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Explaining the Slow Pace of Energy Technological Innovation: Why Market Conditions Matter

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Abstract

As a useful complement to numerous innovation policy studies from a normative perspective, this paper provides a positive framework to analyze the basic economic mechanism of energy technological innovation and explain its slow pace of technological progress. We find that the capital-intensiveness of energy technology is an inhibiting factor to catalyze market size effect and slows innovations and diffusions of energy technology in the market. We also show that the substantial homogeneity of energy products leads to both a monopolistic market structure on the supply side and a weak level of positive pecuniary externality on the demand side, both dampening the incentive of innovation. On the basis of our economic analysis, we recommend that a package of policy responses to accelerating energy innovation should include 1) downsizing “heavy” assets of energy technologies; 2) deregulating monopolistic energy-supplying markets; and 3) differentiating the homogenous energy products.

Keywords
The Economics of Technological Innovation; Market Size Effect; Love-for-variety effect; Energy Technology; IT Technology

JEL Classification
Q55, Q58, Q43, Q48, O31.

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Explaining the Slow Pace of Energy Technological Innovation: Why Market Conditions Matter?

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Abstract: There is a growing body of literature mentioning the slow progress of energy technology, but the reasons why energy sector is perplexed by slow innovation remain unexplained. This paper investigates a basic mechanism that underlines the slow pace of energy technological progress. We find that the capital-intensiveness of energy technology is an inhibiting factor to catalyze market size effect and thus slows innovations and diffusions of energy technology. We also show that the substantial homogeneity of energy products leads to both a monopolistic market structure (thus lower competition and efficiency improvement) in the supply side and a weaker level of pecuniary externality and household consumption in the demand side, thus dampening the incentive of innovation. Potential policy responses for accelerating energy technological innovation should involve: 1) downsizing heavy physical assets of energy technologies; 2) deregulating monopolistic markets of energy supply; and 3) differentiating the variety of end-use energy products.

Keywords: Energy Technological Innovation; Market Size Effect; Love-for-variety effect

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1. Introduction

In the face of the pressing challenges of energy security and climate change mitigation, both developed and developing countries have demonstrated strong interests in energy innovation and innovation-enhancing energy policies, particularly with respect to the development of low-carbon energy technologies. However, a real fact is that the energy sector still faces a surprisingly low level of innovative activities in both R&D spending (inputs of innovation) and patenting (outputs of innovation) (Nemet and Kammen, 2007; Margolis and Kammen, 1999a,b; Henderson and Newell, 2010; Newell, 2011).

With the exception of previous peak spending periods in the late 1970s (due to the Arab Oil Embargo) and year 2009 stimulus spending (for recovery from economic recessions), the U.S. public expenditure on energy R&D remains dramatically low over the past four decades (1973-2013). As compared to other budget categories like national defense, health care, and space programs (more than 100 billions of dollars), R&D spending for energy technologies are dramatically small with a level of less than 10 billion of dollars (Henderson and Newell, 2010). Actually, all International Energy Agency (IEA) member countries experience such a trend of underinvestment in energy R&D. Except for year 2009 one-time "green" stimulus spending,[1] total public budgets for energy R&D in all IEA countries have declined in real terms over the past 30 years (the pre-stimulus nominal levels just above the amount budgeted in 1976). The relative share of energy R&D in total R&D budget has declined significantly from 12% in 1981 to 4% in 2008, and energy R&D expenditure in IEA countries is about 0.03% of GDP in 2008 (IEA, 2010). Extending to the global scale, the IEA also argues that a great deal more must be done to bridge the gap between the USD 10 billion in annual pre-stimulus spending and the estimated USD 40 - 90 billion needed to meet future energy supply and environmental needs (IEA, 2010).[2] In terms of patenting, the number of energy-specific patents filed dramatically fall over time as an outcome of the declining energy R&D spending, which are orders of magnitude smaller than the total number of granted patents (Margolis and Kammen, 1999a,b; Nemet and Kammen, 2007).

In this context, we are motivated to investigate the following important issues: (1) why there is

[1] "Green" stimulus budgets are normally one-time increases in funds, and new commitments to energy R&D may be ending. Whether the sudden push for energy R&D expenditure is sustainable over the medium to long term is uncertain (IEA, 2010).

[2] At the sectoral level, R&D intensity (R&D expenditure as a share of output sales) also shows the trend of underinvestment in energy technology. Innovation-intensive sectors such as information technologies (IT) feature a high level of R&D intensity (>10%), while that intensity in energy sector is less than 1% (Margolis and Kammen, 1999a,b; Neuhoff, 2005; Henderson and Newell, 2010).

insufficient incentive of R&D and innovation in energy sectors, (2) which factors disrupt the effective functioning of energy innovation and slows the pace of energy technological progress, and (3) which policies are needed for accelerating energy technology innovation. To address these issues, we draw on the paradigm of "technology push/market pull" as a benchmark framework to analyze the economics of energy technology innovation. By doing that, we are devoted to better understand the mechanism that slows energy technological progress, and motivate potential policy responses for accelerating energy technological innovations.

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 (e.g., Noberg-Bohm, 2000; Grubb, 2004; Gallagher et al., 2006; Sagar and van der Zwaan, 2006; Nemet and Kammen, 2007; Newell 2008; Anadon and Holdren 2009; Weiss and Bonvillian 2009; Narayanamurti et al., 2009; Henderson and Newell, 2010; Newell, 2010, 2011; Anadon, 2010; Grübler et al. 2012). While these works have a virtue of providing helpful policy prescriptions and an important starting point for further studies, the frustrating limitation is that they lack an economic exposition of the basic mechanism that underlines energy technological innovation. Such an economic analysis is particularly needed on the ground that without having a good understanding of the underlying mechanism, it will become difficult to serve the purpose of designing appropriate policy responses for accelerating energy technological progress. Therefore, to fill the gap in the existing literature, this paper contributes to an economic exposition of the basic mechanism that helps explain the slow pace of energy technological progress.

