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環境創新國際研討會
發表論文與會議心得報告書

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摘　要

參加此會議的目的為發表論文及與各國學者做學術交流，參加此會議之正式名稱是2011年慶應大學環境創新國際研討會，由KeioUniversity籌畫主辦，會議在十二月十六日到十七日之間在日本東京慶應大學舉行， 全程共安排了 6 場次，每場十五分鐘的演講與論文簡報，本人有幸參與該次會議發表論文，獲益良多。本屆會議出席人員有150位學術界精英及專家學者。本屆研討會秘書處由眾多的投稿論文中，經論文審查委員會評審後選出 41 篇於會議中發表。本人獲邀發表學術論文乙篇，於12月16日下午3:30作論文發表，本篇論文為永續經營領域文章，發表論文題目為:(中文) 綠色生物科技:創新研究為永續發展;(英文) **Green Biotechnology: A study of innovation for sustainable development**，內容主要是綠色生物科技如何建立管理與行銷競爭優勢, 以生物科技產業為實證個案。實證結果將提供一些公司與政府部門為綠色生物科技產業化發展的策略與經營思考方向，並可為台灣綠色生物科技產業提供創新策略思考模式。本人除了於會議中發表個人學術著作外，亦全程參與相關研究領域的其他學者之論文發表與討論，並和與會的各國學者專家進行學術交流，對於後續在學術研究、教學內容上多所啓迪。主辦單位亦於會議準備時將所有獲邀發表之論文作成論文摘要集，方便與會者於會議期間參閱，於會議結束後攜回，作為繼續從事學術研究的重要參考資料。本屆國際性學術研討會非常成功，議程安排緊密且恰當、獲邀發表的論文皆為佳作，內容新穎、豐富且具創新性。本人能有幸與會感到收穫頗豐，除了能夠精進個人學術專攻永續發展領域的研究能力外，更可透過學術討論交流領略全世界永續發展學術研究趨勢，吸取別人的新知與經驗，有助於未來在永續發展方面之研究思維。

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壹、目　　的

參加此會議的目的爲發表論文及與各國學者做學術交流，參加此會議之正式名稱爲 2011 年慶應大學環境創新國際研討會，由慶應大學籌畫主辦，會議在十二月十六日到十七日之間在東京慶應大學舉行， 全程共安排了 6 場次，每場十五分鐘的演講與論文簡報，本人有幸參與該次會議發表論文，獲益良多。該會議提供來自世界各國的永續發展相關領域之學者專家進行學術交流平台，會議大約有 150 人參加，而且經常有永續發展國際級學者專家及實務界菁英與會，由於主辦單位慶應大學之用心規劃，該會議均受歷屆與會學者之肯定與好評。本屆研討會秘書處由眾多的投稿論文中，經論文審查委員會評審後選出 41 篇於會議中發表。相關統計如下:

Conference Statistics

Number of Submissions: 125

Number of Accepted Papers: 41

Number of Sessions: 6

Rejection Rate: 78%

Number of Authors' Countries: 10

Estimated Number of Participants: 150

貳、過　程

12/15　10:00-14:50　抵達東京，完成研討會報到手續並領取大會手冊及論文集。

12/16　09:00-9:40　參與 Opening Rmarks 的研討議題以適應報告環境，並聽取國際學者之 Keynote Speech。

09:40-10:45　聽取 Session 1: Adaptation and Network Building in the Asia Pacific Region(APAN)的國際學者之論文發表，並與來自美國、日本及台灣的學者進行交流。

11:00-12:15　聽取 Session 1: Adaptation and Network Building in the Asia Pacific Region(APAN)的國際學者之論文發表，並與來自美國、日本及台灣的學者進行交流。

13:15-15:15　參與前場次 Session 2: Approaches to Resilience Building Through Post-disaster Reconstruction 的研討議題以適應報告環境，並聽取國際學者之論文發表。

15:30-17:30　17：00 於 Session 3: Green Economics and Resilient Society in a Post-Fukushima Era 場次針對本研究論文進行口頭報告，聽取 feedback，並與國際學者進行討論，作爲後續論文修正的參考。

