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

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Summary

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 explains 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

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.

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1. Introduction

In the face of the twin pressing challenges of energy security and climate change, both developed and developing countries have demonstrated strong interests in energy innovation and innovation-enhancing 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 U.S. dollars), R&D spending for energy technologies are dramatically small with a level of less than 10 billion of U.S. 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 U.S.$ 10 billion in annual pre-stimulus spending and the estimated U.S.$ 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).

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[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).

In this context, we are motivated to investigate the following important issues: (1) why there is insufficient incentive of R&D and innovation in energy sectors, (2) which factors disrupt the effective functioning of energy innovation systems and thus slow the pace of technological progress, and (3) which innovation policies need to be put in place in order to accelerate energy innovation. To address these issues, we draw on the paradigm of "technology push/market pull" as a framework to analyze the economics of energy innovation. By doing that, we aim to identify the factors that inhibit energy innovation, understand its effects on techno-economic systems, and motivate policy proposition for accelerating energy innovations.

Note that, given the urgency and novelty of energy technological innovation issues, it is not surprisingly that a large body of recent studies have explored the policy issues related to energy innovation (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). In general, these works have the virtue of providing helpful policy prescriptions and are characterized as an important starting point for further studies. That said, the frustrating limitation of the existing works is that, due to the normative nature of policy analysis, they lack a rigorous exposition of the basic positive issues concerning the economic mechanisms of energy innovation. Such a positive economic analysis is particularly needed on the ground that without having a good understanding of the basic positive issues (what's the underlying mechanism involved in energy innovation), it will become challenging to serve the purpose of normative policy analysis (which policies should be made to accelerate energy innovation). Therefore, to fill the gap in current literature, this paper contributes to a useful complement by providing a positive investigation of the economic mechanism specific to energy technological innovation.

The rest of the paper is organized as follows: Section 2 briefly introduces the "technology push v.s. market pull" framework. We begin our economic analysis in Section 3 by clarifying the market size effect and its impact on energy technological innovation. We continue in Section 4 by investigating the effect of market structure on innovation incentives. Based on the positive economic analysis, Section 5 presents some policy recommendations that potentially help accelerate energy technological innovation. Section 6 concludes.

2. Technology Push and Market Pull

The methodological framework used in our analysis is building on the idea of "technology push/market pull".[3] We claim that innovation is a dynamic, 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. In general, an innovation process involves the following stages.

1) Basic R&D: research is undertaken by university researchers, government and industrial laboratories to create general-purpose technological and scientific 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 and cost performances of the technologies are demonstrated to potential investors to identify the market potential;
4) Deployment: specific products embodying the technologies are produced for small-scale deployments in the marketplace;
5) Market accumulation: the new product accumulates its market shares as the consumers' acceptance grows;
6) Large-scale diffusion: with technical performance improved by the learning-by-doing and economies of scale, new technology penetrates in the market for large-scale diffusions.

Clearly, different innovation stages are interconnected in the innovation process, and it combines the elements of "technology push" (forces stimulating knowledge generation) and "market pull" (forces inducing market demands for innovation), leading to the "technology push v.s. market pull" paradigm.[4] This then raise a major issue for the analysis of innovation: whether innovation is mainly determined by scientific knowledge constraints in particular technology fields (technology push), or whether it is primarily stimulated by profit motivations (market pull). Scientists and economists typically give different answers. Scientific accounts of innovation come down on a science-driven view. The core of this argument is that 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.[5]

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[3] For an articulation of the "technology push/market pull" paradigm, see von Hippel (1976), Gibbons and Johnston (1974), Mowery and Rosenberg (1979), Walsh (1984), Freeman (1994), Freeman and Soete (1997), Nemet (2009).

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

[5] 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

To be relevant to the economic analysis, we believe that market demand and profitability drives innovations, and changes in market conditions create opportunities for firms to invest in innovation to satisfy the unmet demand.[6] If technological innovation is primarily spurred by profitability in the marketplaces, then the characteristics of market conditions, especially market size and market structure, will have important implications for innovation and hence deserve particular examination. 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 treated as an economic activity and responds to profit incentives.[7]

Moreover, within our economic framework, we emphasize that innovation is an outcome of interactions among different economic actors, operating within specific market conditions. Considerations should thus be given to the economic system in which innovation occurs, involving different actors (incumbents or entrepreneurs), different patterns of behaviors (R&D or conventional production), different market structures (monopolistic or competitive), and different policy incentives (feed-in tariff or quantitative portfolio). Such a framework can help offer deeper insights into the causes that slow energy technological innovation.[8]

To articulate the market-driven aspect of innovation, the following sections will examine two determinants of innovation: market size (Sections 3), and market structure (Sections 4).

proceeds differently compared to IT, with the latter experiencing a much faster pace 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

[6] 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 (e.g., 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; Popp et al., 2009).

