impacts, but also laid the foundation for advancements in many areas of technology. Among other things, one is electronic and information technology (IT) that controls orbital spaceflight and long-distance telecommunications, and the other is solar cell technology that provides electrical power for the lunar flights. This historical event marks the same starting point in time for the inventions of IT and solar technologies, but afterwards the development of both technologies proceed quite differently and demonstrate diverging trajectories of technological progress.

Fabricated in the late 1960s, early applications of solar or photovoltaic (PV) cell in spacecraft were followed by commercial production for niche markets in the 1970-1980s, and today this industry still struggles to survive, since the costs for solar cell-generated electricity remain well above conventional fossil energy alternatives without massive subsidies. There have been many quite developments in PV cell technologies over the past several decades, but none have radically altered the evolutionary pattern of innovation, which over time looks like a relatively smooth progression ([Henderson and Newell, 2010](#); [Newell, 2011](#)). In contrast, successive waves of IT revolution have performed new tasks, many of which would earlier have been all but inconceivable. Semiconductor firms designed early transistors and integrated circuit (IC) chips in response to government demand for costly defense and space programs in the 1960s. Just within a few years, they were selling inexpensive chips for consumer products like radios and TV when electronic products began penetrating into individual families during the 1970s. IC chips then led to microprocessors and microprocessors led to the revolution of mobile telephones and personal computers during the 1980-1990s, and contributed to the popularization of software, internet, portable devices, and wireless applications today ([Berndt and Rappaport, 2001](#)). Technological innovations in IT also stimulated widespread application in many other industries and spawned countless further innovations there that transformed the models of businesses worldwide ([Jorgenson and Stiroh, 2000](#); [Brynjolfsson and Hitt, 2003](#)). As a result, although IT and PV cell technologies began at about the same time, sales of IT-related electronic products grew much faster, by 2012 reaching \$250 billion worldwide as compared with solar PV sale revenues of just \$17 billion ([Marketbuzz, 2013](#)).

Extending to the broad set of energy-related technologies (i.e., oil, gas, coal, hydropower, nuclear, geothermal, solar, wind), a real fact is that entire energy sectors face a surprisingly slow pace of innovation and technological progress, even if countries in the world have shown strong interests in innovation in energy sectors (particularly invention of carbon-free renewable energy technologies) as

a solution to the pressing challenge of energy security and climate mitigation ([Margolis and Kammen, 1999a,b](#); [Nemet and Kammen, 2007](#); [Popp et al., 2009](#); [Henderson and Newell, 2010](#); [Newell, 2011](#)). Viewed from the standpoint of innovation inputs - R&D spending, public expenditure on energy R&D remains dramatically low over the past several decades.¹ For example, over the time period 1974-2009 the US government spending on energy R&D is dramatically low with a level of less than \$10 billion annually, as compared to other budget categories like defense, health care, and space programs with each receiving a budget of more than \$100 billions ([U.S. Department of Energy, 2010](#); [Henderson and Newell, 2010](#)). The International Energy Agency (IEA) member countries also experience a trend of underinvestment in energy R&D, with total public budgets for energy R&D in all IEA countries declining in real terms over the past 30 years. The relative share of energy R&D in total R&D budget has declined significantly from 12% in 1981 to 4% in 2008, and expenditure on energy R&D is about 0.03% of GDP in 2008 ([IEA, 2010](#)).² Meanwhile, for private R&D spending firms in almost any industry seek to innovate themselves for meeting the changing market demands, but energy industry is an exception with sharp declines in R&D spending. In the early 1990s, when R&D intensity (R&D expenditure as a share of sales revenues) across all US industries averaged 3-4 percent, that intensity in energy industries is less than 1%. More recently, the industry-wide average increased somewhat, to about 3.4 percent of revenues, while the figure for energy sector R&D dropped to only 0.1 percent ([Margolis and Kammen, 1999a,b](#); [Neuhoff, 2005](#); [Henderson and Newell, 2010](#); [NSF, 2012](#)). Moreover, from the standpoint of innovation outputs – patenting, it also shows a slow pace of technological innovation in energy sectors. The number of energy-specific patents dramatically falls over time as an outcome of the declining energy R&D spending, with a number of 100-150 patents granted per year. This number is orders of magnitude smaller than the total number of granted patents which amounts to 100-150 thousand per year ([Margolis and Kammen, 1999a,b](#); [Nemet and Kammen, 2007](#)).³

Given the urgency and novelty of the above-described issues related to energy technological innovation, it is not surprisingly that a growing body of literature has discussed the slow progress of energy technology with some proposals of innovation-enhancing policy responses ([Noberg-Bohm,](#)

¹ The only exceptions are previous peak spending during the late 1970s due to the Arab Oil Embargo and year 2009 stimulus spending for recovery from economic recessions.

² This is except for year 2009 “green” stimulus spending, but “green” stimulus budgets are one-time increases in funds, and new commitments to energy R&D may be ending. Given that most of the IEA countries risk falling into a budget deficit, whether the sudden push for energy R&D expenditure is sustainable over the long term is uncertain ([IEA, 2010](#)).

³ This is according to the US Patent and Trademark Office’s “Patent Bibliographic Database” ([PTO, 1998](#)). The data on energy technology patents is generated from keyword searches that include: oil, natural gas, coal, photovoltaic, hydroelectric, hydropower, nuclear, geothermal, solar, wind.

2000; Holdren and Sagar, 2002; Grubb, 2004; Jaffe et al., 2005; Gallagher et al., 2006, 2012; Sagar and van der Zwaan, 2006; Nemet and Kammen, 2007; Anadon and Holdren 2009; Narayanamurti et al., 2009; Newell, 2008, 2010, 2011; Anadon, 2010; Grübler et al. 2012). While these existing works have the virtue of contributing to potential policy recipes for accelerating energy innovation (normative issues), the limitation is that they all lack a rigorous analysis of the basic positive issue: why energy sector is often perplexed by a slow pace of technological progress compared to fast-innovation sectors like IT. A deep exposition of this positive issue is particularly helpful, because without a full understanding of the mechanism that underlies energy technological innovation, it would become difficult to serve the purpose of designing appropriate policy responses for accelerating energy technological progress. Therefore, to fill this gap in the existing literature, our work contributes to a rigorous economic exposition of the basic mechanism that helps explain the slow pace of energy technological progress.

Building on a variety-expanding endogenous technological change model, we show that in decentralized market equilibrium the growth rate of energy technology variety is lower than that of IT variety. This stems from the fact that in market fundamentals the homogeneity of end-use energy goods is less likely to harness the pecuniary externality embedded in the household's love-for-variety preference, and in technological fundamentals the capital-intensiveness of energy technology inhibits the non-pecuniary technological externality due to knowledge spillovers.⁴ Moreover, it is shown that a social planner solution can accelerate the speed of energy technological progress, but still cannot achieve an outcome in which energy technology variety grows faster than IT variety. Finally, by targeting the subsidies on energy technology R&D and the use of intermediate primary energy inputs by secondary energy producers, the decentralized market equilibrium can achieve an outcome in which energy technology variety grows faster than IT variety.

The rest of this paper is organized as follows. We begin in [Sections 2-3](#) by describing the variety-expanding endogenous technological change model and characterization of the decentralized market equilibrium. We continue in [Sections 4-5](#) by investigating the balanced growth path and transitional dynamics of the model. As a comparison to the decentralized market equilibrium, [Sections 6-7](#) present a social optimal solution and efficiency-improving policy intervention that helps accelerate energy technological innovation. [Section 8](#) concludes.

⁴ In this regard, our conclusions generally coincide with the so-called “technology push/market pull” paradigm, that is, transformative technological change requires the simultaneous leveraging and coupling of both “technology supply push” and “market demand pull” as suggested by [von Hippel \(1976\)](#); [Mowery and Rosenberg \(1979\)](#); [Kleinknecht and Verspagen \(1990\)](#); [Dosi \(1982\)](#); [Arthur \(2007\)](#); [Nemet \(2009\)](#).

2. The Model

2.1 The Household

Consider that the economy is in continuous time $t \in [0, \infty]$ and involves a representative household in the demand side and two sectors – energy and IT sectors – in the supply side. The economy has a constant population equal to $2L$ which is supplied inelastically as workforces, and the workforce endowment is equally allocated between energy and IT sectors, each with the same amount of L .⁵ The preference of the representative household is specified as

$$\int_0^{\infty} \exp(-\rho t) \cdot [\ln C_E(t) + \ln C_T(t)] \cdot dt \quad , \quad (1)$$

where ρ is the time discount rate, and the household derives utility from consuming two end-use goods - energy products C_E and IT products C_T . The utility derived are additively separable, and the logarithmic preference is strictly increasing, concave, and twice differentiable for C_E and C_T , and satisfies the Inada conditions. Moreover, the end-use energy goods stand for the numeraire in this economy, so throughout the price of final energy goods at each date is normalized to unity, and we denote the price of IT product C_T by P_T .⁶ Characterizing the demand side also needs to specify the budget constraint of the household

$$P_T(t) \cdot C_T(t) + C_E(t) + \dot{A}(t) = r(t) \cdot A(t) + w(t) \cdot 2L \quad , \quad (2)$$

where $A(t)$ is the asset holdings of this household,⁷ $r(t)$ is market interest rate, and $w(t) \cdot 2L$ is income earnings of the household which inelastically supplies the constant workforce endowment.

⁵ By setting the same amount of workforce endowment in both sectors, the subsequent analysis can focus on the fundamental reasons that underlie the slow pace of energy technology innovation, rather than the effect due to differences in the input of workforce.

⁶ The reason for this treatment is that end-use energy goods (i.e. electric utility) have a substantial degree of homogeneity in terms of varieties and functions, while IT products are characterized by a substantial degree of heterogeneity in the sense that there exists a large variety of differentiated end-use IT product with new attributes and functions.