The rest of this paper is organized as follows. Section 2 briefly introduces the idea of "technology push v.s. market pull" as our analytical framework. We begin the economic analysis in Section 3 by clarifying the market size effect and its effect on energy technological innovation. We continue in Section 4 by investigating the effect of market structure on innovation incentives. Section 5 presents some policy responses for helping accelerate energy technological innovation. Section 6 concludes.

2. Technology Push and Market Pull

The methodological framework used in our analysis builds on the idea of "technology push/market pull" (von Hippel, 1976; Gibbons and Johnston, 1974; Mowery and Rosenberg, 1979). It is claimed that innovation is an evolving process involved with sequential and interconnected multiple stages, not a single piecemeal event centering on R&D. Innovation is more than R&D investment, and a focus on R&D is important, but only touches on a small part of the broader innovation process

(Walsh, 1984; Freeman, 1994; Freeman and Soete, 1997; Nemet, 2009). In general, an innovation process involves the following stages.

1) Basic R&D: research are undertaken by university, government and industrial laboratories to create general-purpose knowledge with potential applications in a wide range of areas;
2) Applied R&D: entrepreneurs adapt the general-purpose knowledge into market-oriented technologies for exploiting business opportunities;
3) Demonstration: technical advances and cost performances of technologies are demonstrated to potential investors and customers to identify the market potential;
4) Deployment: specific products embodying core technologies are produced for small-scale deployments in the marketplace;
5) Market accumulation: new products with advanced technologies accumulate their market shares as the consumer acceptance grows;
6) Large-scale diffusion: with the performance improved by learning-by-doing and economies of scale, new technology penetrates into the market for large-scale diffusions.

It is straightforward to find that different innovation stages are interconnected in the innovation process, and it combines the elements of "technology push" (forces stimulating knowledge creation) and "market pull" (forces inducing market demands for innovation), thus leading to the "technology push v.s. market pull" paradigm.[3] This then raise another issue: whether innovation is determined by scientific knowledge constraints in particular technology fields (technology push), or whether it is stimulated by profit motivations (market pull). Scientific accounts of technological innovation boil down to a science-driven view: innovation depends on the autonomous progress of scientific understanding and knowledge in R&D stages, and scientific knowledge constraints play an important role in shaping the evolutionary paths in particular fields of technologies.[4]

In contrast, an economic relevant perspective believes that market demand and profitability drives innovations, and changes in market conditions create opportunities for firms to invest in

[3] Stages (1)-(3) in the innovation process are the driver of "technology push", while Stages (4)-(6) are the force of "market full".

[4] Taking energy innovation as an example, while researchers embarked on R&D in photovoltaics (PV) and IT technologies at almost the same time in the 1950s, PV technology development proceeds differently compared to IT, with the latter experiences a much faster speed of technology progress. From a science-driven (technology push) perspective, this divergence pattern is due in substantial part to different scientific fundamentals that constrain knowledge breakthroughs in the basic R&D phase. While the seemingly limitless potentials of quantum effects help IT technologies sustain the pace of the well-known Moore's Law (the number of transistor embodied in a chip doubles every two years), the law of nature (the Carnot thermodynamic efficiency limit) imposes an impenetrable ceiling on energy conversion efficiency improvement, keeping PV technologies from following a path similar to IT technologies.

innovation to satisfy the unmet demand (Schmookler, 1962; 1966).[5] Provided that innovation is primarily determined by profitability in the marketplaces, characteristics of market conditions, especially market size and market structure, tend to have important implications for innovation and thus deserve particular investigation. This logic thus motivates us to focus on the market-pulling side and adopt a market-driven view to examine the mechanism of energy innovation, where innovation is thought of as an economic activity and responds to profit incentives.[6] Moreover, we emphasize that innovation is an outcome of interactions among different agents, operating within specific market conditions. Considerations should thus be given to different economic actors (incumbents or entrepreneurs), different economic behaviors (R&D-related knowledge creation or conventional output production), different market structures (monopolistic or competitive), and different public policy responses (environmental, competition, innovation policies). Such a framework would help offer deeper insights into the mechanism that underlines the slow progress of energy technological innovation.[7]

To articulate the market-driven aspect of innovation, the following sections examine two effects on energy technological innovation: market size (Sections 3), and market structure (Sections 4). Our analysis is performed in a way of comparing slow-innovating energy technology with fast-innovating information technology (IT). Such a comparative perspective helps clarify the differences between energy and IT innovation, and improve our understanding of the slow pace of energy innovation.

3. Market Size Effect

Drawing on the insights from the endogenous growth theory (Romer, 1986, 1990; Rivera-Batiz and

[5] 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 are 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), Acemoglu (2002), Sue Wing (2003), and Popp et al. (2009).