[7] 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.

[8] 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).

Our analysis is undertaken in a way of comparing energy technology (slow innovation) with IT technology (fast innovation). Such a comparative approach may help clarify the differences between energy and IT innovation, and improve our understanding of the causes that slow energy innovation.

3. Market Size Effect

Drawing on the insights from the endogenous growth theory (Romer, 1986, 1990; Rivera-Batiz and Romer, 1991), this section aims to demonstrate that a particular technology that enables to mobilize the market size effect is more likely to create profitability and thus the incentive of innovation. To explain this point, we consider a particular industrial sector with individual firms. For simplicity, we suppose that all firms have access to the same production function for the final good (the representative firm assumption). Thus, the representative (or aggregate) production function in this particular sector is written as:

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

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

We assume that the production function exhibits constant returns to scale in capital and labor (standard rival inputs). More specifically:

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

for all $\lambda > 1$. Intuitively, when capital and labor double, the firm can open a replica of the same production facility that doubles the outputs of final goods. Naturally, endogenizing A leads to increasing returns to scale to all three inputs K, L, and A, because knowledge A (as a nonrival input) is freely accessible to new facility, and new production facility does not need to replicate A. More specifically, the property of increasing returns can 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 will be made by using an advanced technology $\lambda \times A$, with the same amount of capital and labor inputs. The second equity comes from the constant returns to scale in K and L. Clearly, the condition $F(\lambda K, \lambda L, \lambda A) > \lambda \cdot F(K, L, A)$ implies the increasing returns to scale in K, L, and A. That is, when the inputs of capital, labor, and technology double, the new production facility will more than double outputs. This property thus implies that in a competitive market the firms can make positive profits from using more non-rival inputs of knowledge.

Intuitively, since the non-rival knowledge can be used as many units as desired without incurring further costs, a larger size of market will induce firms to use more of the non-rival knowledge for pursing increasing returns and profitability – the so-called market size effect. In contrast, there is no market size effect for the standard rival inputs like labor and capital. That is, a larger size of market does not necessarily induce firms to use them more intensively, because more outputs produced (for serving a larger market) means that more of the rival inputs have to be used and incur more costs. There is thus no profit gain from using more standard rival inputs (as suggested by the property of constant return to scale).

We now use the market size effect to explain the slow pace of energy innovation. It is notable that energy technologies are capital-intensive with a large part of rival "hardware". [9] Putting it into the production function $F(K, L, A)$, we find that with knowledge as a minor input $A \gg 0$, Eq. (3) become $F(\lambda K, \lambda L, \lambda A) \approx F(\lambda K, \lambda L, A) = \lambda \cdot F(K, L, A)$ ($\lambda \cdot A \approx A$ given $A \gg 0$). This implies that production technology in energy sectors is more likely to exhibit a constant return to scale and thus zero profit gain from making use of energy technology in a larger market. As a result, energy technology with higher inputs of rival capital is less likely to take advantage of the market size effect, slowing the innovation and diffusion speed of new energy technology in the marketplace.

In contrast, IT technologies are often characterized by lower capital intensity and higher knowledge intensity in terms of using innovative ideas and knowledge as major parts. This trend becomes more evident as applications of new-generation IT products are increasingly intertwined with software, internet, and digital services that *de facto* are free of capital - the

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[9] 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).

so-called asset-light mode of innovation. With a larger contribution of knowledge $A >> 0$, production function will become $F(\lambda K, \lambda L, \lambda A) > F(\lambda K, \lambda L, A) = \lambda \cdot F(K, L, A)$ ($\lambda A > A$ given $A >> 0$). This implies that production technology in IT sectors exhibits a substantial degree of increasing returns to scale and thus positive profit gains from using IT technology in new marketplaces. Accordingly, the knowledge-intensive IT technology is more likely to mobilize the market size effect for accelerating technology innovation and diffusion.

4. Market Structure Effect

4.1 Supply-side structure

We next turn to investigating the effect on innovation of market structure in both the supply (Section 4.1) and the demand sides (Section 4.2). Before discussing the differences between energy and IT market structures, we need to distinguish the characteristics of products. In general, products produced by different energy technologies feature a substantial degree of homogeneity. Energy products, often as a homogenous commodity input into intermediate and final use, have less differentiation in terms of variety, attribute, and function. By contrast, IT products are characterized by a substantial degree of heterogeneity in varieties, and there is the differential function and utility from consuming differentiated IT product varieties.