⁷ As detailed later, the asset holdings consist of market values of firms (each has the technology to produce a differentiated variety of products) that are owned by the representative household,

$A(t) = \int_0^{N_E(t)} V_E(i, t) \cdot di + \int_0^{N_T(t)} V_T(j, t) \cdot dj$, where $N_E(t), N_T(t)$ are the number of differentiated energy and IT technology variety, and $V_E(i, t), V_T(j, t)$ are the market value of the firms owning each energy and IT technology variety.

2.2 Energy Sectors

In the supply side of the economy, the energy sectors involves a number of primary energy firms that produce and supply a variety of differentiated intermediate primary energy (i.e., coal, oil, natural gas, hydropower, solar, wind, geothermal, bioenergy), and these primary energy resources are then used as intermediate production inputs by a representative final energy firm to produce homogenous end-use, secondary energy products (i.e., electric utility) with a production function,

$$Y_E(t) = \frac{1}{1-a} E(t)^{1-a} \cdot L^a, \quad (3)$$

where the production function has the constant returns to scale properties, L is the workforce employment for energy production, and

$$E(t) = \left[\int_0^{N_E(t)} x_E(i, t)^{\frac{\varepsilon_E - 1}{\varepsilon_E}} di \right]^{\frac{\varepsilon_E}{\varepsilon_E - 1}}, \quad (4)$$

is the primary energy input composite formulated as a Dixit-Stiglitz CES aggregate of differentiated variety of primary energy inputs. $x_E(i, t)$ is the amount of intermediate input of primary energy variety $i \in [0, N_E(t)]$, and $N_E(t)$ measures the number of differentiated primary energy varieties. ε_E is the elasticity of substitution between primary energy varieties. Since the differentiated variety of intermediate primary energy inputs are largely substitutable in producing the homogeneous secondary energy products, the value of ε_E is thus sufficiently high. Moreover, as the final-use, secondary energy products (i.e., electric utility) have a substantial degree of homogeneity in terms of attributes and functions, the effect that the expanding variety of primary energy inputs has is to raise the productivity of producing end-use energy products, creating a form of process innovation for energy technological progress. Accordingly, in our model energy technological progress is described by an expanding variety of differentiated primary energy used to produce homogenous secondary energy products.⁸ By setting $\varepsilon_E \equiv 1/a$ for normalization, the production function Eqs. (3)-(4) can be rewritten as,

$$Y_E(t) = \frac{1}{1-a} \left(\int_0^{N_E(t)} x_E(i, t)^{1-a} di \right) \cdot L^a. \quad (5)$$

⁸ To be specific, in addition to traditional fossil fuel-based energy technologies, energy sectors also involves a large number of differentiated varieties of primary energy technologies based on nuclear, hydropower, solar, wind, ocean wave, bioenergy, and geothermal etc. The variety-expanding model used here is closely related to and builds on the endogenous growth models, for example, [Romer \(1986, 1990\)](#); [Smulders and de Nooij \(2003\)](#); [van Zon and Yetkiner \(2003\)](#); [Acemoglu et al. \(2012\)](#).

The demand for primary energy input variety $i \in [0, N_E(t)]$ is determined by the representative firm that produces end-use, secondary energy products, and the problem of this end-use energy firm is described as maximization of the instantaneous flow profits at each point in time,

$$\max \frac{1}{1-a} \left[\int_0^{N_E(t)} x_E(i, t)^{1-a} di \right] \cdot L^a - \int_0^{N_E(t)} p_E(i, t) \cdot x_E(i, t) \cdot di - w(t) \cdot L, \quad (6)$$

where the flow profit is obtained by subtracting the costs of using primary energy inputs and labor from the output of final energy production. The first-order necessary condition of this problem with respect to $x_E(i, t)$ yields the isoelastic demand for primary energy input variety $i \in [0, N_E(t)]$,

$$x_E(i, t) = p_E(i, t)^{-1/a} \cdot L = p_E(i, t)^{-\varepsilon_E} \cdot L. \quad (7)$$

The analysis proceeds to the primary energy firms that produce and supply each differentiated variety of intermediate primary energy input. Consider that there is a fully-enforced patent system where a particular energy firm who invents the blueprint for a new variety of primary energy technology receives a perpetual patent on using this variety and thus possesses *ex post* monopoly power. Hence, the market value (i.e., net present discounted value) of the monopolistic energy firm that owns the blueprint of each primary energy variety $i \in [0, N_E(t)]$ is given by

$$V_E(i, t) = \int_t^\infty \exp \left[- \int_t^s r(s') \cdot ds' \right] \cdot \pi_E(i, s) \cdot ds$$

$$\text{s.t. } \pi_E(i, s) = p_E(i, s) \cdot x_E(i, s) - \psi \cdot x_E(i, s), \quad (8)$$

where $\pi_E(i, t)$ is the flow profit of energy monopolistic firm owing the blueprint of primary energy variety $i \in [0, N_E(t)]$ at time t , $p_E(i, t), x_E(i, t)$ are the profit-maximizing price and quantity choices. Once the technology blueprint for a particular primary energy variety is created, the monopolist can produce and supply one unit of that variety of primary energy at a marginal cost ψ (in unit of the final energy numeraire goods). Alternatively, the market value of each primary energy firm [Eq. \(8\)](#) can be rewritten in the Hamilton-Jacobi-Bellman (HJB) form,

$$r(t) \cdot V_E(i, t) = \dot{V}_E(i, t) + \pi_E(i, t), \quad (9)$$

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

As compared to the development of IT-related devices, energy technology development is often characterized by capital-intensiveness in the sense that R&D activities in energy sectors need to intensively use “heavy” physical capital like hardware, equipments, and machines, thus creating a so-called “asset-heavy” pattern of innovation. To generate sustained energy technological progress, the “asset-heavy” innovation pattern requires allocating more and more resources from production outputs to finance R&D spending (Fri, 2003; Grubb, 2004; Worrell and Biermans, 2005; Sagar and van der Zwaan, 2006; Gallagher et al., 2006; Grübler et al., 1999, 2012). Accordingly, in our model the innovation possibility frontier (IPF) of energy technology R&D takes the form as

$$\dot{N}_E(t) = \eta \cdot R_E(t) \quad , \quad (10)$$

where starting with some initial stock $N_E(0)$, energy technology variety $N_E(t)$ is augmented by energy R&D spending $R_E(t)$, and greater spending on energy R&D leads to more invention of new energy technology variety. η is the sector-wide efficiency of undertaking R&D, with a large number of different research firms undertaking uncertain R&D, there is no aggregate uncertainty of R&D for the whole sector. Consider the case in which there is a positive amount of energy R&D spending and thus technological progress in energy sectors, the IPF implies the free-entry condition (FEC) of energy R&D which takes the form as

$$\eta \cdot V_E(i, t) = 1 \quad , \quad (11)$$

where one unit of energy R&D spending generates a flow rate η of new variety of primary energy technology blueprints, each with a market value given by Eq. (8).

Finally, the end-use energy products satisfy the market clearing condition at each point in time,

$$C_E(t) + X_E(t) + R_E(t) = Y_E(t) \quad , \quad (12)$$

where the market clearing imply that the outputs of final energy goods Y_E serve household energy consumption C_E , spending on intermediate primary energy inputs X_E , and spending on energy R&D R_E . In explicit, C_E is given by the household problem given in Eq. (1), R_E is determined by the IPF of energy R&D given in Eq. (10), and the expenditure on intermediate primary energy input takes a form as

$$X_E(t) = \int_0^{N_E(t)} \psi \cdot x_E(i, t) \cdot di \quad . \quad (13)$$

where one unit of each variety of primary energy input is produced and supplied at the marginal cost of ψ in unit of the end-use energy goods (the numeraire).

2.3 IT Sectors

Relative to the homogeneity of end-use energy goods, IT products are substantially differentiated and heterogeneous in their attributes, characteristics and functions. Research leads to invention of new, differentiated IT-related consumer products that are valued directly by the household with love-for-variety preferences: the larger the number of the variety of IT products, the higher the utility derived from consumption. Technological progress in IT sectors can thus be viewed as a form of product innovation. Accordingly, the composite of IT product is specified as a CES aggregate of differentiate IT product varieties,

$$C_T(t) = \left[\int_0^{N_T(t)} c_T(j, t)^{\frac{\varepsilon_T - 1}{\varepsilon_T}} dj \right]^{\frac{\varepsilon_T}{\varepsilon_T - 1}}, \quad (14)$$

where $C_T(t)$ is the aggregate consumption of IT product composite at time t , and $c_T(j, t)$ is the consumption of IT product specific to individual variety $j \in [0, N_T(t)]$. $N_T(t)$ is the number of differentiated IT product varieties, with ε_T denoting the elasticity of substitution between different varieties of IT products. Since IT products with substantial heterogeneity in attributes and functions are weakly substitutable in serving the household with love-for-variety preference, the value of ε_T is sufficiently lower. For our exposition technological progress in IT sector is thus characterized by the expanding variety of IT products.

Given the Dixit-Stiglitz preference, the isoelastic demand function for individual IT product variety $j \in [0, N_T(t)]$ is given by

$$c_T(j, t) = \left[\frac{p_T(j, t)}{P_T(t)} \right]^{-\varepsilon_T} \cdot C_T(t), \quad (15)$$

with the ideal price index of IT product composite

$$P_T(t) = \left[\int_0^{N_T(t)} p_T(j, t)^{1-\varepsilon_T} dj \right]^{\frac{1}{1-\varepsilon_T}}, \quad (16)$$

where $p_T(j, t)$ is the price of IT product specific to a particular variety $j \in [0, N_T(t)]$.

Due to the fact that the differentiated variety of IT consumer products are enjoyed directly by the love-for-variety household, the demand for IT product of the variety $j \in [0, N_T(t)]$ at each point in time is equal to the output supply of the corresponding IT firm that produces with a linear production function,

$$c_T(j, t) = y_T(j, t) = l_{TP}(j, t) \quad , \quad (17)$$

where $y_T(j, t)$ is the output of IT monopolistic firm supplying the corresponding IT product variety $j \in [0, N_T(t)]$ at time t , and $l_{TP}(j, t)$ is the workforce employed by this IT firm.