發 表 論 文 題 目

(中文) : 綠色生物科技:創新研究爲永續發展

（英文）**Green Biotechnology: A study of innovation for sustainable development**

12/17　09:00-10:15　參與 Session 4: Local Communities and Resiliency in the Face of Climate Change Adaptation 的研討議題，並聽取國際學者之論文發表。

10:45-12:00 參與 Session 4: Local Communities and Resiliency in the Face of Climate Change Adaptation 的研討議題，並聽取國際學者之論文發表。

12:00-13:00 參與大會午宴，並與來自各國的學者進行交流。

13:00-15:00 聆聽 Session 5:Understanding Resiliency Through Project BasedLearning 的論文發表。

15:30-17:30 參與 Session 6: Discussion for further Collaboration 總結報告。

19:00-21:00 參與大會晚宴，並與來自各國的學者進行交流。

參、心得與建議

特別感謝國立中興大學補助經費，2011 年慶應大學環境創新國際研討會主要著重於永續發展之相關課題研究發表，對於本人擔任大學教職之專業教學、研究與服務皆有顯著之幫助，而此次參與會議過程，本人也積極參與許多永續發展專業研究發表與公開社交活動，因此對於本人永續發展學術研究的水準皆能有所貢獻。因為2011 年慶應大學環境創新國際研討會是永續發展學術研究知名的會議之一，許多永續發展學術研究領域的專家學者都出席本會，針對永續發展學術研究領域相關的重要議題,做了精闢的論文發表,使本人受益良多。而在論文發表及 Discussion for further Collaboration 的場次，和來自世界各地的學者交換學術心得，除了增進相關知識外，同時也結交他國的朋友，此為另一寶貴的收獲。

能夠參與這次國際會議，將自己的研究成果呈現出來，並與他人直接面對面討論，不管是在思考、膽量及語言方面都是非常好的訓練及經驗。雖然永續發展會議每年劃分的主題雖然不太一樣，但還是包含了永續發展領域絕大部份的研究，將永續發展研究論文與其他各國研究者分享，覺得有很大的收穫，一方面可以了解其他永續發展研究者對本人發表論文的批評與看法；另一方面，也獲得改善永續發展研究論文的許多建議，可供後續修正與研究參考。此外，能夠參加這類型的國際會議，對於目前各國研究人才水準有一個初步的了解，對於自己的學習與信心有正面的幫助。同時，結識其他各國永續發展研究人員也提供未來研究的機會。

此次會議藉由眾多來自永續發展領域的專家學者對於理論與實務研究的熱忱與討論未來永續發展教育與研究的發展，目的是為了追求更好的學術研究，以及理論與實務之結合。在會議過程中，不同國家的學者針對永續發展相關的主題皆進行廣泛且深入的討論，藉以累積知識，令人獲益匪淺。會議的晚宴，主辦者之致詞、頒發紀念狀、充分交流意見並相約明年再相見的熱絡氣氛下，劃下完美的句點。

肆、附錄二：發表論文

Green Biotechnology: A study of innovation for sustainable development

By Chih-Wen Wu
National Chung Hsing University, Taiwan

Abstract

The goal of this research is to understand how policy can better encourage technological innovation that promotes sustainable development. In particular, this research examined green biotechnology innovations, which are technological processes and products designed to lessen negative environmental and health impacts, while still improving performance and profitability under the climate changes. Globalization has taken its toll in the country providing both positive and negative attributes to the economy. Social issues such as poverty and hunger continue to increase due to the domino effects of illiteracy, unemployment, and unfair distribution of food programs in the developing country. Even though, there are many anti-hunger and anti-poverty programs in the world, the inconsistencies of these programs do not benefit the majority of the people living in poverty. The only way to solve the problem is to implement best practices and manage the flow of funding and the distribution of goods under a one-system paradigm. The author constructed a qualitative model for the green biotechnology innovation system, to identify the major factors that help or impede innovation in that system, and to evaluate the impact on the system of a variety of potential policy interventions. I developed system-specific and general insights about the role of policy in encouraging innovation for sustainability in today's complex and globalizing world. These research findings are: (1) Innovations that promote sustainable development can face additional barriers because their costs and benefits are particularly "leaky" across spatial and temporal boundaries. (2) Innovations for sustainable development seek to address, the system of innovation for sustainable development itself is highly transnational. (3) Regardless of local contexts, technical barriers present a common challenge to the development and implementation of innovations for sustainable development. (4) Efforts to foster innovation for sustainable development need to include analysis of the where in the innovation system interventions are effective. (5) Innovation for sustainable development requires smart, strategic engagement between different combinations of stakeholders. These findings are a foundation for further work to understand the particular intricacies of sustainable innovations. This and future work can be used not just to expand and refine existing theory, but also to improve the ability of policy-makers to craft appropriate and effective policies and programs.