Accordingly, energy innovation features a pattern of "process innovation": innovation that reduces the costs of producing existing products. Introduction of new power generation technology that produces electricity (existing products) at a lower cost is such an example. In this context, energy innovations typically incur direct price competitions and replacements between technology incumbents and innovators (with different costs of producing the same homogenous energy goods).[10] The competitive nature of innovation thus implies that there is an inherent conflict of interests between incumbents and innovators, and the incumbents will become a natural constituency in favor of certain types of distortionary policies that limit market entry and shape a monopolistic market structure in energy industries.[11]

[10] In contrast, IT innovations are characterized by a pattern of "product innovation": innovations create products with differentiated function, attributes, and utility. 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.

[11] 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.

To explain it, we suppose that the current incumbent energy firm has a leading-edge technology that produces energy at the 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 firm owning the leading-edge technology at time t is represented as:

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

where $\pi(c,t)$ denotes the current flow profits of the incumbent firm that produces energy at the lowest MC c at time t. $p(c,t)$ and $x(c,t)$ are endogenous price and quantity choices of the incumbent firms for maximizing intertemporal profit. Eq. (4) assumes that at each time point t, only the leading-edge technology (that produces energy at the lowest MC) is adopted in production. This treatment thus reflects the competitive nature of innovation in the energy domain: when an energy technology with a lower MC of production is created, it will replace the incumbent energy technology.[12]

We proceed by rewriting the value function $V(c,t)$ in a Hamiltion-Jacobi-Bellman (HJB) form given by:

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

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 of interest rates and monopolistic profits, respectively. The last term reflects the competitive essence of innovation: the existing incumbent will lose its monopoly position and be replaced by new innovators (who have technologies that produce at a lower cost) – the so-called Schumpeterian creative destruction (Schumpeter, 1934; 1942).

Accordingly, $z(c,t)$ represents the rate at which innovation occurs at time t (the rate at which the technology incumbent is replaced by new entrants). Consider in a balanced growth path (BGP) equilibrium, where interest rate, flow profit, and the rate of innovation are all constant over time, $r(t) = r^*$, $\pi(c,t) = \pi^*$, $z(c,t) = z^*$, for all t. A BGP also implies a constant maximized value $\dot{V}(c,t) = 0$, then from Eq.(5), we derive:

[12] 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.

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

where in a BGP equilibrium the value possessed by technology incumbents V^* depends on an effective discount rate $r^* + z^*$. To maximize the value V^*, technology incumbents tend to lower the rate of innovation z^* by erecting entry barriers. With the entry barriers raising start-up costs, the incentives of new entrants to innovate will be discouraged, leading to innovation and replacement at a slower rate.

Intuitively, due to the homogeneity of energy goods, energy innovation often comes with direct price completion and conflicts of interest, in the sense that innovators will replace the monopoly positions enjoyed by current incumbents. This raises the possibility that market regulations limiting new entrants may arise as a way of protecting the monopolistic profits of politically powerful incumbents.[13] A monopolistic structure is thus likely to emerge in energy markets, which is different from the competitive market structure in IT industries where innovators have free entry into the deregulated markets.

As a consequence, private firms in the regulated energy markets have lower incentive to innovate as compared to those in the deregulated IT markets. To explain this point, image that in the deregulated IT market, there is a large number N of competitive firms with access to the existing technology that produces one unit of final product at the MC $\psi > 0$. Suppose that one of these firms has access to R&D for advancing technology, if this firm incurs a cost $\mu > 0$ on R&D spending, it can innovate and reduce the MC to ψ / λ, where $\lambda > 1$.

In an equilibrium without R&D and innovation, this firm will charge a price that is equal to MC, $P_I^N = \psi$, where the superscript "N" is the no-innovation case, and the subscript "I" denotes the IT market. The resulting profit gains of this firm will be:

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

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

Consider that if this firm carries out innovation and creates a new production technology, it will obtain a fully enforced patent to protect the innovation excludability and thus possess

[13] 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 makes 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.

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 firm considered will have 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" denotes an innovation case. If this innovating firm spends $\mu > 0$ on R&D, it will innovate and reduce its MC of production to $\lambda^{-1}\times\psi$. To maximize monopoly profits, this innovating firm will set a monopoly pricing rule as:

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

where the profit-maximizing monopoly pricing rule is set as the constant markups over the MC. ε_D denotes the elasticity of market demand. The innovating firm chooses the monopoly price P_I^I, and captures an market $D(P_I^I)$.[14] It can be verified that the profits made by this innovating 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 is potentially profitable with an *ex post* monopoly.