Meanwhile, the IT firm inventing the blueprint of a particular variety of IT consumer products possesses a perpetual monopoly power within a fully-enforced patenting system, thus the net present discounted value of the monopolist firm owning each IT product variety $j \in [0, N_T(t)]$ takes the form as:

$$\begin{aligned} V_T(j, t) &= \int_t^\infty \exp\left[-\int_t^s r(s') \cdot ds'\right] \cdot \pi_T(j, s) \cdot ds \\ \text{s.t.} \quad \pi_T(j, s) &= p_T(j, s) \cdot c_T(j, s) - w(s) \cdot l_{TP}(j, s) \end{aligned} \quad (18)$$

where $w(t) \cdot l_{TP}(j, t)$ is the labor costs of the firm to produce a quantity $c_T(j, t)$ of output given the linear production function and the wage rate at time t $w(t)$. $p_T(j, s) \cdot c_T(j, s)$ is output sales revenue, which is consistent with the isoelastic demand function [Eq. \(15\)](#). Alternatively, the market value of each IT firm [Eq. \(18\)](#) can be rewritten in the HJB form,

$$r(t) \cdot V_T(j, t) = \dot{V}_T(j, t) + \pi_T(j, t) \quad (19)$$

where [Eq. \(19\)](#) characterizes the inter-temporal no-arbitrage condition for the market value of each IT monopolistic firms producing the corresponding differentiated variety of IT product.

As compared to the “asset-heavy” innovation pattern of energy technology, IT technology is often characterized by a lower intensity of heavy physical assets and a higher intensity of intangible assets like ideas, skills, and knowledge. For example, new-generation IT technologies are increasingly intertwined with digital software and programs, internet, and wireless network that *de facto* are free of heavy physical asset, creating a so-called “asset-light” mode of innovation. Accordingly, relative to energy technological innovation that intensively uses heavy capital such as hardware, equipments, and machines, innovation in IT sectors tends to employ workforces such as researchers as the key factors of undertaking R&D and knowledge creation. Moreover, given that R&D workforces are often scarce factors, IT sectors cannot sustain technological progress unless there is technology spillovers, making the scarce factors used in R&D increasingly productive over time ([Dewan and Min. 1997](#); [Jorgenson and Stiroh, 1999](#); [Samuelson and Varian 2002](#); [Brynjolfsson and Hitt 2000](#); [Varian 2000](#); [Bakos and Brynjolfsson 1999](#)). Accordingly, the innovation possibility frontier in IT sectors describing the law of motion of IT product variety takes the form as:

$$\dot{N}_T(t) = \eta \cdot N_T(t) \cdot L_{TR}(t) \quad , \quad (20)$$

where $L_{TR}(t)$ is the amount of workforce allocated to undertake R&D and knowledge creation in IT sectors, and the term $N_T(t)$ on the right-hand side captures knowledge spillovers from the existing technology stock. The larger the existing stock of technology, the higher the productivity of current R&D workforce to create new knowledge - “standing on the shoulder of past giants.” The IPF further implies the free entry condition (FEC) of R&D for creating new IT technology variety,

$$\eta \cdot N_T(t) \cdot V_T(j, t) = w(t) \quad , \quad (21)$$

where the left-hand side is the return from hiring one more workforce to undertake R&D for creating new IT product variety, which depends on the rate of variety expansion $\eta \cdot N_T(t)$ and the market value of IT product variety $V_T(j, t)$.⁹ The RHS is the cost of employing one more workforce for R&D, that is, the equilibrium wage rate w .

Finally, given that the workforces employed in IT sectors are allocated to both conventional output production and R&D-related technology creation, the labor market clearing condition in IT sector should satisfy

$$\int_0^{N_T(t)} l_{TP}(j, t) \cdot dj + L_{TR}(t) = L_{TP}(t) + L_{TR}(t) = L \quad . \quad (22)$$

where $l_{TP}(j, t)$ is the workforce employed to produce each IT product variety $j \in [0, N_T(t)]$, $L_{TP}(t), L_{TR}(t)$ are the workforce employed for conventional output production and new technology R&D, which sums up to the total amount of workforce endowment in IT sector L .

3. Characterization of Market Equilibrium

Given the above-described model, a decentralized market equilibrium is defined as an allocation in which energy and IT firms choose $[p_E(i, t), x_E(i, t), p_T(j, t), c_T(j, t)]_{i \in [0, N_E(t)], j \in [0, N_T(t)], t=0}^{\infty}$ to maximize their market values (Eq. (8), (18)), the dynamics of the market values of energy and IT

⁹ This market-driven view that profit opportunities are the primary determinant of innovation is articulated in the seminal work of [Schmookler \(1962, 1966\)](#), arguing that innovation is largely an economic activity which, like other economic activities, is pursued for profit gains. The studies by [Griliches \(1957\)](#), and [Griliches and Schmookler \(1963\)](#) also provide empirical supports for the market-driven perspective that technological innovation is closely linked to the profitability in commercial markets. Similar conclusions are also reached in more recent studies, especially in the induced innovation literature. For example, [Lichtenberg \(1986\)](#), [Jaffe and Palmer \(1997\)](#), [Newell et al. \(1999\)](#), [Goulder and Schneider \(1999\)](#), [Grubb et al. \(2002\)](#), [Popp \(2002\)](#), and [Acemoglu \(2002\)](#).

monopolistic firms $[V_E(i, t), V_T(j, t)]_{i \in [0, N_E(t)], j \in [0, N_T(t)], t=0}^\infty$ are determined by the HJB equations (Eq. (9), (19)), the number of energy technology and IT variety $[N_E(t), N_T(t)]_{t=0}^\infty$ evolves according to innovation possibility frontier (Eq. (10), (20)) and free entry conditions of R&D (Eq. (11), (21)), the evolution of household's energy consumption $[C_E(t)]_{t=0}^\infty$, spending on intermediate primary energy inputs $[X_E(t)]_{t=0}^\infty$, energy R&D expenditure $[R_E(t)]_{t=0}^\infty$, and final energy goods outputs $[Y_E(t)]_{t=0}^\infty$ is consistent with energy market clearing condition (Eq. (12)), the evolution of demand for and supply of IT product variety $[c_T(j, t), y_T(j, t)]_{j \in [0, N_T(t)], t=0}^\infty$ is consistent with IT market clearing condition (Eq. (17)), the evolution of workforce employment $[l_{TP}(j, t), L_{TR}(t)]_{j \in [0, N_T(t)], t=0}^\infty$ is consistent with labor market clearing condition (Eq. (22)), and the evolution of interest rate and wage rate $[r(t), w(t)]_{t=0}^\infty$ is consistent with market clearing.

Characterization of the market equilibrium begins with the demand side of the model. Solving the household's problem yields the dynamic equation that characterizes the time path of household consumption of final-use, secondary energy goods (see [Appendix A](#) for derivation),

$$\frac{\dot{C}_E(t)}{C_E(t)} = r(t) - \rho, \quad (23)$$

and the time path of the aggregate consumption of IT product composite,

$$\frac{\dot{C}_T(t)}{C_T(t)} + \frac{\dot{P}_T(t)}{P_T(t)} = r(t) - \rho. \quad (24)$$

Turn to the supply side. Recall that, each energy monopolistic firm owning the blueprint of each differentiated variety of primary energy technology is motivated to maximize the intertemporal flow profits given in Eq. (8), which requires the maximization of instantaneous flow profit at each point in time. By solving this problem, the profit-maximizing choices of price, quantity, and profits made by primary energy firms can be determined, which is summarized by the following result.

Lemma 1 *In the above-described model that features endogenous technological progress with an expanding variety of energy technology, given the isoelastic demand for primary energy input as given by Eq. (7), the energy monopolistic firm that produces and supplies each differentiated variety $i \in [0, N_E(t)]$ of primary energy would charge a pricing rule as a constant markup over their marginal cost of production,*

$$p_E(i, t) = \frac{\varepsilon_E}{\varepsilon_E - 1} \psi = 1, \quad (25)$$

where ψ denotes the marginal cost of producing each primary energy input (in unit of the numeraire final

energy goods), we set $\psi \equiv 1 - \varepsilon_E^{-1}$ for normalization. Primary energy firm produces and supplies each variety of primary energy input with a quantity of

$$x_E(i, t) = p_E(i, t)^{-\varepsilon_E} \cdot L = L \quad , \quad (26)$$

and obtain instantaneous flow profit,

$$\pi_E(i, t) = p_E(i, t) \cdot x_E(i, t) - \psi \cdot x_E(i, t) = \varepsilon_E^{-1} L \quad , \quad (27)$$

where the profit-maximizing choices of price, quantity, and profits are independent on primary energy varieties, i.e., $p_E(i, t) = p_E(t) = 1$, $x_E(i, t) = x_E(t) = L$, and $\pi_E(i, t) = \pi_E(t) = \varepsilon_E^{-1} L$ for all primary energy variety $i \in [0, N_E(t)]$.

Proof. Given $x_E(i, t) = p_E(i, t)^{-\varepsilon_E} \cdot L$, taking F.O.C. of profit flow $\pi_E(i, s) = [p_E(i, s) - \psi] \cdot x_E(i, s)$ with respect to $p_E(i, t)$ yields $p_E(i, t)^{-\varepsilon_E} \cdot L + [p_E(i, s) - \psi] \cdot (-\varepsilon_E) \cdot p_E(i, s)^{-\varepsilon_E - 1} L = 0$, from which we obtain the profit-maximizing pricing rule $p_E(i, t) = \varepsilon_E \cdot \psi / (\varepsilon_E - 1)$. Once the profit-maximizing choice of price is determined, it is straightforward to pin down the profit-maximizing choices of quantity, and profits as given in Eqs. (26)-(27). ■

Based on the Lemma 1, aggregating the whole set of primary energy inputs varieties obtains the total outputs of end-use, secondary energy products

$$Y_E(t) = \frac{1}{1-a} \left[\int_0^{N_E(t)} x_E(i, t)^{1-a} di \right] \cdot L^a = \frac{\varepsilon_E}{\varepsilon_E - 1} \cdot L \cdot N_E(t) \quad , \quad (28)$$

and the total expenditures on intermediate primary energy inputs

$$X_E(t) = \int_0^{N_E(t)} \psi \cdot x_E(i, t) \cdot di = \frac{\varepsilon_E - 1}{\varepsilon_E} \cdot L \cdot N_E(t) \quad . \quad (29)$$

Proceeding analogously, consider IT sectors where each monopolistic firm owning the blueprint of each differentiated IT product variety is motivated to maximize the intertemporal flow profits given in Eq. (18), which requires the maximization of instantaneous flow profit at each point in time. By solving the problem of profit maximization, the endogenous choices of price, quantity, and profits are summarized by the following result.