[6] That said, our arguments do not mean a dichotomy between the “technology push” and “market pull”. Rather, we agree that transformative technological change requires the simultaneous leveraging and coupling of both “technology supply push” and “market demand pull” as suggested by Nelson and Winter (1977), Mowery and Rosenberg (1979), Kleinknecht and Verspagen (1990), Arthur (2007); Dosi, 1982. Klevorick et al., 1995

[7] The importance of potential economic feedbacks and interactions in the innovation system has been acknowledged in a large number of studies (e.g., Nelson and Winter, 1977; Nelson, 1993; Rosenberg, 1994; Geels, 2004; Dosi, 1982; Nelson and Winter, 1982; Freeman 1994; Lundvall, 1992; Klevorick et al., 1995; Hekkert et al., 2007; Bergek et al., 2008; Gallagher et al., 2006, 2012)

Romer, 1991), this section aims to show that a particular technology that enables to mobilize the market size effect is more likely to induce the incentive of innovation. To explain this point, we consider a particular industrial sector with all individual firms having the same production function for the final good (the representative firm assumption). Thus, the representative production function in this particular sector takes the form as,

$$Y = F(K, L, A) \tag{1}$$

where Y is the amount of production output of the final good, K is capital stock, L is labor, and A is technology. The capital stock K corresponds to the inputs of tangible physical capital assets like hardware, machines, and equipments. We can also think of A as a broad notion of intangible technology asset like knowledge, ideas, and blueprints concerning how to produce final goods. A major assumption used throughout is that technology is a non-rival (its use by one firm does not preclude its use by others) and non-excludable (it is impossible to prevent others from using it). The resulting implication is that technology is freely available to all potential firms in this particular sector and other firms do not have to pay for making use of this technology.

We assume that the production function exhibits constant returns to scale (CRS) in physical capital and labor (standard rival inputs), that is,

$$F(\lambda K, \lambda L, A) = \lambda \cdot F(K, L, A) \quad , \tag{2}$$

for all $\lambda > 1$. Intuitively, when physical capital and labor double, the firm can replicate the same production facility and double the outputs of final goods. Naturally, endogenizing the input of technology A leads to increasing returns to scale to all three inputs K, L, and A, because the non-rival input of knowledge is freely accessible to new production facility that does not need to replicate the non-excludable knowledge. The property of increasing returns can thus be expressed as:

$$F(\lambda K, \lambda L, \lambda A) > F(\lambda K, \lambda L, A) = \lambda \cdot F(K, L, A) \quad , \tag{3}$$

for all $\lambda > 1$, where the first inequity holds for the reason that more outputs would be made by using more advanced technology $\lambda \cdot A$, with the same amount of physical capital and labor inputs. The second equity comes from the constant returns to scale in standard rival inputs of K and L. Eq. (3) thus shows that there is an increasing return to scale in K, L, and A. That is, when the inputs of physical capital, labor, and technology double, the new production facility would more than double outputs. The property of increasing returns further implies that in a competitive economy the firms can make positive profits by using more non-rival inputs of knowledge.

Intuitively, since the non-rival input of knowledge can be used as many units as desired without incurring further costs, a larger size of market deployment would induce firms to create and apply a higher level of knowledge for harnessing the increasing returns and profitability, creating a so-called market size effect. In contrast, there is no market size effect for the standard rival inputs like labor and physical capital, that is, a larger size of market does not necessarily induce firms to use them more intensively. This is because a greater level output production for a larger market translates into a greater level of rival inputs have to be used and incur more costs, and there is thus no profit gain from using more standard rival inputs as required by the constant return to scale production.

We now explain the slow progress of energy technological innovation from the perspective of market size effect. It is notable that energy technology are characterized by capital-intensiveness in the sense that energy sectors often intensively use "heavy" tangible capital like hardware, equipment, and machines, without applying much "light" intangible assets like ideas and knowledge. [8] Putting that perspective into the production function $F(K,L,A)$, we find that with knowledge as a minor input in production, the condition $F(\lambda K,\lambda L,\lambda A) \approx F(\lambda K,\lambda L,A) = \lambda F(K,L,A)$ tends to hold, which implies that production in energy sectors is more likely to exhibit a constant return to scale and thus have no profit gain. As a result, energy technology with an intensive use of rival inputs like physical capital is less likely to take advantage of the market size effect, thus slowing the pace of innovation and diffusion of new energy technology in the marketplace.

In contrast, IT 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. With a greater contribution of intangible knowledge, production technology in IT sectors tend to satisfy the increasing returns to scale $F(\lambda K,\lambda L,\lambda A) > F(\lambda K,\lambda L,A) = \lambda F(K,L,A)$ and thus positive profit gains. Accordingly, the knowledge-intensive IT is more likely to harness the market size effect for accelerating technology innovation and diffusion.

4. Market Structure Effect

4.1 Supply-side structure

We continues to investigate the effect on innovation of market structure in both supply (Section 4.1)

[8] This is especially the case for centralized power generation systems that intensively use "heavy" capital assets such as hardware, equipments, and machines. As compared to other equipments or consumer products, energy technology investments are often characterized by high upfront costs, a high degree of infrastructure, and long payback periods. The capital intensiveness tends to slow capital turnover and the diffusion speed of new energy technologies (Holdren and Sagar, 2002; Grubb, 2004; Worrell and Biermans, 2005; Grübler et al., 1999, 2012).

and demand sides (Section 4.2). Before discussing the differences between energy and IT market structures, we need to distinguish their different characteristics of products. In general, products produced by different energy technologies feature a substantial degree of homogeneity in the sense that energy products are often used as an input of homogenous commodity into intermediate and final use, energy products thus have less differentiation in terms of variety, attribute, and function. By contrast, IT-related devices and products feature a substantial degree of heterogeneity in varieties, and consumers obtain utility from consuming new differentiated variety of IT products.