As compared to zero profit $\pi_I^N = 0$ in the equilibrium without innovation, the firm in question has an incentive to innovate for pursing positive profit gains $\pi_I^I > 0$. This situation corresponds to the deregulated IT market where we start with perfect competitions among a large number of competitive 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 a firm in the competitive IT market.

Let's turn to the energy market with entry controls. The same environment is assumed as in IT markets, but the exception is that in the energy market there is already a monopolist incumbent that has the existing technology to produce energy at $MC = \psi$. With an existing monopoly position, this incumbent firm will choose its monopoly price as:

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

[14] 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, $P_I^I \leq \psi$.

where the superscript "N" corresponds to the 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 the MC to $\lambda^{-1}\cdot\psi$, this energy incumbent make 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: $\Delta\pi_E^I = \pi_E^I - \pi_E^N = D(P_E^I)\cdot(P_E^I - \lambda^{-1}\cdot\psi) - \mu - D(P_E^N)\cdot(P_E^N - \psi)$.

It is verified that $\Delta\pi_E^I < \Delta\pi_I^I$, that is, the value of innovation to a monopolist incumbent firm in the energy market is less than that to a competitive firm in the IT market. As a result, the monopolist incumbent in the energy sector has a lower incentive to innovate than do the competitive firms in the IT sector.[15] This result provides the following economic intuitions: in the regulated energy market, innovation often reduces the monopoly profits of the technology incumbent in making use of its existing profit-making technologies, energy incumbents thus have lower incentive to innovate and replace their own existing technologies. In contrast, firms in the competitive IT market have zero *ex ante* profit to replace, and thus have stronger innovation incentive to escape competition for positive *ex post* profits gains.[16]

4.2 Demand-side structure

In this section, we turn to the demand-side market structure and its effect on innovation. The

[15] 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).

[16] 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).

history of past energy transitions highlights the importance of consumers and their demands in pulling new technologies into widespread market diffusion. Having a good understanding of the consumer preferences and behaviors thus holds important implications for identifying the factors that slow energy technology innovation.

Building on the workhorse model of Dixit-Stiglitz monopolistic completion (Dixit and Stiglitz, 1977), we consider an economy admitting a representative consumer with preferences for two types of goods:

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

where C is a composite index of the consumption of a particular product (e.g., energy or IT product), and y denotes consumptions of the numeraire good. The quantity index, 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:

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

where c_i denotes 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, and we assume that $\varepsilon > 1$.

The composite index of the consumption bundle C is often referred to as a "Dixit-Stiglitz preference", which is characterized by a *love-for-variety* effect. To see this feature, we consider the case in which the consumer chooses a total of $\bar{C}$ units of this particular product, distributed equally across the N differentiated varieties: $c_1 = \cdots = c_N = \bar{C} / N$. Substituting it into the utility function in Eq. (12), we obtain:

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

which is strictly increasing in the variety N given the elasticity of substitution, $\varepsilon > 1$. This implies that for consumptions of a fixed total $\bar{C}$ 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. This reflects the essence of the *love-for-variety* preferences.

To analyze the effects of consumer's *love-for-variety* preferences on innovation, we solve the consumer problem of maximizing the utility Eq. (12) subject to the budget constraint as:

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

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.

The problem can be solved in two steps. First, whatever the value of the consumption bundle, C, each variety c_i is chosen so as to minimize the cost of attaining C. This means solving the expenditure minimization problem as:

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

Solving this problem gives the isoelastic demand function for each individual variety c_i of this particular product as:

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

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

denotes the ideal price index, which measures the minimum cost of purchasing a unit of the composite index C of that particular goods. As Eq. (17) shows, market demands for each product variety declines as its price rises. This implies that the firm producing each product variety faces a downward-sloping demand curve and has some degree of monopolistic power (the feature of Dixit-Stiglitz monopolistically competitive market structure).

In the second step of solving the consumer's problem, the consumption choice between C and y is determined by maximizing the utility function Eq. (12) subject to the budge constraint:

$$\max_{C,y} \quad u(C,y) \qquad s.t. \quad P \cdot C + y \leq m \tag{19}$$

where the budge constraint, Eq. (19), is equivalent to Eq. (15), both representing expenditure on consuming the particular product C. The F.O.C. to this problem gives equality of marginal rates of substitutions to the price ratios between C and y:

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

where the joint concavity of $u(C,y)$ and the budge constraint $P\cdot C+y=m$ implies that this FOC can be rewritten as:

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

for some explicit function $g(.,.)$ that is increasing in its first argument P.