Lemma 2 *In the above-described model that features endogenous technological progress with an expanding variety of IT, given the isoelastic demand for IT product variety as given by Eq. (15), IT monopolistic firms that produce each IT product variety $j \in [0, N_T(t)]$ charge the profit-maximizing pricing rule as,*

$$p_T(j, t) = p_T(t) = \frac{\varepsilon_T}{\varepsilon_T - 1} \cdot w(t) , \quad (30)$$

where the monopoly price is a constant markup over the wage rate (the marginal cost of production). The IT firms produces and supplies each variety of IT product with a quantity of

$$c_T(j, t) = \left[\frac{p_T(j, t)}{P_T(t)} \right]^{-\varepsilon_T} \cdot C_T(t) = c_T(t) = \frac{L_{TP}(t)}{N_T(t)} , \quad (31)$$

and obtains the instantaneous flow profit,

$$\pi_T(j, t) = p_T(j, t) \cdot c_T(j, t) - w(t) \cdot c_T(j, t) = \frac{1}{\varepsilon - 1} \cdot w(t) \cdot \frac{L_{TP}(t)}{N_T(t)} . \quad (32)$$

Proof. Given that the price charged $p_T(j, t)$ is independent of product variety $j \in [0, N_T(t)]$, both the output of each IT product variety $c_T(j, t) = [p_T(j, t) / P_T(t)]^{-\varepsilon_T} \cdot C_T(t) = c_T(t)$ and the input of workforce employed by IT firms $c_T(j, t) = l_{TP}(j, t) = l_{TP}(t)$ are independent of IT product variety $j \in [0, N_T(t)]$. The labor market clearing condition in IT sector [Eq. \(22\)](#) thus implies that, $N_T(t) \cdot l_{TP}(t) + L_{TR}(t) = L_{TP}(t) + L_{TR}(t) = L$. With $L_{TP}(t)$ denoting the total amount of workforce employed in IT sector for output production, we obtain the amount of output of individual IT product variety $c_T(j, t) = c_T(t) = L_{TP}(t) / N_T(t)$ for all $j \in [0, N_T(t)]$. Given $p_T(j, t), c_T(j, t)$ are independent of product variety $j \in [0, N_T(t)]$, [Eq. \(18\)](#) implies that both instantaneous flow profits and the market values of each IT monopolistic firm are independent of IT product varieties, $\pi_T(j, t) = \pi_T(t), V_T(j, t) = V_T(t)$. ■

Based on the output of each individual variety of IT product given in [Eq. \(31\)](#), the amount of aggregate consumption of IT product composite is determined by,

$$C_T(t) = \left[\int_0^{N_T(t)} c_T(j, t)^{\frac{\varepsilon_T - 1}{\varepsilon_T}} dj \right]^{\frac{\varepsilon_T}{\varepsilon_T - 1}} = N_T(t)^{\frac{\varepsilon_T}{\varepsilon_T - 1}} \cdot c_T(t) = L_{TP}(t) \cdot N_T(t)^{\frac{1}{\varepsilon_T - 1}} , \quad (33)$$

and the corresponding ideal price index of the IT product composite is given by,

$$P_T(t) = \frac{\varepsilon_T}{\varepsilon_T - 1} \cdot w(t) \cdot N_T(t)^{\frac{1}{1 - \varepsilon_T}} . \quad (34)$$

4. Balanced Growth Path

We continue to characterize the balanced growth path (BGP) of the model. The BGP is defined as the steady state of this above-described market equilibrium where energy goods consumption $C_E(t)$ and production output $Y_E(t)$, and the number of primary energy variety $N_E(t)$ grow at a constant rate. The BGP also requires that consumption of IT product composite $C_T(t)$ and the number of IT product variety $N_T(t)$ grow at a constant rate.

We start with characterizing the BGP in energy sectors. The FEC of energy R&D Eq. (11) implies that the market value is constant $\dot{V}_E^* = 0$ in the BGP, Eq. (27) implies that the current flow profit is constant $\dot{\pi}_E^* = 0$, and the market interest rate is constant. The HJB equation of the market value Eq. (9) thus implies that the BGP level of the market value of each primary energy firm takes the form, $V_E^* = \pi_E^* / r^* = \varepsilon_E^{-1} L / r^*$, where the asterisk (*) refers to the corresponding BGP values. Substituting it into the FEC of R&D, Eq. (11), the BGP level of market interest rate is given by,

$$\eta \cdot \frac{\varepsilon_E^{-1} L}{r^*} = 1 \Rightarrow r^* = \frac{\eta L}{\varepsilon_E} \quad , \quad (35)$$

Substituting Eq. (35) into Eq. (23) yields the BGP growth rate of household consumption of final energy goods,

$$g_{C_E}^* \equiv \frac{\dot{C}_E^*}{C_E^*} = r^* - \rho = \frac{\eta L}{\varepsilon_E} - \rho \quad . \quad (36)$$

Given that the energy market clearing condition always holds $C_E(t) + X_E(t) + R_E(t) = Y_E(t)$, we obtain that final energy consumption should grow at the same rate as the output of energy goods in the BGP.¹⁰ Furthermore, Eq. (28) implies that the BGP growth rate of final energy goods outputs is equal to that of energy technology variety,

$$g_E^* = g_{C_E}^* = g_{Y_E}^* = g_{N_E}^* = \frac{\eta L}{\varepsilon_E} - \rho \quad , \quad (37)$$

¹⁰ Differentiating the energy market clearing condition Eq. (12) with respect to time t obtains $(C_E(t)/Y_E(t)) \cdot g_{C_E}(t) + (X_E(t)/Y_E(t)) \cdot g_{X_E}(t) + (R_E(t)/Y_E(t)) \cdot g_{R_E}(t) = g_{Y_E}(t)$, where $g_{C_E}(t) \equiv \dot{C}_E(t)/C_E(t)$, $g_{X_E}(t) \equiv \dot{X}_E(t)/X_E(t)$, $g_{R_E}(t) \equiv \dot{R}_E(t)/R_E(t)$, $g_{Y_E}(t) \equiv \dot{Y}_E(t)/Y_E(t)$ is the growth rate of C_E , X_E , R_E , and Y_E at time t, respectively. Household energy consumption, spending on intermediate energy inputs, energy R&D expenditure, final energy goods outputs, and energy technology varieties thus all grow at the same rate in the BGP, $g_{C_E}^* = g_{X_E}^* = g_{R_E}^* = g_{Y_E}^* = g_{N_E}^* = g_E^*$, where the asterisk (*) refers to the BGP values.

where $g_{Y_E}^* \equiv \dot{Y}_E^* / Y_E^*$, $g_{C_E}^* \equiv \dot{C}_E^* / C_E^*$, $g_{N_E}^* \equiv \dot{N}_E^* / N_E^*$ denote the BGP growth rate of end-use energy outputs, final energy consumption, and primary energy technology variety, respectively.

Turn to the characterization of the BGP in IT sector. Substituting the flow profit [Eq. \(32\)](#) into the FEC of R&D [Eq. \(21\)](#) obtains $\eta \cdot L_{TP}(t) \cdot V_T(t) = (\varepsilon_T - 1) \cdot \pi_T(t)$. Given that the amount of workforce allocated for IT production L_{TP}^* remains constant in the BGP, thus flow profits and market values have the same BGP growth rates, $g_{\pi_T}^* = g_{V_T}^*$, where $g_{\pi_T}^* \equiv \dot{\pi}_T^* / \pi_T^*$, $g_{V_T}^* \equiv \dot{V}_T^* / V_T^*$ are the BGP growth rate of flow profits and market values of each IT monopolistic firm, respectively, and the asterisk (*) corresponds to BGP values. Moreover, the FEC of R&D [Eq. \(21\)](#) implies $g_{N_T}^* + g_{V_T}^* = g_w^*$, where $g_{N_T}^* \equiv \dot{N}_T^* / N_T^*$ is the BGP growth rate of the number of IT variety, and $g_w^* \equiv \dot{w}^* / w^*$ the BGP growth rate of wage rate. Given that the market value grow at a rate of $g_{V_T}^*$ in the BGP $\dot{V}_T^* = g_{V_T}^* \cdot V_T^*$, the HJB [Eq. \(19\)](#) implies that the BGP market value owned by each IT firm is equal to $V_T^* = \pi_T^* / (r^* - g_{V_T}^*) = \pi_T^* / (r^* - g_w^* + g_{N_T}^*)$. Accordingly, we obtain the following condition that should satisfy in the BGP,

$$\eta \cdot L_{TP}^* = (\varepsilon_T - 1) \cdot (r^* - g_w^* + g_{N_T}^*) \quad , \quad (38)$$

where $g_{N_T}^* \equiv \dot{N}_T^* / N_T^* = \eta \cdot L_{TR}^* = \eta \cdot (L - L_{TP}^*)$ is the BGP growth rate of the number of IT variety given by the IPF for IT sector [Eq. \(20\)](#), and the household budget constraint requires that the BGP growth rate of wage rate should be equal to the growth rate of consumption, $g_w^* = r^* - \rho$. Based on [Eq. \(38\)](#), the BGP amount of workforce employed in IT sectors for conventional output production and new technology R&D is determined by,

$$L_{TP}^* = \frac{(\varepsilon_T - 1) \cdot (\rho + \eta L)}{\varepsilon_T \cdot \eta} \quad , \quad L_{TR}^* = \frac{\eta L - (\varepsilon_T - 1) \cdot \rho}{\varepsilon_T \cdot \eta} \quad . \quad (39)$$

We thus obtain the BGP growth rate of the number of IT variety

$$g_{N_T}^* \equiv \frac{\dot{N}_T^*}{N_T^*} = \eta \cdot L_{TR}^* = \frac{\eta L - (\varepsilon_T - 1) \cdot \rho}{\varepsilon_T} \quad , \quad (40)$$

and the BGP growth rate of consumption of IT product (according to [Eq. \(33\)](#))

$$g_{C_T}^* \equiv \frac{\dot{C}_T^*}{C_T^*} = \frac{1}{\varepsilon_T - 1} \cdot g_{N_T}^* = \frac{1}{\varepsilon_T - 1} \cdot \frac{\eta L - (\varepsilon_T - 1) \cdot \rho}{\varepsilon_T} \quad . \quad (41)$$

These results concerning the BGP are summarized in the next proposition.