Accordingly, IT innovation is characterized as a pattern of "product innovation" in the sense that IT innovations create products with differentiated function, attributes, and utility. [9] In contrast, technological innovation in energy sectors can be thought of as a pattern of "process innovation": introduction and application of new energy technology serves to reduce the costs of producing the existing homogenous products/services, i.e., electric utility. In this context, energy innovations typically incur direct price competitions and replacements between technology incumbents and new innovators, both with different costs of producing the same homogenous energy goods. The competitive nature of energy technological innovation implies that there is an inherent conflict of interests between incumbents and innovators, and the incumbents tend to become a natural constituency in favor of certain types of distortionary policies that limit market entry and thus shape a monopolistic market structure in energy industries.[10]

To explain this point in a formal way, we suppose that the existing incumbent energy firm has a leading-edge technology that produces energy goods at a marginal cost (MC). A perpetual patent system exists to protect firms with a leading-edge technology that produces at the lowest MC. Thus, the net present discounted value of this incumbent energy firm owning the leading-edge technology at time t is represented as:

$$V(t) = \int_t^{\infty} \exp\left[-\int_t^{s} r(s')\cdot ds'\right]\cdot \pi(s)\cdot ds \qquad (4)$$
$$s.t.\ \ \pi(t) = p(t)\cdot x(t) - MC\cdot x(t)$$

where $\pi(t)$ denotes the current flow profits of the incumbent firm that produces energy at the MC at

[9] For instance, microprocessors lead to various distinct hardware devices and contribute to the internet and innumerable digital applications and services. Clearly, a newly created IT variety with distinct functions can mostly be used (coexist) alongside existing varieties.

[10] Here we adopt the term of "monopolistic market structures" to represent all kinds of imperfect market structures. In fact, the oligopolistic market structures that often emerge in the energy industries can also lead to a formulation of monopolistic market structures through either explicit or tacit collusion.

time t. $p(t)$ and $x(t)$ are endogenous price and quantity choices of the incumbent energy firms for maximizing intertemporal profit. Eq. (4) assumes that at each time point t, only energy firms with the leading-edge technologies that produce energy at the lowest MC is active in energy production, thus reflecting the competitive nature of innovation in energy sectors. That is, when innovators create a new type of energy technology that enables to produce electric utility with a lower MC, it will replace the incumbent energy technology. [11] The analysis proceeds by rewriting the value function $V(t)$ in a Hamilton-Jacobi-Bellman (HJB) form given by:

$$\pi(t)+\dot{V}(t)-r(t)\cdot V(t)-z(t)\cdot V(t)=0 \tag{5}$$

where the first term represents the gain of current profit flow. The second term comes from the fact that the maximized value can vary over time. The third and fourth terms correspond to the losses of value due to losses on interest rates and monopolistic profits, respectively. The last term reflects the competitive essence of innovation: the existing incumbent would lose its monopoly position and be replaced by new innovators who have advanced technologies producing at a lower cost – a so-called Schumpeterian creative destruction (Schumpeter, 1934; 1942).

Accordingly, $z(t)$ denotes the rate at which innovation creating new energy technology occurs at time t, that is, the rate at which the existing technology incumbent is replaced by new innovators. For simplicity, we consider in a balanced growth path (BGP) equilibrium where interest rate, flow profit, and the rate of innovation are all constant over time, $r(t)=r^*$, $\pi(t)=\pi^*$, $z(t)=z^*$. A BGP thus implies a constant market value owned by the existing energy technology incumbent $\dot{V}(t)=0$, then from Eq.(5), we obtain

$$r^*\cdot V^*-0=\pi^*-z^*\cdot V^* \quad \Rightarrow \quad V^*=\frac{\pi^*}{r^*+z^*} \tag{6}$$

where in the BGP equilibrium the market value possessed by energy technology incumbents V^* depends on an effective discount rate r^*+z^*. To maximize the market value V^*, the technology incumbents in energy sectors tend to lower the rate of innovation z^* by erecting entry barriers. With the entry barriers raising start-up costs, the innovative incentives of firms with new energy technologies like solar and wind would be discouraged, leading to a slow pace of technological innovation and diffusion in energy sectors.

Intuitively, due to the homogenous nature of energy products/services, technological innovation in energy sectors often comes with direct price completion and conflicts of interest, in the sense that

[11] This assumption holds on the ground that energy technologies producing the homogenous energy goods with different MC of production are largely perfect substitutes, and only the leading-edge technology having the lowest MC of production is adopted in equilibrium.

new energy technology introduced by innovators would directly replace the monopoly positions enjoyed by existing energy incumbents. This raises the possibility that energy market regulations limiting new entrants may arise as a way of protecting monopolistic profits of energy incumbents.[12] A monopolistic market structure is thus more likely to emerge in energy sectors, and this imperfect competitive energy market is fundamentally different from the competitive market structure in IT sectors where new innovators have free entry into IT markets.

As a result, private firms in energy sectors with market regulation have a lower innovative incentive to create new technology as compared to those in IT markets already deregulated. To explain this point, image that in the IT market where there is a large number of competitive firms with access to the existing technology producing one unit of IT product at the MC ψ. Suppose that one of these firms undertakes R&D for technology advance, that is, if this firm incurs a cost μ on R&D spending, it can innovate and reduce its MC of production to a level of ψ/λ, where $\lambda > 1$. In an equilibrium without R&D and technological innovation, this IT firm charges a price that is equal to MC, $P_I^N = \psi$, where the superscript "N" is the no-innovation case, and the subscript "I" the IT market. The resulting profit gains of firms in competitive IT sector is given by,

$$\pi_I^N = (P_I^N - \psi) \cdot Q_I^N = 0 \tag{7}$$

where Q_I^N denotes the amount of products supplied by this firm in the IT market.