INTRODUCTION

My goal in this research is to understand how policy can better encourage technological innovation that promotes sustainable development. In particular, This study was undertaken with a view toward identifying a number of the key elements for the construction of a new conceptual framework to understand the dynamics of technological innovations that provide both private and social benefit. By analyzing innovations in the biotechnology sector, particularly green biotechnology, which is "is the design of biotechnology products and processes that reduce or eliminate the use or generation of hazardous substances (Anastas and Warner, 1998)". Conceptually, I integrate models of public goods provision with models of innovation systems in order to understand how the knowledge and investment capital of multiple actors can be mobilized in ways that create public as well as private goods. Methodologically, I bring a global systems perspective to bear on a case study of the development and spread of green biotechnology innovations in Taiwan. Empirically, I construct a qualitative model for the green biotechnology innovation system, to identify the major factors that help or impede innovation in that system, and to evaluate the impact on the system (positive or negative) of a variety of potential policy interventions. I develop both system-specific and general insights about the role of policy in encouraging innovation for sustainability in today's complex and globalizing world.

The global population is facing a set of serious challenges. The same technologies that have improved agriculture, medicine, and led to modern manufacturing have also been the source of considerable degradation of environmental resources. The remaining challenges associated with large, global development objectives, like such as the UN Millennium Development Goals, cannot be attained without the use of new technologies. For this reason, it is important to understand how technological innovation can be deployed to promote sustainable development, so that quality of life continues to improve without irreversible harm being done to environmental resources. A large part of the work on innovation systems comes from either the economics or the business literature. The main focus has been the impact of technological innovation on the competitiveness and economic growth of firms (in the business literature) and nations (in the economics literature).

Almost all of this work examines innovation in the context of the private provision of technologies for the market. There is much less work on the role of technological innovation systems which provide public goods. What examples there are come from agriculture and public health, and were for a long time predicated on the assumption that innovation with' a public goods aspect required public investment, either in academic research or in public research centers, with little or no participation from the private sector. There is a need to combine the theory of public goods provision with the theory of innovation systems, in order to better understand the dynamics involved with the provision of innovation for sustainable development. While this research uses an empirical study from the area of green biotechnology, its findings are used to develop an understanding of an expanded conceptual framework for innovation. While it is only a study of a single sector, it helps point to important questions and areas for future research that are needed to create a fuller framework, one that will be more broadly applicable for those technologies crucial to progress towards sustainable development. In the remainder of this article, I present the underlying theoretical background. I also describe the research methodology and the organization of the rest of the research. Finally, a list of the key findings will be discussed.

BACKGROUND

Innovation for sustainable development, from a theoretical perspective, is the intersection of innovation, and sustainable development. This means that there is a basic body of theory that can be applied to the problem as a first step in understanding the phenomena, and also as the foundation for the construction of new conceptual frameworks. Markets, however, almost always deviate from perfect competition. For a variety of reasons, the market is unable to attain the most efficient equilibrium. Understanding which of these failures apply, and the appropriate policy responses, is the first step in a deeper understanding of the real-world dynamics of innovation for sustainable development.