Proposition 1 *In the above-described model that features endogenous technological progress with an expanding variety of energy technology and IT, there is a BGP in which the consumption of end-use secondary energy goods and the number of primary energy technology variety grow at a rate of g_E^* given by Eq. (37). The BGP also requires that consumption of IT products grows at a rate of g_{CT}^* given by Eq. (41), and the number of IT varieties increases at a rate of g_{NT}^* given by Eq. (40). In particular, given that the elasticity of substitution of primary energy input variety is much larger than that of IT product variety, i.e., $\varepsilon_E \gg \varepsilon_T$, the BGP growth rates of IT product consumption and technology variety are strictly larger than that rate of energy goods consumption and technology variety. Moreover, in the BGP the price index of IT product composite would decrease over time, while the price of end-use, secondary energy products remains relatively stable.*

Proof. See [Appendix B](#). ■

[Proposition 1](#) suggests that in the long-run sustained growth IT-related product consumption and technology variety tend to increase at a faster pace as compared to energy goods consumption and technology variety. The fundamental reasons are as follows. Innovation in energy sectors is generally characterized by a form of process innovation, that is, although R&D leads to new variety of differentiated primary energy, the end-use, secondary energy products (electric utility) converted by these differentiated primary energy inputs are substantially homogeneous in functions. Therefore, energy innovation consists simply of new ways of converting energy from primary to end-use, secondary forms without creating new differentiated end-products to harness the love-for-variety effect in market fundamentals. As a result, primary energy inputs become strongly substitutable in the process of producing end-use energy products, and new variety of renewable primary energy like solar and wind is more likely to be replaced by incumbent variety of fossil-based energy like coal and gas, thus slowing the pace of creating new energy technology variety.

In contrast, innovation in IT sectors features a form of product innovation in the sense that new variety of IT products created by innovation are generally new end-use products with differentiated functions that create differentiated markets for them, and the household with a love-for-variety preference can derive greater utility when consuming a greater variety of them. As a result, the differentiated varieties of IT products are weakly substitutable, and new variety of IT product is less likely to be replaced by incumbent IT product variety. The love-for-variety effect embedded in the preferences thus creates a pecuniary externality that potentially stimulates consumption of IT-related products and creation of new IT variety.

5. Transitional Dynamics

This section will show that there is no transitional dynamics in the above-described model. Given that the flow profit $\pi_E(i, t)$ is independent of primary energy variety as given in Eq. (27), the market value of energy firms is independent of primary energy variety and takes the form as

$$r(t) \cdot V_E(t) - \dot{V}_E(t) = \pi_E(t) = \varepsilon_E^{-1} L \quad . \quad (42)$$

Meanwhile, the FEC of energy R&D requires that $\eta \cdot V_E(t) = 1$ for all time t when there is positive spending on R&D for energy technological progress, which implies that $\dot{V}_E(t) = 0$ for all time t . Substituting it into Eq. (42) yields $r(t) = \varepsilon_E^{-1} \eta L$ for each point in time t , which is the same as the market interest rate r^* in the BGP.

Turn to IT sectors, Eq. (32) implies that the current flow profit of each IT monopolistic firm is independent of product varieties $\pi_T(t) = \pi_T(j, t)$, the market value Eq. (19) thus takes the form as,

$$r(t) \cdot V_T(t) - \dot{V}_T(t) = \pi_T(t) \quad , \quad (43)$$

and rearranging Eq. (43) obtains

$$V_T(t) = \frac{\pi_T(t)}{r(t) - g_{V_T}(t)} \quad , \quad (44)$$

where $g_{V_T}(t) \equiv \dot{V}_T(t) / V_T(t)$ is the growth rate of the market value of IT monopolistic firms at time t . From the FEC of IT R&D Eq. (21), we have $g_{N_T}(t) + g_{V_T}(t) = g_w(t)$, where $g_{N_T}(t)$, $g_{V_T}(t)$, $g_w(t)$ is the growth rate of IT technology variety, market value, and wage rate at time t , respectively. Plugging it into Eq. (44) obtains

$$V_T(t) = \frac{\pi_T(t)}{r(t) - g_w(t) + g_{N_T}(t)} \quad . \quad (45)$$

Then substituting the flow profit Eq. (32) into the FEC of R&D Eq. (21) into Eq. (45) obtains

$$\eta \cdot L_{TP}(t) = (\varepsilon_T - 1) \cdot [r(t) - g_w(t) + g_{N_T}(t)] \quad . \quad (46)$$

Plugging the innovation possibility frontier of IT technology Eq. (20) and the growth rate of wage rate $g_w(t) = r(t) - \rho$ into Eq. (46), we derive the amount of workforce employed in IT sectors for output production and technology research in transitional dynamics periods,

$$L_{TP}(t) = \frac{(\varepsilon_T - 1) \cdot (\rho + \eta L)}{\varepsilon_T \cdot \eta} \quad L_{TR}(t) = \frac{\eta L - (\varepsilon_T - 1) \cdot \rho}{\varepsilon_T \cdot \eta} \quad , \quad (47)$$

which are the same as those in the BGP given in Eq. (39). Based on Eq. (47), we derive the growth rate of IT technology varieties $g_{N_T}(t) \equiv \dot{N}_T(t) / N_T(t)$ and product consumption $g_{C_T}(t) \equiv \dot{C}_T(t) / C_T(t)$ for each point in time during the transitional dynamics, which are the same as those rates in the BGP. These results can be summarized in the following proposition.

Proposition 2 *In the above-described model that features endogenous technological progress with an expanding variety of energy technology and IT, given the initial stock of energy technology and IT variety $N_E(0), N_T(0)$, there is a market equilibrium path in which the number of energy technology variety $N_E(t)$ grows at a rate of $g_{E_T}^*$ given in Eq. (37), and the number of IT variety $N_T(t)$ grows at a rate of $g_{N_T}^*$ given in Eq. (40).*

Proof. The preceding discussion can establish all the claims in this proposition.

6. Social Optimal Allocation

In the above-described decentralized market equilibrium, monopolistic firms in both energy and IT sectors charge a markup in supplying their differentiated variety of primary energy input and IT product. The presence of monopoly markup in the market equilibrium thus leads to a Pareto suboptimal outcome where the number of technology variety used in the economy is not necessarily socially optimal. Then a next key issue arises: can a social planner achieve an outcome in which energy technology advances faster than IT? This issue will be addressed in this section.

To contrast the market equilibrium and social optimal allocation, we set up the social planner problem that maximizes the utility of the representative household Eq. (1), subject to market clearing conditions Eq. (12), (17), and the innovation possibility frontier Eq. (10), (20), with initial technology conditions $N_E(0), N_T(0)$. The social planner chooses the optimal time paths of product consumption $[C_E^S(t), C_T^S(t)]_{t=0}^{\infty}$ and technology variety $[N_E^S(t), N_T^S(t)]_{t=0}^{\infty}$, where superscript “S” corresponds to the social optimum.

We proceed to rewriting the energy market clearing condition as

$$C_E^S(t) + R_E^S(t) = Y_E^S(t) - X_E^S(t) = \frac{1}{1-a} \left[\int_0^{N_E(t)} x_E^S(i, t)^{1-a} di \right] \cdot L^a - \int_0^{N_E(t)} \psi \cdot x_E^S(i, t) \cdot di \quad , \quad (48)$$

where the first term on the right-hand side is the output of final energy goods Eq. (3), and the second

term is expenditure on intermediate primary energy inputs Eq. (13). Given the number of energy technology variety $N_E(t)$, a static maximization of the right-hand side of Eq. (48) gives the social optimal level of using individual primary energy input variety $i \in [0, N_E(t)]$,

$$x_E^S(i, t) = (1 - \varepsilon_E^{-1})^{-\varepsilon_E} \cdot L \quad . \quad (49)$$

Substituting Eq. (49) into Eq. (48) obtains the energy market clearing condition

$$C_E^S(t) + R_E^S(t) = (1 - \varepsilon_E^{-1})^{-\varepsilon_E} \varepsilon_E^{-1} L \cdot N_E^S(t) \quad . \quad (50)$$