Next we turn to the production side of the economy. Suppose that each product variety is produced and supplied by a particular firm facing a constant MC of production that is equal to ψ, we thus specify the profit maximization problem of this monopolistic firm as:

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

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 of production:

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

for each product variety $i=1,2,..,N$. Since each firm i producing variety c_i charges the same monopolistic price, the ideal price index P can be rewritten as:

$$P=(N\cdot p^{1-\varepsilon})^{\frac{1}{1-\varepsilon}}=N^{-\frac{1}{\varepsilon-1}}\cdot p=N^{-\frac{1}{\varepsilon-1}}\cdot\frac{\varepsilon}{\varepsilon-1}\cdot\psi \tag{24}$$

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 this firm as:

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

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

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

Now we substitute for P from Eq. (24) into Eq. (21) and Eq. (26), and capture the effects of consumer's *love-for-variety* preferences on innovation by firms as:

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

and

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

It can be verified that depending on the function of $g(.)$, consumer's aggregate consumption C and firms' profits π are increasing in the number of differentiated product varieties N. A greater number of available varieties typically reduce profits made by the firm producing each product variety, the *love-for-variety* effect embedded in the Dixit-Stiglitz preference, however, creates a countervailing effect that potentially increases market demand and profits. Intuitively, the *love-for-variety* effect serves as a positive pecuniary externality, in the sense that introduction of a new variety has a positive effect to raise the demand for other varieties. As a result, a larger number of varieties N raise the utility from consuming that particular product and boost output sales and profits gains in producing that particular product.

This result thus helps explain a key reason for the slow pace of energy innovation. Since the homogenous energy products have a small number of differentiated varieties, the positive pecuniary externality is thus weaker, leading to lower market demands for energy products.[17] The lower demands then shrink the output sales and corporate profits of energy firms, giving rise to a lower level of financial resources for energy R&D and innovation. In contrast, the IT products with a large number of differentiated varieties tend to mobilize the *love-for-variety* effect and positive pecuniary externality. Accordingly, market demands for IT products will be stronger, creating more profit gains to support R&D for developing new product varieties.

5. Policy Implications

So far the above economic analysis has captured the factors inhibiting energy innovation. This section addresses public policy implications of these findings for accelerating energy innovation. An important implication is that sole reliance on traditional innovation policies centering on R&D expenditure (technology-push) proves to be ineffective. Policymaking should target at market-pulling measures that guide and regulate energy supply and demand markets, so that the goal of major technological transformation for a sustainable energy future can be achieved. We thus propose "3D" principles to guide the designs of energy innovation policies as follows.

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[17] 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.

5.1 Downsizing the "heavy" assets of energy technologies

As argued in Section 3 concerning the market size effect, traditional fossil fuel-burning 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 lower pace of technology innovation and diffusion in the market.

To overcome this problem inherent in traditional centralized power generation systems, policymaking should aim to downsize the "heavy" assets of existing 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 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 advantage of the market size effect, the thin-film cells are expected to gain growing market shares and achieve large-scale deployments in the decentralized household networks.

5.2 Deregulating the monopolistic energy-supplying markets

As articulated in Section 4.1 (supply-side market structure), new energy technology often faces potential conflicts of interest with existing incumbents (due to the replacement effect). This raises the possibility that market regulations for limiting innovators may arise as a way of protecting the monopolistic rents of current technology incumbents. The monopolist thus has lower incentives to innovate than does the firms in a competitive industry.

Therefore, to stimulate innovation incentives in energy industries, policymakers should take measures to create an "innovator-friendly" competitive energy market through structural reform. Antitrust and deregulation are particularly needed to support the entry of new firms. As new entrants have stronger incentives to innovate, transforming the monopolistic energy market structures into an efficient, competitive organizational form is a key step to boosting competition and innovation in the energy sectors. Consider the worldwide PV industry, this flourishing field of new energy technology is largely due to its competitive market structure that features intense inter-firm competitions, where vigorous competitions play a crucial role in substantial improvements of the technical performance of this new technology.

5.3 Differentiating the homogenous energy products

As proposed in Section 4.2 (demand-side market structure), energy technology is less likely to take advantage of the *love-for-variety* effect and positive pecuniary externality due to a lower level of varieties differentiation. As a result, consumer demands for energy products are lower, shrinking corporate profits available to fund energy technology R&D.

It is worth noting that the substantial homogeneity of energy products is largely due to the "no intervention" market conditions that fail to internalize the non-market environmental externality. Without corrections for the environmental cost of "dirty" energy technologies and the environmental benefit of "clean" ones, both types of technologies largely serve as perfect substitutes. Put differently, with the same market-based benefits (homogenous energy goods), the huge cost gap between "clean" technologies (high production cost) and traditional "dirty" ones (low production cost) necessitates a direct substitution and replacement of the latter for the former.