Consider that the IT firm considered carries out R&D for creating new technology, and it obtains a fully enforced patent to protect the excludability of innovation and thus possess *ex post* monopoly power. The monopoly position enables this innovating firm to earn profits from innovation, and thus encourage R&D spending in the first place. In this context, the IT firm considered has an incentive to innovate and become an *ex post* monopolist that chooses its price to maximize profits as

$$\pi_I^I = D(P_I^I) \cdot (P_I^I - \lambda^{-1} \cdot \psi) - \mu \tag{8}$$

where the superscript "I" represents an innovation case. If this innovating firm spends μ on R&D, it would innovate and reduce its MC of production to a level of $\lambda^{-1} \cdot \psi$. This innovating IT firm will set

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[12] Fossil energy technology incumbents are often politically powerful, in the sense that traditional fossil fuel technologies have already found multiple applications across many sectors, industries, and end-users. Such strong dependence creates a self-reinforcing mechanism that make it difficult to dislodge the dominant technological regime, leading to "technology lock-in" of fossil energy technologies (Frankel, 1955; Arthur, 1989; Cowan, 1990; Cowan and Hulten, 1996; Unruh, 2000; Watson, 2004). As a result, new energy technologies, even when economically feasible, still face higher market entry costs compared to established technologies.

a profit-maximizing monopoly pricing,

$$P_I^I = \frac{\lambda^{-1} \cdot \psi}{1 - \varepsilon_D^{-1}} \tag{9}$$

where the profit-maximizing monopoly pricing is a constant markups over the MC. ε_D denotes the elasticity of market demand. The innovating IT firm chooses the monopoly price P_I^I, and captures the market demand $D(P_I^I)$.[13] It is verified that profits made by this innovating IT firm can be strictly positive, $\pi_I^I = D(P_I^I) \cdot (P_I^I - \lambda^{-1} \cdot \psi) - \mu > 0$, implying that innovation in IT sector is profitable in the presence of an *ex post* monopoly. Compared to zero profit gain $\pi_I^N = 0$ in the non-innovation equilibrium, the IT firm in question has an incentive to innovate in pursuit of positive profit gains $\pi_I^I > 0$. This situation corresponds to a deregulated IT market starting with perfect competitions among a large number of competitive IT firms, but one of these firms innovates to escape competition and gains *ex post* monopolistic profits, $\Delta\pi_I^I = \pi_I^I - \pi_I^N = \pi_I^I > 0$, which represents the value of innovation to individual firm in a competitive IT sector.

Turn to the energy sectors with market regulation and entry controls. The same environment is assumed as in IT markets, but the exception is that in energy markets there is already a monopolistic incumbent that has the existing technology to produce energy at $MC = \psi$. With an existing monopoly position, this incumbent energy firm chooses its profit-maximizing monopoly price as:

$$P_E^N = \frac{\psi}{1 - \varepsilon_D^{-1}} \tag{10}$$

where the superscript "N" corresponds to a non-innovation case, and the subscript "E" to the energy market. With the profit-maximizing pricing rule, Eq. (10), the energy incumbent enjoys an existing monopolistic profit, $\pi_E^N = D(P_E^N) \cdot (P_E^N - \psi)$. Now suppose that the energy incumbent undertakes an innovation by reducing its MC of production from ψ to $\lambda^{-1} \cdot \psi$, it still remains a monopolist and charges a monopoly price as:

$$P_E^I = \frac{\lambda^{-1} \cdot \psi}{1 - \varepsilon_D^{-1}} \tag{11}$$

where the superscript "I" denotes the innovation case. As innovation reduces its MC to $\lambda^{-1} \cdot \psi$, this

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13 To set this unconstrained monopolistic pricing, we implicitly assume that the innovation is drastic, $\lambda \geq 1/(1 - \varepsilon_D^{-1})$, so that the monopolistic price charged by this innovator is below the price charged by other firms in the market, $P_I^I \leq \psi$.

energy incumbent makes profits, $\pi_E^I = D(P_E^I)\cdot(P_E^I - \lambda^{-1}\cdot\psi) - \mu$. Thus, the value of innovation to this monopolistic energy incumbent is equal to the additional profit gains from innovation, that is, $\Delta\pi_E^I = \pi_E^I - \pi_E^N = D(P_E^I)\cdot(P_E^I - \lambda^{-1}\cdot\psi) - \mu - D(P_E^N)\cdot(P_E^N - \psi)$.

It is verified that $\Delta\pi_E^I < \Delta\pi_I^I$, that is, the value of innovation to a monopolist incumbent firm in energy markets is less than that to a competitive firm in IT markets. As a result, the monopolist incumbent energy firm has a lower incentive to innovate than do a competitive IT firm. This result explains the fact that existing companies in energy-related industries – those that produce energy, those that manufacture the equipment to produce, convert, and use energy, and those that distribute energy – either will not engage in as much R&D as would be socially optimal, or will engage in R&D but delay the introduction of new technologies (Weyant, 2011). Moreover, the underlying economic intuitions are as follow. In energy sectors with market regulation, technological innovation would reduce the monopolistic profits of technology incumbents in making use of its existing profit-making technologies, energy incumbents thus have lower incentives to innovate and replace their own existing technologies. In contrast, firms in competitive IT markets have zero *ex ante* profit to replace, and thus have stronger innovation incentive to escape competition for positive *ex post* profits gains.[14]

4.2 Demand-side structure

This section turns to considering the effect on innovation of demand-side market structures. The history of technology transitions highlights the importance of consumer demands in pulling new technologies into widespread market diffusion. Thus having a good understanding of consumer preferences and their behaviors offers important implications for the slow pace of energy technology innovation.