Meanwhile, for the market clearing condition in IT sector, the demand for each IT product variety $j \in [0, N_T(t)]$ at each point in time is equal to the output supply of the corresponding IT firm with a linear production function $c_T(j, t) = y_T(j, t) = l_{TP}(j, t)$. The social planner maximizes the aggregate demand for IT product composite,

$$C_T(t) = \left[\int_0^{N_T(t)} c_T(j, t)^{\frac{\varepsilon_T-1}{\varepsilon_T}} dj \right]^{\frac{\varepsilon_T}{\varepsilon_T-1}} = \left[\int_0^{N_T(t)} l_{TP}(j, t)^{\frac{\varepsilon_T-1}{\varepsilon_T}} dj \right]^{\frac{\varepsilon_T}{\varepsilon_T-1}} \quad , \quad (51)$$

subject to the constraint of workforce employed in IT sector for output production,

$$\int_0^{N_T(t)} l_{TP}(j, t) \cdot dj = L_{TP}(t) \quad . \quad (52)$$

Given $N_T(t)$, a static optimization yields the social optimal level of demand for each IT product variety $j \in [0, N_T(t)]$: $c_T^S(j, t) = c_T^S(t) = L_{TP}^S(t) / N_T^S(t)$. Substituting it into Eq. (51), the market clearing condition in IT sector implies that

$$C_T^S(t) = \left[\int_0^{N_T(t)} c_T^S(j, t)^{\frac{\varepsilon_T-1}{\varepsilon_T}} dj \right]^{\frac{\varepsilon_T}{\varepsilon_T-1}} = N_T^S(t)^{\frac{1}{\varepsilon_T-1}} \cdot L_{TP}^S(t) \quad . \quad (53)$$

The optimal growth path is a solution to the social planner problem of maximizing the utility of the representative household Eq. (1), subject to the market clearing conditions Eq. (50), (53), and the innovation possibility frontiers for both energy and IT technology R&D, $\dot{N}_E^S(t) = \eta \cdot R_E^S(t)$, $\dot{N}_T^S(t) = \eta \cdot N_T^S(t) \cdot L_{TR}^S(t) = \eta \cdot N_T^S(t) \cdot [L - L_{TP}^S(t)]$. Solving the social planner problem obtains the following result.

Proposition 3 *In the above-described model that features endogenous technological progress with an expanding variety of energy technology and IT, the decentralized market equilibrium is Pareto suboptimal. In the social optimal allocation, energy technology variety expands at a growth rate of*

$$g_{N_E}^S \equiv \frac{\dot{N}_E^S(t)}{N_E^S(t)} = \eta \cdot L \cdot \varepsilon_E^{-1} \cdot (1 - \varepsilon_E^{-1})^{-\varepsilon_E} - \rho \quad . \quad (54)$$

Given that $(1 - \varepsilon_E^{-1})^{-\varepsilon_E} > 1$ always holds when the elasticity of substitution is $\varepsilon_E > 1$, the social optimal growth rate of energy technology variety $g_{N_E}^S$ given in Eq. (54) is strictly larger than the market equilibrium growth rate of energy technology variety g_{N_E} given in Eq. (37). Meanwhile, in the social optimal allocation the number of IT product variety expands at a growth rate of

$$g_{N_T}^S = \frac{\dot{N}_T^S(t)}{N_T^S(t)} = \eta L - (\varepsilon_T - 1)\rho \quad , \quad (55)$$

which is also strictly greater than the market equilibrium growth rate of IT variety g_{N_T} given in Eq. (40) when the elasticity of substitution is $\varepsilon_T > 1$. Moreover, although the social planner can achieve an outcome in which the optimal growth rates of both energy technology and IT variety are strictly larger than their market equilibrium growth rates, energy technology still grows at a pace that is relatively lower than IT.

Proof. See Appendix C. ■

Proposition 3 provides the following economic intuitions. First, for technological progress in energy sectors with a form of process innovation, energy technology variety expands at a faster rate in social optimum. The source of inefficiency in market equilibrium is related to the monopoly markup charged by energy firms that supply differentiated intermediate primary energy inputs to the competitive final energy firms that produce homogenous secondary energy products (i.e., electricity). This monopoly markup lowers the potential demand for the number of differentiated primary energy input and thus the growth rate of energy technology – a so-called pecuniary externality. Since the social planner charges no markup for pursuing the greater social value of innovation, the social optimum involves using a larger number of differentiated primary energy input and thus a higher rate of energy technological progress.¹¹

Second, for technological progress in IT sectors feature a form of product innovation, the source of inefficiency in market equilibrium is not due to the markup charged by monopolistic IT firms that supply differentiated variety of end-use IT products, because there is no impact of price markup on IT product consumption by the household with love-for-variety preferences and thus no efficiency

¹¹ In the model, Eq. (49) gives the social optimal level of using individual primary energy variety, $x_E^S(i, t) = (1 - \varepsilon_E^{-1})^{-\varepsilon_E} L$. In contrast, in Eq. (7) the market equilibrium level of using each variety of primary energy input is given as $x_E(i, t) = L$. Given $\varepsilon_E > 1$, $x_E^S(i, t) > x_E(i, t)$ holds.

loss due to monopoly markup.¹² In fact, the source of inefficiency in IT sector is not because of the pecuniary externality isolated in energy sector but the non-pecuniary externality due to knowledge spillover. Given that the workforces such as researchers allocated to R&D are scarce factors, IT sector cannot sustain technological progress unless there is knowledge spillover - the current workforces “stand on the shoulders of past giants” and take advantage of the higher productivity of knowledge creation. Accordingly, in the market equilibrium IT firms disregard the non-pecuniary externality effect of their own efforts on raising the productivity of future innovative activity and undersupply the workforce for R&D. To internalize the technological externality due to knowledge spillovers, the social planner can achieve an efficiency-improving outcome by allocating more workforces to IT R&D.¹³ Hence the social optimal growth rate of IT variety is larger than that in the market equilibrium.

Finally, as compared to the varieties of IT products that are weakly substitutable in serving the love-for-variety household, the differentiated varieties of primary energy are largely substitutable given that they are used as intermediate inputs to produce homogeneous end-use secondary energy products. The larger possibility of substitution implies that the monopoly power of primary energy firms supplying each differentiated primary energy input would be weaker, and efficiency losses in energy sectors due to the presence of monopoly markup would be lower in the market equilibrium. In this case, when a social planner is introduced to correct for this distortion and improve efficiency, energy sectors can achieve an improvement in efficiency, but these efficiency gains would be small. Therefore, in the social optimum the variety of both energy technology and IT can grow faster than that in the market equilibrium, but energy technology still grows at a pace that is lower than IT.

7. Policy Intervention in Market Equilibrium

When the social planner solution still cannot achieve an outcome in which energy technology grows faster than IT, this section considers some policy interventions for achieving that outcome in market equilibrium. One possible public policy that accelerates energy technological progress in market equilibrium is subsidizing energy R&D through non-distortionary taxation. With subsidies to energy technology research, the free-entry condition (FEC) of energy R&D now takes the form as

¹² In the model, the structure of demand for individual IT product variety is the same between the social optimum and market equilibrium as given in Eq. (31).

¹³ In the model, the socially optimal amount of workforce allocated to IT R&D is equal to $L_{TR}^S(t) = L - (\varepsilon_T - 1)\eta^{-1}\rho$, as given in Eq. (C17) in Appendix C, and the market equilibrium amount of workforce allocated to IT R&D is equal to $L_{TR} = \varepsilon_T^{-1} \cdot [L - (\varepsilon_T - 1)\eta^{-1}\rho]$, as given in Eq. (39).

$$\eta \cdot V_E(i, t) = 1 - \tau_R \quad , \quad (56)$$

where τ_R is the rate of subsidies to energy technology R&D, that is, one unit of R&D spending costs private energy firms $1 - \tau_R$ units in the presence of R&D subsidy. R&D spending generates a flow rate η of new variety of energy technology blueprints, each with a market value given by Eq. (8). Given that the market value is equal to $V_E(t) = \pi(t) / r(t) = \varepsilon_E^{-1} L / r(t)$, substituting it into Eq. (56) obtains the market interest rate,

$$\eta \cdot \frac{\varepsilon_E^{-1} L}{r(t)} = 1 - \tau_R \Rightarrow r(t) = \frac{\eta \cdot L}{(1 - \tau_R) \cdot \varepsilon_E} \quad , \quad (57)$$

and the growth rate of energy technology variety,

$$g_{N_E} \equiv \frac{\dot{N}_E(t)}{N_E(t)} = r(t) - \rho = \frac{\eta \cdot L}{(1 - \tau_R) \cdot \varepsilon_E} - \rho \quad , \quad (58)$$

As compared with the growth rate of IT variety given in Eq. (40), energy technology variety can grow faster than IT variety in the market equilibrium when the rate of energy R&D subsidy is set to satisfy the following condition

$$\frac{\eta \cdot L}{(1 - \tau_R) \cdot \varepsilon_E} - \rho > \frac{\eta L - (\varepsilon_T - 1) \cdot \rho}{\varepsilon_T} \Rightarrow \tau_R > 1 - \frac{\varepsilon_T}{\varepsilon_E} \frac{\eta L + \rho}{\eta L} \quad . \quad (59)$$

Alternative policy intervention is subsidizing the use of intermediate primary energy inputs by secondary energy producers. Recall that, efficiency loss in energy markets stems from the fact that secondary energy firms do not use as many units of intermediate primary energy inputs as desired due to the monopoly markup charged by monopolistic energy firms. Accordingly, in the demand side subsidizing the use of intermediate primary energy inputs by secondary energy firms can boost invention of new primary energy technology in the supply side. With this kind of public subsidy, the demand for each variety of intermediate primary energy input takes the form as

$$x_E(i, t) = [(1 - \tau_P) \cdot p_E(i, t)]^{-\varepsilon_E} \cdot L \quad , \quad (60)$$

where τ_P is the rate of subsidy to use intermediate primary energy input by secondary energy producers. Given the isoelastic demand function Eq. (60), each energy monopolistic firm charges a profit-maximizing pricing $p_E(i, t) = \psi / (1 - a) = 1$ (setting $\psi \equiv 1 - a$ for normalization), produce each variety of primary energy goods with a quantity of $x_E(i, t) = (1 - \tau_P)^{-\varepsilon_E} \cdot L$, and obtain flow profit $\pi_E(i, t) = (1 - \tau_P)^{-\varepsilon_E} \cdot \varepsilon_E^{-1} \cdot L$. Substituting it into the FEC of energy R&D Eq. (11), the market

interest rate is determined by,

$$\eta \cdot \frac{(1-\tau_P)^{-\varepsilon_E} \cdot \varepsilon_E^{-1} \cdot L}{r(t)} = 1 \Rightarrow r(t) = (1-\tau_P)^{-\varepsilon_E} \varepsilon_E^{-1} \eta L, \quad (61)$$

and the growth rate of energy technology variety is given by

$$g_{N_E} \equiv \frac{\dot{N}_E(t)}{N_E(t)} = r(t) - \rho = (1-\tau_P)^{-\varepsilon_E} \varepsilon_E^{-1} \eta L - \rho. \quad (62)$$