In this context, to catalyze the *love-for-variety* effect and positive pecuniary externality, one of policy priorities is to differentiate energy product varieties by distinguishing fossil fuel-burning energy technologies with environmental-friendly ones in terms of their different environmental costs and benefits. Hence, two policy schemes should be explicitly considered. One is non-economic instruments. For instance, government should launch specific education programs to promote the environmental awareness of individuals, so that their utilities will spontaneously value environmental attributes embedded in clean energy technologies. With the environmental quality valued by consumer preferences, clean energy technology is more likely to become a distinct variety (an imperfect substitute) from traditional fossil one, thus catalyzing the *love-for-variety* effect and positive pecuniary externality to accelerate energy technological innovation.

The other policy scheme includes the economic instruments that convert the non-market immeasurable environmental benefits into measurable market-based values. For example, the non-market environmental values possessed by clean energy technologies can be materialized by creating a market for environmental goods. In this regard, carbon markets should thus be established to provide expectations on the distinct values of carbon savings and incentives to create clean technologies. While carbon markets play a pivotal role in fostering long-term energy innovation, it is still necessary to implement complementary policy to stabilize and underpin the price of carbon in the short term,[18] which includes both price and quantity instruments. For the former, considerations should be given to fiscal incentives such as feed-in tariffs, tax credits or subsidies for renewable energy, and carbon tax on fossil fuels.[19]

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[18] 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.

[19] 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

The quantity tools include renewable quantitative portfolio standards mandated by the government.[20]

6. Conclusions

Energy technological innovation and innovation-enhancing policies have drawn substantial attentions as a way of addressing the twin challenges of energy security and climate change. However, the fact is that the energy sector still faces a surprisingly low level of innovation. This paper adopts a positive economic framework to explore the mechanism of energy innovation and capture the main causes that slow energy innovation.

We find that energy technology that intensively uses rival input of capital often exhibits constant returns to scale and zero profit gain in making use of energy technology in a larger market. As a result, energy technology often finds it difficult to take advantage of the *market size effect*, thus slowing the innovation and diffusion of energy technology in the market.

Our findings also suggest that the homogeneous nature of energy goods will bring about *market structure effects*. On the one hand, in energy supply side the homogeneity potentially incurs competition between technology incumbents and innovators. This raises the possibility that a monopolistic market structure limiting new entrants may arise as a way of protecting the monopolistic rents of incumbents. Energy incumbents enjoying their own profit-making technologies thus have lower incentives to innovate than do new entrants in a competitive energy market. On the other hand, on the energy demand side the homogeneity implies that energy technology is less likely to catalyze the consumers' *love-for-variety effect* and positive pecuniary externality. This leads to lower market demands for energy products and corporate profits of energy firms, which shrinks the financial resources for energy R&D and innovation.

Based on the understanding of the market size and market structure effects, we propose the following three overarching policy principles: (1) downsizing the "heavy" assets of capital-intensive technology portfolios by integrating knowledge-intensive, small-scale decentralized "light" technology assets; (2) deregulating the monopolistic energy-supplying markets by promoting vigorous competition and the entry of new firms; and (3)

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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.

[20] 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.

differentiating the homogenous energy products by distinguishing fossil energy technologies with environmental-friendly ones on the energy-demand side. These general principles may serve to guide specific policymaking aimed to accelerate energy technological innovation.

References

Acemoglu, D., 2002. Directed technical change. Review of Economic Studies 69, 781-809.

Aghion P., Blundell R., Griffith R., Howitt P., Prantl S., 2009. The effects of entry on incumbent innovation and productivity. The Review of Economics and Statistics 91(1), 20-32.

Aghion, P, Bloom, N., Blundell, R., Griffith, R., Howitt, P., 2005. Competition and innovation: an inverted-U relationship. Quarterly Journal of Economics 120(2), 701-728.

Anadon, L., 2010. Missions-oriented RD&D institutions in energy between 2000 and 20120: a comparative analysis of China, the United Kingdom, and the United States. Research Policy 41(10), 1742-1756.

Anadon, L., Holdren, J., 2009. Policy for energy technology innovation. Chap. 5 in Acting in time on energy policy. Brookings Institution Press. Washington, D.C.

Arrow, K., 1962a. The economic implications of learning by doing. The Review of Economic Studies 29(3), 155 - 173.

Arrow, K., 1962b. Economic welfare and the allocation on resources for invention. In Nelson, R. R. (ed.), The rate and direction of inventive activity: Economic and social factors. Princeton University Press. Princeton.

Arthur , B. , 1989. Competing technologies, increasing returns, and lock-in by historical events. The Economic Journal 99 (394), 116–131.

Arthur, W., 2007. The structure of invention. Research Policy 36 (2), 274-287.