The analysis is closely related to and builds on the Dixit-Stiglitz monopolistic competition model (Dixit and Stiglitz, 1977), we consider an economy admitting a representative consumer with preferences for two types of goods:

$$U = U(C, y) \quad , \tag{12}$$

[14] This result echoes Arrow's Replacement Effect: technology incumbents who currently enjoy monopolistic profits have low incentive to innovate and replace their own profit-making technologies. The new entrants, once the monopolistic market is deregulated, would have stronger incentives to innovate (Arrow, 1962a,b). The intuition that a competitive market structure that allows new entrants play a critical role in spurring innovation goes back to Arrow (1962a,b) and has been confirmed by important studies (e.g., Mansfield, 1963; Scherer, 1965; Markham, 1965; Comanor, 1967; Shrieves, 1978; Loury, 1979; Kamien and Schwartz, 1982; Cohen and Levin, 1989; Sutton, 1996; Aghion et al., 2005; 2007).

where C is the consumption of a particular product (energy or IT product), and y is consumption of a numeraire good. The quantity of the composite product, C, is a subutility function defined over N differentiated varieties $c_1,\ldots,c_N$ of that particular product, and C is defined by a constant elasticity of substitution (CES) function as:

$$C=\left(\sum_{i=1}^{N} c_i^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}} \quad , \tag{13}$$

where c_i is the consumption of each variety of that particular product, and N is the range of available product varieties. In this specification, the parameter ε is the elasticity of substitution between any two differentiated varieties of that product, and for gross substitutes we assume that $\varepsilon>1$. The CES specification of the consumption bundle reflects the "Dixit-Stiglitz preference" with a *love-for-variety* effect,

$$U=U\left(\left[N\cdot(\bar{C}/N)^{\frac{\varepsilon-1}{\varepsilon}}\right]^{\frac{\varepsilon}{\varepsilon-1}},y\right)=U\left(N^{\frac{1}{\varepsilon-1}}\cdot\bar{C},y\right) \quad , \tag{14}$$

where we consider the case in which the consumer chooses a total of $\bar{C}$ units of this particular product, distributed equally across N differentiated varieties: $c_1=\cdots=c_N=\bar{C}/N$. It is notable that the utility is strictly increasing in the variety N given the elasticity of substitution, $\varepsilon>1$. This implies that for consumptions of a fixed total amount of a particular product, the larger is the number of differentiated varieties of that particular good, the higher is the utility gained from consuming that product, thus reflecting the essence of *love-for-variety* preferences of consumers.

To analyze the effect on innovation of *love-for-variety* preferences and resulting demands, we solve the consumer problem of maximizing the utility Eq. (12) subject to the budget constraint,

$$\sum_{i=1}^{N} p_i\cdot c_i+y\leq m \quad , \tag{15}$$

where the price of product variety c_i is denoted by p_i and the total income by m. The price of the numeraire good y is normalized to unity. Firstly, consider that each variety c_i is chosen so as to minimize the cost of attaining a given amount of consumption bundle C, we solve this expenditure minimization problem,

$$\min_{c_1,\ldots,c_N} \quad \sum_{i=1}^{N} p_i\cdot c_i \quad s.t. \quad C=\left(\sum_{i=1}^{N} c_i^{\frac{\varepsilon-1}{\varepsilon}}\right)^{\frac{\varepsilon}{\varepsilon-1}} \quad , \tag{16}$$

and obtain the isoelastic demand function for each individual variety c_i of this particular product,

$$c_i = \left(\frac{p_i}{P}\right)^{-\varepsilon} \cdot C \tag{17}$$

where $$P = \left(\sum_{i=1}^{N} p_i^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}} \tag{18}$$

denotes the ideal price index of this particular product, which measures the minimum cost of purchasing a unit of the composite index C of that particular goods. In the second step, we solve for the consumption choice C, y by maximizing the utility function subject to the budge constraint,

$$\max_{C,y} \quad U(C,y) \qquad s.t. \quad \sum_{i=1}^{N} p_i \cdot c_i + y = P \cdot C + y \leq m \quad . \tag{19}$$

The first-order necessary condition to this problem gives equality of marginal rates of substitutions to the price ratios between C and y,

$$\frac{\partial U(C,y)/\partial y}{\partial U(C,y)/\partial C} = \frac{\partial U((m-y)/P,y)/\partial y}{\partial U((m-y)/P,y)/\partial C} = \frac{1}{P} \quad , \tag{20}$$

which implies some explicit function $g(.,.)$ that explicitly determine the consumption choice C, y

$$y = g(P,m) \qquad C = \frac{m - g(P,m)}{P} \quad . \tag{21}$$

where a straightforward property of the function $g(.,.)$ is that it is increasing in its first argument P. That is, given a fix amount of income level m, as the price of this particular product P rises, consumption of this particular product C decreases, and demand of numeraire good y increases..