As compared with the growth rate of IT given in Eq. (40), energy technology variety can grow faster than IT variety in the market equilibrium when the subsidy to use intermediate primary energy is set to satisfy the following condition

$$(1-\tau_P)^{-\varepsilon_E} \frac{\eta L}{\varepsilon_E} - \rho > \frac{\eta L - (\varepsilon_T - 1) \cdot \rho}{\varepsilon_T} \Rightarrow \tau_P > 1 - \left[\frac{\varepsilon_T}{\varepsilon_E} \frac{\eta L}{\rho + \eta L} \right]^{\frac{1}{\varepsilon_E}}. \quad (63)$$

8. Conclusion

A growing body of literature has pointed out the slow pace of energy technological progress as compared to other technologies like information technology (IT), but the underlying reasons why energy innovation is so slow still remain unexplained. This paper contributes to a rigorous economic exposition of the fundamental mechanism that explains the slow pace of energy technological innovation. Based on a variety-expanding endogenous technological change model, energy technological progress is described as the expanding variety of differentiated primary energy (i.e., coal, oil, gas, hydropower, solar, wind, geothermal, bioenergy) used to produce homogenous end-use, secondary energy goods (i.e., electric utility), and IT technological progress is represented as the expanding variety of differentiated end-use IT products that are directly valued by the household with a love-for-variety preference.

We show that in market equilibrium the growth rate of the number of energy technology variety is lower than that of IT variety. The key reasons are two-fold. First, although energy sector involves a variety of differentiated primary energy technology, end-use secondary energy goods (i.e., electric utility) consumed by the household have a substantial degree of homogeneity in terms of attributes and functions. Hence the effect of energy technological innovation is to increase the productivity of producing homogenous end-use, secondary energy products through an expanding variety of primary energy inputs (a form of process innovation). In contrast, end-use products in IT sectors are substantially heterogeneous in their attributes, characteristics and functions, and the effect of IT

innovation is thus creating new variety of IT products that are directly consumed and valued by the love-for-variety household (a form of product innovation). In the market fundamentals, since the household derives greater utility when consuming a greater variety of differentiated products, the heterogeneous IT products is more likely to harness the pecuniary externality embedded in the household's love-for-variety preference, thus stimulating demand for creation of new IT product variety. In contrast, the homogeneity of end-use, secondary energy good becomes an inhibiting factor that dampens the pecuniary externality and the incentive of creating new energy variety.

Second, in technological fundamental technology development in energy sectors is characterized by an intensive use of heavy assets like hardware, equipments, and machines, creating a so-called "asset-heavy" pattern of innovation. To sustain technological progress, energy sectors require allocating more and more resources from production outputs to finance R&D spending. The capital-intensiveness of energy technology with an intensive use of rival physical assets thus becomes the factor that inhibits the non-pecuniary externality due to knowledge spillovers, slowing the pace of energy technology invention and diffusion. In contrast, the "asset-light" mode of IT innovation with an intensive use of intangible assets like ideas, skills, and knowledge is more likely to harness the technological externality due to knowledge spillovers for sustained technological progress, thus achieving a faster growth of IT innovation and diffusion.

Moreover, a social planner solution can boost energy technological progress, but still cannot achieve an outcome in which energy technology advances faster than IT. In the market equilibrium, this monopoly markup charged by energy monopolistic firms lowers the potential demand for the number of differentiated primary energy input and thus the growth rate of energy technology. The social planner charges no markup for pursuing the greater social value of innovation, and the social optimum thus involves using a larger number of differentiated primary energy input and a higher rate of energy technological progress. However, relative to the variety of IT products that are weakly substitutable in serving the love-for-variety household, the differentiated varieties of primary energy are largely substitutable given that they are used as intermediate inputs to produce homogeneous end-use secondary energy products. The larger possibility of substitution implies that the monopoly power of energy firms supplying each differentiated primary energy input would be weak, and efficiency losses in energy sectors due to the presence of monopoly markup would be small in the market equilibrium. In this case, when a social planner is introduced to correct for this distortion and improve efficiency, energy sectors can achieve an improvement in efficiency, but these efficiency gains would be small. Therefore, in the social optimum the variety of both energy technology and IT can grow faster than that in the market equilibrium, but energy technology still grows at a pace that is lower than IT. Given that the social planner solution still cannot achieve an outcome in which energy technology grows faster than IT, some efficiency-improving policies can be applied in the

market equilibrium for accelerating the pace of energy technology progress. In particular, by targeting the subsidies on energy technology R&D and the use of intermediate primary energy inputs through non-distortionary taxation, the decentralized market equilibrium can achieve an outcome in which energy technology grows faster than IT.

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Appendix

Appendix A: Solving the Household Problem

Solving the household's problem requires setting the current-value Hamilton as,

$$H(C_T, C_E, A, \lambda) = \ln C_T(t) + \ln C_E(t) + \lambda(t) \cdot [r(t) \cdot A(t) + w(t) \cdot 2L - P_T(t) \cdot C_T(t) - C_E(t)] \quad (A1)$$

The first order condition necessary conditions with respect to four endogenous variables (control, state, co-state variables)

$$C_E : H_{C_E}(C_E, C_T, A, \lambda) = C_E(t)^{-1} - \lambda(t) = 0 \quad (A2)$$

$$C_T : H_{C_T}(C_E, C_T, A, \lambda) = C_T(t)^{-1} - \lambda(t) \cdot P_T(t) = 0 \quad (A3)$$

$$A : H_A(C_E, C_T, A, \lambda) = \lambda(t) \cdot r(t) = \rho \cdot \lambda(t) - \dot{\lambda}(t) \quad (A4)$$

$$\lambda : H_\lambda(C_E, C_T, A, \lambda) = r(t) \cdot A(t) + w(t) \cdot 2L - P_T(t) \cdot C_T(t) - C_E(t) = \dot{A}(t) \quad (A5)$$

Differentiating Eq. (A2) with respect to time t obtain

$$\frac{\dot{C}_E(t)}{C_E(t)} = -\frac{\dot{\lambda}(t)}{\lambda(t)} \quad (A6)$$

and differentiating Eq. (A3) with respect to time t obtain

$$\frac{\dot{P}_T(t)}{P_T(t)} + \frac{\dot{C}_T(t)}{C_T(t)} = -\frac{\dot{\lambda}(t)}{\lambda(t)} \quad (A7)$$

Substituting (A2) into (A6-A7) obtains the Euler equation of consumption of energy and IT products

$$\frac{\dot{C}_E(t)}{C_E(t)} = -\frac{\dot{\lambda}(t)}{\lambda(t)} = r(t) - \rho, \quad \frac{\dot{P}_T(t)}{P_T(t)} + \frac{\dot{C}_T(t)}{C_T(t)} = r(t) - \rho \quad (A8)$$

and the transversality condition

$$\lim_{t \rightarrow +\infty} A(t) \cdot \exp\left[-\int_0^t r(s) \cdot ds\right] = 0 \quad (\text{A9})$$

Appendix B: Proof of Proposition 1

The BGP growth rate of energy technology and IT variety $g_{N_E}^*$, $g_{N_T}^*$ is given by Eq. (41) and Eq. (47), and the difference in their growth rate is equal to

$$g_{N_T}^* - g_{N_E}^* = \frac{\eta L}{\varepsilon_T} - \rho + \frac{\rho}{\varepsilon_T} - \frac{\eta L}{\varepsilon_E} + \rho = \eta L \frac{\varepsilon_E - \varepsilon_T}{\varepsilon_T \varepsilon_E} + \frac{\rho}{\varepsilon_T}$$

Given that the differentiated variety in both energy and IT sector are gross substitutes, and the elasticity of substitution of primary energy input variety is sufficiently larger than that of IT product variety $\varepsilon_E \gg \varepsilon_T > 1$, we have $g_{N_T}^* > g_{N_E}^*$. Moreover, the BGP growth rate of the consumption of energy and IT products $g_{C_E}^*$, $g_{C_T}^*$ is given by Eq. (36) and Eq. (41), and the difference in their growth rate is equal to

$$g_{C_T}^* - g_{C_E}^* = \frac{\eta L}{\varepsilon_T(\varepsilon_T - 1)} - \frac{\rho}{\varepsilon_T} - \frac{\eta L}{\varepsilon_E} + \rho = \eta L \cdot \frac{\varepsilon_E - \varepsilon_T(\varepsilon_T - 1)}{\varepsilon_E \varepsilon_T(\varepsilon_T - 1)} + \rho \cdot \frac{\varepsilon_T - 1}{\varepsilon_T}$$

Given that $\varepsilon_E \gg \varepsilon_T > 1$, we have $g_{C_T}^* > g_{C_E}^*$. Finally, with the choice of treating the final-use energy good as the numeraire, there is thus no change in the price of end-use energy goods $g_{P_E}^* = 0$, and Eq. (34) implies that the BGP growth rate of the price of IT product composite is determined by

$$g_{P_T}^* \equiv \frac{\dot{P}_T^*}{P_T^*} = \frac{1}{1 - \varepsilon} g_{N_T}^* + g_w^* = \frac{\eta L - (\varepsilon_T - 1) \cdot \rho}{(1 - \varepsilon_T) \cdot \varepsilon_T} + \frac{\eta L}{\varepsilon_E} - \rho = \eta L \cdot \frac{\varepsilon_E + (1 - \varepsilon_T) \cdot \varepsilon_T}{(1 - \varepsilon_T) \cdot \varepsilon_T \cdot \varepsilon_E} + \rho \cdot \frac{1 - \varepsilon_T}{\varepsilon_T} < 0 \quad .$$

Given that $\varepsilon_E \gg \varepsilon_T > 1$, we obtain $g_{P_T}^* < g_{P_E}^*$.