Bergek, A., Jacobsson, S., Carisson, B., Lindmark S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. Research Policy 37 (3), 407–407.

Cohen, W., Levin, R., 1989. Empirical studies of innovation and market structure. In Schmalensee, R. and Willig R., (eds.), Handbook of industrial organization, vol. 2, Elsevier.

Comanor, W., 1967. Market structure, product differentiation, and industrial research. Quarterly Journal of Economics 81(4), 639-657.

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

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

Dixit, K, Stiglitz, J., 1977. Monopolistic competition and optimum product diversity. American Economic Review 67 (3): 297-308.

Dosi, G., 1982. Technological paradigms and technological trajectories: a suggested interpretation of the determinants and direction of technical change. Research Policy 11, 147-162.

Frankel, M., 1955. Obsolescence and technological change in a maturing economy. American Economic Review 45 (3), 296–320.

Freeman, C., 1994. The economics of technical change. Cambridge Journal of Economics 18 (5), 463–463.

Freeman, C., Soete, L., 1997. The economics of industrial innovation. The MIT Press, Cambridge, MA.

Gallagher, K., Grübler, A., Kuhl, L., Nemet, G., Wilson, C., 2012. The energy technology innovation system. Annual Review of Environment and Resources 37, 137-162.

Gallagher, K., Holdren, J., Sagar, A., 2006. Energy technology innovation. Annual Review of Environment and Resources 31, 193-237.

Geels, F., 2004. From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory. Research Policy 33(6): 897-920.

Gibbons, M., Johnston, R., 1974. The roles of science in technological innovation, Research Policy 3(3), 220–242

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

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

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

Grubb M., Koehler, J., Anderson, D., 2002. Induced technical change in energy/environmental modelling: analytic approaches and policy implications. Annual Review of Environment and Resources 27, 271-308.

Grubb, M., 2004. Technology innovation and climate change policy: an overview of issues and options. Keio Economic Studies 41(2): 103-132.

Grübler, A., Aguayo, F., Gallagher, K., Hekkert, M., Jiang, K., Mytelka, L., Neij, L., Nemet, G., Wilson, C., 2012. Policies for the energy technology innovation system. Chap. 24 in Global energy assessment - Toward a sustainable future. Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria, pp. 1665-1744.

Grübler, A., Nakićenović N., Victor, D., 1999. Dynamics of energy technologies and global change. Energy Policy 27 (5), 247–280.

Grübler, A., Nakićenović, N., Victor, D., 1999. Modeling technological change: implications for the global environment. Annual Review of Energy and the Environment 24, 545-69.

Hekkert, M., Suurs, R., Negro, S., Kuhlmann, S., Smits, R., 2007. Functions of innovation systems: a new approach for analysing technological change. Technological Forecasting and Social Change 74 (4), 413–432.

Henderson, R., Newell, R., 2010. Accelerating energy innovation: insights from multiple sectors. NBER Working Paper 16529. National Bureau of Economic Research, Cambridge, MA.

Holdren, J., Sagar, A., 2002. Assessing the global energy innovation system: some key issues. Energy Policy 30(6), 465-469.

International Energy Agency (IEA), 2010. Global gaps in clean energy RD&D. Paris:

OECD/IEA.

Jaffe, A., Palmer, K., 1997. Environmental regulation and Innovation: a panel data study. Review of Economics and Statistics 79, 610-619.

Kamien, M., Schwartz, N., 1982. Market structure and innovation. Cambridge University Press.

Kleinknecht, A., Verspagen, B., 1990. Demand and innovation: Schmookler reexamined. Research Policy 19(4), 387-394.

Klevorick, A., Levin, R., Nelson, R., Winter, S., 1995. On the sources and significance of interindustry differences in technological opportunities. Research Policy 24 (2), 185-205.

Lichtenberg, F., 1986. Energy prices and induced innovation. Research Policy 15(2), 67-75.

Loury, G., 1979. Market structure and innovation. Quarterly Journal of Economics 93(3), 395-410.

Lundvall, B., (ed.) 1992. National systems of innovation: towards a theory of innovation and interactive learning. Pinter Publishers, London.

Mansfield, E., 1963. Size of firm, market structure, and innovation. Journal of Political Economy 71(6), 556-576.

Margolis, R., Kammen, D., 1999a. Underinvestment: the energy technology and R&D policy challenge. Science 285, 690-692.

Margolis, R., Kammen, D., 1999b. Evidence of under-investment in energy R&D in the United States and the impact of Federal Policy. Energy Policy 27(10), 575-584.

Markham, H., 1965. Market structure, business conduct, and innovation. American Economic Review 55, 323-332.