The analysis proceeds to the side of supply each variety of this particular product. Suppose that each differentiated variety of this particular product is produced and supplied by a particular firm facing a constant MC of production that is equal to ψ, and this particular firm thus face a profit maximization problem that takes the form as,

$$\max_{p_i} \quad c_i \cdot (p_i - \psi) = \max_{p_i} \quad [(p_i / P)^{-\varepsilon} \cdot C] \cdot (p_i - \psi) \tag{22}$$

where the objective of this firm is to choose the monopoly price p_i for profit maximization. Solving this problem derives the profit-maximizing pricing in the form of a constant markup over the MC:

$$p_i = \frac{\varepsilon \cdot \psi}{\varepsilon - 1} \tag{23}$$

for each variety $i = 1, 2, .., N$ of this particular product. Since individual firms that produce each variety charges the same monopolistic price, the price index of this particular product composite is written as:

$$P = \frac{\varepsilon \cdot \psi}{\varepsilon - 1} \cdot N^{-\frac{1}{\varepsilon - 1}} \quad . \tag{24}$$

Given the price charged by each firm, Eq. (23), the isoelastic demand function, Eq. (17), gives the quantity of product variety c_i supplied by the corresponding firm as:

$$c_i = (p_i / P)^{-\varepsilon} \cdot C = N^{-\frac{\varepsilon}{\varepsilon - 1}} \cdot C \quad , \tag{25}$$

hence the profit made by each monopolistic firm $i = 1, 2, .., N$ is given by:

$$\pi_i = c_i \cdot (p_i - \psi) = \frac{\psi}{\varepsilon - 1} \cdot N^{-\frac{\varepsilon}{\varepsilon - 1}} \cdot C \ . \tag{26}$$

Substituting P into Eq. (21) and Eq. (26) can obtain the following equations that characterize the effects on innovation of demand-side market structures,

$$C = \frac{m - g(P, m)}{P} = N^{\frac{1}{\varepsilon - 1}} \cdot \frac{\varepsilon - 1}{\varepsilon \psi} \cdot [m - g(N^{-\frac{1}{\varepsilon - 1}} \cdot \varepsilon \cdot \psi / (\varepsilon - 1), m)] \quad , \tag{27}$$

and

$$\pi_i = \frac{1}{\varepsilon N} \cdot [m - g(N^{-\frac{1}{\varepsilon - 1}} \cdot \varepsilon \cdot \psi / (\varepsilon - 1), m)] \quad . \tag{28}$$

Given that the function $g(.,.)$ is increasing in its first argument, aggregate consumption C in the demand side and corporate profits π in the supply side are increasing in the number of differentiated varieties N for this particular product. A greater number of product variety typically reduce profits made by the firm producing the corresponding product variety, but the positive pecuniary externality embedded in the love-for-variety consumer preference creates a countervailing effect that potentially increases market demand for the product with a large number of differentiated varieties. Intuitively, due to the love-for-variety effect in the demand side, introduction of new variety has an effect to create positive pecuniary externality and raise the demand for other varieties. As a result, through this the love-for-variety effect, a larger number of varieties can raise the utility from consuming that particular product and boost output sales and profits gains in producing that particular product.

Accordingly, this result provides a key reason that explains the slow pace of energy innovation. Since energy products have a substantial degree of homogeneity with a small number of product varieties, the effect of positive pecuniary externality is weaker such that the market demands for energy products are low.[15] The lower demands then shrink the output sales and corporate profits of energy firms, giving rise to a lower level of resources available for financing energy R&D and innovation. In contrast, the large number of differentiated product varieties in IT sector is more likely to take advantage of the positive pecuniary externality due to the love-for-variety preference, market demands for IT products would thus be strong, which creates more profit gains to support R&D for developing new variety of IT products.

5. Policy Implications

Based on the above-described analysis on the mechanism that underlines energy innovation, this section provides some policy implications for accelerating energy technological innovation. An important implication is that sole reliance on traditional innovation policies centering on R&D expenditure (technology-push) may not be effective. Policymakers should consider implementation of market-pulling measures that guide and regulate the supply and demand in energy markets, so that the goal of major technological transformation for a sustainable energy future is achievable. We thus propose the following three policy implications that may help accelerate energy innovation.

(1) Downsizing heavy assets of energy technologies

As discussed in Section 3 concerning the market size effect, traditional fossil fuel-based technologies are mostly capital-intensive in making use of heavy assets. The rival nature of these heavy physical assets makes energy technologies less likely to mobilize the market size effect, thus leading to a slow pace of technology innovation and diffusion in the marketplace. To overcome this weakness inherent in traditional centralized power generation systems, innovation policies for addressing energy and climate issues should consider downsizing the heavy assets in existing energy technology portfolios by integrating more knowledge-intensive, small-scale decentralized light technology assets. The thin-film cell technology is a good example that should figure prominently in future energy technology portfolios. This new type of PV technology is tailored through micro-structural and nano-structural engineering, and is characterized by lightweight materials and structures. By taking

[15] A clear evidence is that customers care more about differentiated product attributes and utilities than the costs of using the homogenous energy inputs. In most cases, households choose personal vehicles, electrical appliances for reasons that have little to do with energy use.

advantage of the market size effect, the thin-film cells are expected to gain a growing market share and achieve large-scale deployments in the decentralized grid networks.

(2) Deregulating the monopolistic energy-supplying markets

As articulated in Section 4.1 regarding the effect on innovation of the supply-side market structure, new energy technology often faces potential conflicts of interest with existing energy technology incumbents. This raises the possibility that market regulations for limiting innovators may arise as a way of protecting the monopolistic profits of the existing technology incumbents. In this context, the energy monopolist has a lower incentive to innovate than does energy firms in a competitive energy market structure. To stimulate innovation in energy industries, policymakers should consider restructuring the existing monopolistic energy market and create an "innovator-friendly" competitive market. Antitrust and deregulation are particularly needed to support the entry of innovators with new energy technologies like renewable solar and wind. As new entrants have stronger incentives to innovate, transforming monopolistic energy market structures into a competitive organizational form is a key step to boosting competition and innovation in energy sectors. Consider the worldwide PV-based energy industry, this flourishing field of new energy technology is primarily due to its competitive market structure promoting intense inter-firm competition, where vigorous competition play a crucial role in substantial cost reduction and technical performance improvement of this new generation of energy technology.