Disaggregating innovation for sustainable development yields two core elements: innovation and sustainable development. I treat the theory of each in turn. First, there is innovation. For the time being, I use the most simplified model of the creation and dissemination of a technological innovation into the market, as a three step process:1. Knowledge production,2. Implementation, and 3. Diffusion. At each step, there are failures that result in deviations from the equilibrium predicted by perfect competition. For knowledge production, the underlying problem is that knowledge, which can also be thought of as research and development, is at least a partial public good. Pure public goods are non-rivalrous (use by one individual does not deplete the resource, or prevent others from using it), and non-excludable (one individual cannot completely control use of the good). Knowledge production, or research, is non-rivalrous, and, in the absence of policy, non-excludable (unless it is kept perfectly secret, which usually defeats the purpose of producing the knowledge to begin with). In this case, one would expect that the market would provide less than the socially optimal amount of knowledge, because once it exists, it can be used by an infinite number of individuals forever, but it is very hard for its creator to benefit from its existence. This provides an incentive for the producers of knowledge to keep it secret for as long as possible. From a societal perspective, this is detrimental, since useful knowledge would have an even larger benefit if it could be used more widely. This is the rationale behind patent law, which encourages disclosure of knowledge, but allows the inventor proprietary rights on its use for a set period of time.

The implementation of a new technology requires more than just the discovery and refinement of knowledge. Theoretically, because of the problems with excludability, a company may underinvest in new technologies. At this point, there is also a problem with imperfect information. For the implementer, new technologies are usually "experience goods (Weimer and Vining 1999)." That is, until an individual experiences their use, their quality is not known with certainty. Since there is no insurance market to deal with uncertainty deriving from using a new technology, once again, economic theory would predict an underinvestment in the implementation of new technologies.

Finally, there is diffusion. As with implementation, there are problems with information failures. Even if a certain technology is known to be effective for one firm, other adopters are uncertain as to how effective it will prove in their own context until after it is in use. Furthermore, there are market failures due to the non-rivalrous and non-excludability of many technologies. Use by one firm does not impact the ability of other firms to use it, nor can they control the number of competitors using the technology. This results in a decreased competitive advantage for adopters, so that the cost of the new technology may be more than the benefit to the firm. These factors can also result in less than optimal investment from the social perspective. The theory described above is just a brief introduction to one set of reasons why we expect to see less than socially optimal investment on the innovation side. Similar fundamental microeconomic theories can be applied to sustainability. We use technology to solve many kinds of problems, but it has also played a role in a range of environmental disasters, from polluted air and water, to resource depletion, toxic contamination, and global climate change. Often technologies designed to solve one particular problem allow for increases in population and affluence that create new environmental challenges, and thus require yet another technological improvement.

There are fundamental reasons why sustainable development would not be the expected outcome of an unregulated competitive market (one where policy is completely absent). Technological development frequently results in externalities (one of the four basic market failures). Beyond this, sustainable development is a dynamic phenomenon, which brings with it a whole new set of problems relating to the allocation of costs and benefits over time. It can also result in the uncertainty inherent in the long time frames which are needed to evaluate the impact of current decisions on future generations. Externalities are the first problem that needs to be addressed in order to understand the challenges in achieving sustainable development, even in theory. Releasing pollution allows the producer to operate at a lower cost, because the impacts are borne by others. So in the absence of laws or other policies, the producer of the pollution has no economic incentive to spend any money reducing their environmental impact. This is despite the fact that the pollution produced may have a real social cost. Coase approached the problem by showing how, depending oh the utilities and prices involved, those negatively impacted by the pollution could pay the polluter to decrease their level of pollution. But this works best where there are no transaction costs. In reality, high transaction costs and the broad impacts of pollution mean that the problem can rarely be solved by a limited number of parties bargaining among themselves. Dealing with externalities that have a broad social effect, both over time and space, are the core reasons behind environmental regulatory policy.

Sustainability also deals with questions of inter-generational equity. Since many of those who will be affected by pollution have not even been born, they are not able to participate in the "market" for pollution. On the other hand, while they may be negatively impacted by some aspects of technological development, they also receive benefit from its development aspect without having to pay for it. The choices of earlier generations have a direct impact on those who follow them. This dynamic aspect complicates the possibility of a market reaching a socially optimally equilibrium. The convention in economics for valuing future benefits is to set a discount rate that places a much higher value on the present (Pezzey 1992). This is justified in a number of ways, including with the argument that future generations will be rich enough to pay to mitigate negative impacts ; the best social outcome is to maximize the short term benefits, and not to take into account either benefits or costs that accrue over the very long term. The counter argument is that if the negative impacts are very large, then future generations may be less well off than the current generation, which provides a counter-argument for negative discounting.