Mowery, D., Rosenberg, N., 1979. The influence of market demand upon innovation: a critical review of some recent empirical studies. Research Policy 8(2), 102-153.

Narayanamurti, V., Anadon, L., Sagar, A., 2009. Transforming energy innovation. Issues in Science and Technology (Fall 2009), 57-64.

Nelson, R., (ed.) 1993. National innovation systems: a comparative analysis. Oxford University Press, New York.

Nelson, R., Winter, S., 1977. In search of useful theory of innovation. Research Policy 6(1), 36-76.

Nelson, R., Winter, S., 1982. An evolutionary theory of economic change. Harvard University Press, Cambridge, MA.

Nemet, G., 2009. Demand-pull, technology-push, and government-led incentives for non-incremental technical change. Research Policy 38, 700-709.

Nemet, G., Kammen, D., 2007. U.S. energy research and development: declining investment, increasing need, and the feasibility of expansion. Energy Policy 35(1), 746-755.

Neuhoff, K., 2005. Large scale deployment of renewables for electricity generation. Oxford Review of Economic Policy 21(1), 88-110.

Newell, R, Jaffe, A., Stavins, R., 1999. The induced innovation hypothesis and energy-saving technological change. Quarterly Journal of Economics 114, 907-940.

Newell, R., 2008. A U.S. innovation strategy for climate change mitigation. The Brookings Institution, Discussion Paper 2008-15, December 2008.

Newell, R., 2010. The role of markets and policies in delivering innovation for climate change mitigation. Oxford Review of Economic Policy 26(2), 253-269.

Newell, R., 2011. The energy innovation system: a historical perspective. In accelerating energy innovation: insights from multiple sectors. Edited by R.H. Henderson and R.G. Newell. University of Chicago Press for the National Bureau of Economic Research.

Newell, R., Jaffe, A., Stavins, R., 1999. The induced innovation hypothesis and energy-saving technological change. The Quarterly Journal of Economics 114(3), 941–975.

Noberg-Bohm, V., 2000. Creating incentives for environmentally enhancing technological change: lessons from 30 years of US energy technology policy. Technological Forecasting and Social Change, 65, 125-148

Popp, D., 2002. Induced innovation and energy prices. American Economic Review 92, 160–180.

Popp, D., Newell, R., Jaffe, A., 2009. Energy, the environment, and technological change. NBER Working Paper 14832. National Bureau of Economic Research, Cambridge, M.A.

Rivera-Batiz, L., Romer, P., 1991. Economic integration and endogenous growth. Quarterly Journal of Economics 106, 531–555.

Romer, P., 1986. Increasing returns and long-run growth. Journal of Political Economy 94, 1002-1037.

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

Rosenberg, N., 1994. Exploring the black box: technology, economics, and history. Cambridge University Press, Cambridge.

Sagar, A.D., van der Zwaan, B., 2006. Technological innovation in the energy sector: R&D, deployment, and learning-by-doing. Energy Policy 34, 2601-2608.

Scherer, F., 1965. Firm size, market structure, opportunity, and the output of patented inventions. American Economic Review 55(5), 1097-1126.

Schmookler, J., 1962. Economic sources of inventive activity. Journal of Economic History 22 (1), 1-20.

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

Schumpeter, J., 1934. The theory of economic development. Harvard University Press. Cambridge, MA.

Schumpeter, J., 1942. Capitalism, Socialism and Democracy. HarperCollins Publishers, New York.

Shrieves, R., 1978. Market structure and innovation: a new perspective. The Journal of Industrial Economics 26(4), 329-347

Sue Wing, I., 2003. Induced technical change and the cost of climate policy. Joint Program on the Science and Policy of Global Change Report no. 112. MIT, Cambridge, MA.

Sutton, J., 1996. Technology and market structure. European Economic Review 40(3), 511-530.

Unruh , G., 2000. Understanding carbon lock-in. Energy Policy 28 (12), 817–830.

von Hippel, E., 1976. The dominant role of users in the scientific instrument innovation process. Research Policy 5(3), 212–239

Walsh, V., 1984. Invention and innovation in the chemical industry: demand-pull or discovery-push. Research Policy 13(4), 211-234.

Watson, J., 2004: Selection environments, flexibility and the success of the gas turbine. Research Policy 33 (8), 1065–1080.

Weiss, C., Bonvillian, W., 2009. Structuring an energy technology revolution. The MIT Press, Cambridge, MA

Weyant, J., 2011. Accelerating the development and diffusion of new energy technologies: beyond the "valley of death". Energy Economics 33, 674-682

Worrell , E., Biermans, G., 2005. Move over! Stock turnover, retrofit and industrial energy efficiency. Energy Policy 33 (7), 949–962.

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