Appendix C: Proof of Proposition 3

The social planner problem takes the form as

$$\max \int_0^\infty \exp(-\rho \cdot t) \cdot [InC_T^S(t) + InC_E^S(t)] \cdot dt \quad (\text{C1})$$

Subject to

$$\dot{N}_T^S(t) = \eta \cdot N_T^S(t) \cdot L_{TR}^S(t) = \eta \cdot N_T^S(t) \cdot [L - L_{TP}^S(t)] \quad (\text{C2})$$

$$\dot{N}_E^S(t) = \eta \cdot R_E^S(t) = \eta \cdot [(1 - \varepsilon_E^{-1})^{-\varepsilon} \cdot \varepsilon_E^{-1} \cdot L \cdot N_E^S(t) - C_E^S(t)] \quad (C3)$$

$$C_T^S(t) = N_T^S(t)^{\frac{1}{\varepsilon_T - 1}} \cdot L_{TP}^S(t) \quad (C4)$$

Substituting (B4) in the utility function, the current-value Hamilton is given by (we drop superscript “S” to simplify notation),

$$\begin{aligned} H(C_E, N_E, L_T^P, N_T) = & \ln C_E(t) + \ln(N_T(t)^{\frac{1}{\varepsilon_T - 1}} \cdot L_T^P(t)) \\ & + \lambda_E(t) \cdot \eta \cdot [(1 - \varepsilon_E^{-1})^{-\varepsilon} \cdot \varepsilon_E^{-1} \cdot L \cdot N_E(t) - C_E(t)] \\ & + \lambda_T(t) \cdot \eta \cdot N_T(t) \cdot [L - L_{TP}(t)] \end{aligned} ,$$

where C_E, L_{TP} are control variables, and N_E, N_T are state variables. The sufficient conditions for a maximum are the first-order conditions

$$C_E : \quad C_E(t)^{-1} - \lambda_E(t) \cdot \eta = 0 \quad , \quad (C5)$$

$$N_E : \quad \lambda_E(t) \cdot \eta \cdot (1 - \varepsilon_E^{-1})^{-\varepsilon} \cdot \varepsilon_E^{-1} \cdot L - \rho = \dot{\lambda}_E(t) \quad , \quad (C6)$$

$$L_{TP} : \quad L_T^P(t)^{-1} - \lambda_T(t) \cdot \eta \cdot N_T(t) = 0 \quad , \quad (C7)$$

$$N_T : \quad (\varepsilon_T - 1)^{-1} \cdot N_T(t)^{-1} + \lambda_T(t) \cdot \eta \cdot (L - L_{TP}(t)) = \rho \cdot \lambda_T(t) - \dot{\lambda}_T(t) \quad . \quad (C8)$$

Based on Eqs. (C5)-(C6), the growth rate of energy consumption in the social optimum is given by

$$\frac{\dot{C}_E(t)}{C_E(t)} = -\frac{\dot{\lambda}_E(t)}{\lambda_E(t)} = \eta \cdot L \cdot \varepsilon_E^{-1} \cdot (1 - \varepsilon_E^{-1})^{-\varepsilon} - \rho \quad . \quad (C9)$$

From the energy market clearing condition, we obtain that the growth rate for energy consumption in the optimal growth path must be equal to the growth rate of energy technology variety,

$$\frac{\dot{N}_E^S(t)}{N_E^S(t)} = \frac{\dot{C}_E^S(t)}{C_E^S(t)} = \eta \cdot \varepsilon_E^{-1} \cdot (1 - \varepsilon_E^{-1})^{-\varepsilon} \cdot L - \rho \quad . \quad (C10)$$

To solve for the growth rate of IT technology variety in the optimal growth path, we substitute (C7) into (C8) and obtain

$$-\frac{\dot{\lambda}_T(t)}{\lambda_T(t)} = \frac{\eta}{\varepsilon_T - 1} L_{TP}(t) + \eta \cdot (L - L_{TP}(t)) - \rho \quad . \quad (C11)$$

Substituting the IT market clearing condition $C_T(t) = N_T(t)^{\frac{1}{\varepsilon_T - 1}} \cdot L_{TP}(t)$ into (C7) obtain

$$1 = \lambda_T(t) \cdot \eta \cdot N_T(t) \cdot C_T(t) \cdot N_T(t)^{\frac{1}{1 - \varepsilon_T}} = \lambda_T(t) \cdot \eta \cdot C_T(t) \cdot N_T(t)^{\frac{2 - \varepsilon_T}{1 - \varepsilon_T}} \quad , \quad (C12)$$

and differentiating (C12) with respect to time t

$$\frac{\dot{\lambda}_T(t)}{\lambda_T(t)} + \frac{\dot{C}_T(t)}{C_T(t)} + \frac{2-\varepsilon_T}{1-\varepsilon_T} \cdot \frac{\dot{N}_T(t)}{N_T(t)} = 0 \quad . \quad (C13)$$

Substituting (C11) and innovation possibility frontier $\dot{N}_T(t)/N_T(t) = \eta \cdot [L - L_{TP}(t)]$ into (C13) obtain

$$-\frac{\eta}{\varepsilon_T - 1} L_{TP}(t) - \eta \cdot (L - L_{TP}(t)) + \rho + \frac{\dot{C}_T(t)}{C_T(t)} + \frac{2-\varepsilon_T}{1-\varepsilon_T} \cdot \eta \cdot [L - L_{TP}(t)] = 0 \quad , \quad (C14)$$

and the growth rate of IT product consumption in the social optimal growth path is given by

$$\frac{\dot{C}_T^S(t)}{C_T^S(t)} = \frac{\eta L}{\varepsilon_T - 1} - \rho \quad . \quad (C15)$$

Furthermore, based on the IT market clearing condition $C_T(t) = N_T(t)^{\frac{1}{\varepsilon_T-1}} \cdot L_{TP}(t)$, we derive the growth rate of IT technology variety in the social optimal growth path as

$$\frac{\dot{N}_T^S(t)}{N_T^S(t)} = (\varepsilon_T - 1) \frac{\dot{C}_T^S(t)}{C_T^S(t)} = (\varepsilon_T - 1) \left(\frac{\eta L}{\varepsilon_T - 1} - \rho \right) = \eta L - (\varepsilon_T - 1)\rho \quad (C16)$$

From (C16), we derive the amount of workforce allocated for R&D and production in IT sector,

$$L_{TR}^S(t) = \frac{1}{\eta} \cdot \frac{\dot{N}_T^S(t)}{N_T^S(t)} = L - (\varepsilon_T - 1)\eta^{-1}\rho \quad , \quad L_{TP}^P(t) = L - L_{TR}^S(t) = (\varepsilon_T - 1)\eta^{-1}\rho \quad (C17)$$

Now it is straightforward to notice that for both energy and IT technology, the optimal growth rate of consumption and technology variety are always greater than the rate in market equilibrium, because inefficiency due to both monopoly markup (pecuniary externality) and knowledge spillovers (non-pecuniary externality) have been corrected by the social planner. Furthermore, we compare the growth rates of energy technology variety with that of IT variety in the optimal growth path,

$$g_E^S(t) = \eta \cdot L \cdot \varepsilon_E^{-1} \cdot (1 - \varepsilon_E^{-1})^{-\varepsilon_E} - \rho, \quad \text{and} \quad g_T^S(t) = \eta L - (\varepsilon_T - 1)\rho \quad , \quad (C18)$$

where $g_E^S(t) \equiv \dot{N}_E^S(t)/N_E^S(t)$, $g_T^S(t) \equiv \dot{N}_T^S(t)/N_T^S(t)$ denotes the optimal growth rate of energy and IT technology variety, respectively. The comparison thus boils down to

$$g_E^S(t) - g_T^S(t) = \eta \cdot L \cdot [\varepsilon_E^{-1} \cdot (1 - \varepsilon_E^{-1})^{-\varepsilon_E} - 1] + (\varepsilon_T - 2) \cdot \rho \quad , \quad (C19)$$

Given that the amount of workforce allocated to production in IT sector is less than the workforce endowment available in IT sector, $L_{TP}^S(t) = (\varepsilon_T - 1)\rho\eta^{-1} < L$. Substituting it into (C19) obtains

$$\eta \cdot L \cdot [\varepsilon_E^{-1} \cdot (1 - \varepsilon_E^{-1})^{-\varepsilon_E} - 1] + (\varepsilon_T - 2) \cdot \rho > \rho \cdot [(\varepsilon_T - 1) \cdot [\varepsilon_E^{-1} \cdot (1 - \varepsilon_E^{-1})^{-\varepsilon_E} - 1] + (\varepsilon_T - 2)] \quad . \quad (C20)$$

Whether the right-hand side of (C20) is positive (social optimal growth rate of energy technology variety is larger than that of IT variety) boils down to

$$\varepsilon_E^{-1} \cdot (1 - \varepsilon_E^{-1})^{-\varepsilon_E} - 1 > \frac{2 - \varepsilon_T}{\varepsilon_T - 1} \Rightarrow \frac{(1 - \varepsilon_E^{-1})^{-\varepsilon_E}}{\varepsilon_E} > \frac{1}{\varepsilon_T - 1} \quad (C21)$$

Given that the different variety of intermediate primary energy inputs are largely substitutable in producing a homogeneous secondary energy products and IT products with substantial heterogeneous functions are weakly substitutable in serving the household with love-for-variety preference, the elasticity of substitution between primary energy inputs ε_E is sufficiently greater than the elasticity of substitution between IT-related end-use products ε_T , then (C21) does not necessarily hold, that is, the social planner solution can't achieve an outcome in which energy technology variety grows faster than IT variety.