This presents a challenge, especially for very long-term policy challenges such as climate change. Since choices of discount rate are matters of preference on the part of those conducting research or analysis, they can become very controversial and often reflect philosophy, as well as financial analysis (Stern 2008; Beckerman and Hepburn 2007, 187; Dasgupta 2007; Nordhaus 2007; Nordhaus 2007; Stern and Stern 2007; Weitzman 2007; Tol 2006).

Finally, the element of uncertainty emerges in sustainability, which is not surprising, given its dynamic and long-term lens. No one knows the future state of the world, and this can severely complicate decision making. For example, models that investigate the costs of policies to combat climate change have to make intelligent predictions about the costs of oil, coal, and other energy sources for decades into the future. A historical examination of oil price predictions reveals that these have never proven to be accurate. Events such as $140bbl oil remain, at present, impossible to predict. However, they do happen, and they can have a dramatic impact. There are ways to deal with this kind of uncertainty, including techniques like scenario planning, but it is difficult and time-consuming. This kind of uncertainty is even more difficult for decision makers and scientists.

Broadly, the potentially harmful consequences of economic activities on the environment constitute an ―externality, an economically significant effect of an activity, the consequences of which are borne by a party or parties other than the party that controls the externality-producing activity. In the case of climate change, activities by firms that emit greenhouse gas(GHGs) into the environment impose a cost to society. The firm that owns the factory has an economic incentive to use only as much labor or steel as it can productively employ, because those inputs are costly to the firm. The cost to society of having some of its labor and steel used up in a given factory is internalized by the firm, because it has to pay for those inputs. But the firm does not have an economic incentive to minimize the external costs of climate change. Climate change policies may attempt to equalize this imbalance by raising the incentive for a firm to minimize the climate change externality. Policy choices accomplish this in one of two general ways—either by financially internalizing the climate change costs so the firm makes its own decisions regarding its production of GHGs, or by imposing a limit on the level of GHGs the firm may emit.

The cost of climate change policies could be in the form of decreased output of desired products, increased use of other variable inputs, purchase of specialized control equipment, or substitution of inferior or more expensive products or production methods to avoid GHG-emitting products or methods. In the short run, setting an efficient climate change policy requires a comparison of the marginal cost of reducing GHGs with the marginal benefit of a cleaner environment. When technology enters the equation, the terms of the tradeoff between the marginal cost of GHG reduction and its marginal social benefit is altered. In particular, technology innovations typically reduce the marginal cost of achieving a given unit of GHG reduction. In most cases, technological change enables a specified level of environmental cleanup or GHG avoidance to be achieved at lower total cost to society. New innovations also make it possible for a lower total level of GHG emissions to be attained more efficiently than would be expected if the cost were higher.

LITERATURE REVIEW

The concept of induced innovation recognizes that research and development (R&D) is a profit-motivated investment activity and that the direction of innovation likely responds positively in the direction of increased relative prices. Since environmental policy implicitly or explicitly makes environmental inputs more expensive, the ―induced innovation,hypothesis suggests an important pathway for the interaction of environmental policy and technology, and for the introduction of impacts on technological change as a criterion for evaluation of different policy instruments.

Innovation generated by policies that establish a GHG emission price is sure to come from a wide array of businesses currently engaged in the development and use of energy producing and consuming technologies, especially in the provision of electricity and transportation services. It will also come from the agro-biotech sector (assuming there are incentives for biological sequestration), from companies that produce and consume other non-CO2 GHGs (e.g., chemical companies), and from less obvious sectors such as the information technology industry (e.g., in the context of energy management and conservation). Estimates suggest that private-sector investments in energy R&D, however, have fallen significantly in real terms since peaking around 1980, in tandem with declines in energy prices and public energy R&D spending. Nonetheless, while the trend appears to have been downward over this period, current private-sector R&D investments relevant to energy technology are extremely difficult to assess, and these estimates provide a poor indication of the overall level of private-sector R&D investment that could and likely will be brought to bear on the climate technology challenge (Newell 2008a).