(3) Differentiating the homogenous energy products

As proposed in Section 4.2 regarding the effect on innovation of the demand-side market structure, energy technology with a lower level of product variety differentiation is less likely to take advantage of positive pecuniary externality embedded in the love-for-variety preference. As a result, the pulling forces in the demand side in energy markets are weak, shrinking output sales and corporate profits available to fund energy technology research and development.

Note that, the substantial homogeneity of energy products is largely due to the fact that there is “no intervention” in the market to internalize the non-market environmental externality. Put differently, without corrections for environmental costs inherent in “dirty” energy technologies and environmental benefit in “clean” ones, both types of energy technologies are largely thought of as homogenous and perfect substitutes. Measured in terms of the same market-based homogenous function like electric utility, the huge cost gap between high-cost “clean” technologies and traditional low-cost “dirty” ones necessitates a direct substitution and replacement of the latter for the former, thus inhibiting the pace of creating new energy technology.

In this context, to catalyze the positive pecuniary externality embedded in love-for-variety preference, public policy responses should consider differentiating energy product varieties by distinguishing fossil fuel-based energy technologies with renewable ones in terms of their different environmental attributes and functions. To implement those policy responses, government, for instance, should launch some non-economic programs that promote environmental awareness of individuals in the society, so that their preference would spontaneously value environmental attributes embedded in clean energy technologies. With the environmental quality valued by consumer preferences, clean energy technology tends to become a distinct variety (an imperfect substitute) as compared to traditional fossil-based one, thus catalyzing the love-for-variety effect and positive pecuniary externality to accelerate energy technological innovation.

Alternative policy responses include economic instruments used to convert the non-market immeasurable environmental benefits into measurable market-based values. For example, the non-market environmental values inherent in clean energy technologies can be materialized by creating a market for environmental goods. In this regard, carbon markets should be established to provide expectations on the distinct values owned by carbon-saving clean energy technologies. While carbon markets play a pivotal role to boost long-term renewable energy innovation, it is also necessary to implement complementary policies that help underpin the price floor of carbon in the short term. [16] Considerations should be given to price-based fiscal incentives such as feed-in tariffs, tax credits or subsidies for renewable energy, and carbon tax on fossil fuels.[17] The quantity-based instruments include renewable quantitative portfolio standards mandated by the government.[18]

In sum, the three following aspects should be considered as the general principles that help guide specific policymaking for accelerating energy technological innovation. (1) Downsizing the heavy assets of the existing capital-intensive energy technologies system for mobilizing the market size effect; (2) Transforming the monopolistic market structure in energy supply side into a competitive one to boost vigorous competition; (3) Differentiating energy products to catalyze the

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[16] The reason is that current carbon markets (e.g., EU emissions trading schemes) are too uncertain and unpredictable in the short run, thus failing to materialize the real values of environmental goods and attract the scale of demand and investment needed in clean energy technologies.

[17] Consider PV cell technology, although government-sponsored R&D has been a major stimulus to innovation, fiscal incentives (subsidizing PV, taxing fossil fuels) have figured prominently in recent policy portfolios. With the environmental benefits internalized by price instruments, PV cell becomes preferable to traditional fossil fuel-based technologies, consumers and manufacturers thus have more incentives to use and invest in PV cell technologies.

[18] Government bodies, which have large annual spending on purchasing office buildings, vehicles, and transit infrastructures, can be major customers for new energy technology. Policymakers should continue to encourage government procurements of energy technologies that private investors may avoid, helping create early markets and foster confidence in clean energy technologies, including those that are not yet price competitive.

positive pecuniary externality embedded in love-for-variety preference.

6. Conclusions

Energy technological innovation and innovation-enhancing policies have drawn substantial attentions as a way of addressing energy security and climate change mitigation. However, a real fact is that energy sectors still face a surprisingly low level of innovation. This paper investigates the basic mechanism that underlines the slow pace of energy technological progress. We find that energy technology that intensively uses the standard rival input of physical capital exhibits constant returns to scale and zero profit gain in deploying energy technology in a larger market. As a result, energy technology finds it difficult to take advantage of the market size effect, thus slowing innovation and diffusion of energy technology in the market.

Our analysis also suggests that the substantial homogeneity of energy goods can create market structure effects. On the one hand, the homogeneity of energy product potentially incurs competition between technology incumbents and innovators in energy supply market. This raises the possibility that a monopolistic fossil-based energy market structure limiting renewable innovators may arise as a way of protecting the monopolistic profits of existing fossil energy incumbents. The incumbent firms enjoying their own profit-making technologies thus have lower incentives to innovate than do new entrants if energy market is restructured into a competitive one. On the other hand, the homogeneity of energy goods implies that energy technology is less likely to take advantage of positive pecuniary externality due to consumer love-for-variety preference in the demand side. This disadvantage thus lowers the market demands for energy products and corporate profitability of energy firms, which shrinks the resources available for financing energy R&D-related innovation.

Based on the analysis of market size and market structure effects, we propose three general policy principles that may help accelerate energy technological innovation. (1) Downsizing heavy assets of capital-intensive technology portfolios by integrating knowledge-intensive, small-scale decentralized light technology assets; (2) Deregulating the monopolistic energy supply markets by promoting vigorous competition and the entry of new firms; (3) Differentiating energy products by distinguishing the polluting fossil-based energy goods with environmental-friendly renewable ones in the energy demand side.

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