In the environmental literature, the relationship between innovation and policy has been explored under two broad themes. Early work focused on theoretical models to compare the effects of various environmental policy mechanisms (e.g., uniform standards, emissions taxes, or tradable permits) on environmentally friendly innovation. These papers tend to predict that market-based policies, such as a tax or tradable permit, will induce more environmentally friendly innovation than a command-and-control policy, although recent papers have shown that a precise ranking is theoretically ambiguous and dependent on a number of factors (see, e.g., Fischer et al. 2003). Empirical studies of the links between environmental policy and innovation were initially limited by a lack of data. Recently, as measures of innovative activity such as patents have become more readily available, empirical economists have begun to estimate the effects that prices and environmental policies have on environmentally friendly innovation.

Popp attributes the gradual decrease in induced innovation over time to diminishing returns. Furthermore, Popp (2002) shows that controlling for diminishing returns to research within a specific field does affect induced innovation estimates. To verify the importance of the existing knowledge stock on innovative activity, Popp uses citation data to create stocks of existing patented knowledge, where patents in the stock are weighted by their propensity to be cited. He finds that the stocks have a significant positive effect on energy patenting. Moreover, both Popp (2002) and Popp (2006c) find evidence that the likelihood of citations to new energy patents falls over time, suggesting that the quality of knowledge available for inventors to build upon also falls. The intuition here is that, as more and more discoveries are made, it gets harder to develop a new innovation that improves upon the existing technology. Since the quality of the knowledge stock is an important determinant of the level of innovative activity, decreasing quality of the knowledge stock over time means that diminishing returns to R&D investment will result in lower levels of induced R&D over time. Moreover, because prior research affects the potential success of future inventors, the returns to research should vary along with the quality of the existing pool of research, rather than monotonically over time.

To verify the value of using patent citation data to measure the returns to research, Popp (2002) also includes regressions in which the stock of knowledge is replaced by a time trend. If diminishing returns proceed monotonically over time, a negative time trend should work as well as the weighted knowledge stocks. That, however, is not the case. These regressions prove unreliable. In fact, the elasticity of energy R&D to energy prices appears negative when a time trend is used in place of the knowledge stocks. Since diminishing returns are a bigger problem when the level of energy R&D is highest, not controlling for this counteracts the positive effect of prices on energy R&D.

Newell et al. (1999) examine the extent to which the energy efficiency of the menu of home appliances available for sale changed in response to energy prices between 1958 and 1993, using an econometric model of induced innovation as changing characteristics of capital goods. Hicks formulated the induced innovation hypothesis in terms of factor prices. Newell et al. (1999) generalize this concept to include inducement by regulatory standards, such as labeling requirements that might increase the value of certain product characteristics by making consumers more aware of them. They find that significant amounts of innovation are due to changes in energy prices and changes in energy-efficiency standards. Most of the response to energy price changes came within less than five years of those changes. Illustrating the importance of information, they find that the effect of energy-price increases on model substitution was strongest after product labeling requirements took effect.

The earliest work that is directly relevant is by Magat (1978), who compares effluent taxes and CAC standards using an innovation possibilities frontier model of induced innovation, where research can be used to augment capital or labor in a standard production function. He compares the output rate, effluent rate, output-effluent ratio, and bias (in terms of labor or capital augmenting technical change), but produced ambiguous results. Subsequently, Magat (1979) compares taxes, subsidies, permits, effluent standards, and technology standards, and shows that all but technology standards would induce innovation biased toward emissions reduction. In Magat‘s model, if taxes and permits are set so that they lead to the same reduction in emissions as an effluent standard at all points in time, then the three instruments provide the same incentives to innovate.

It was only recently that theoretical work followed up on Magat‘s attempt in the late 1970‘s to rank policy instruments according to their innovation-stimulating effects. Fischer et al. (2003) find that an unambiguous ranking of policy instruments was not possible. Rather, the ranking of policy instruments depended on the innovator‘s ability to appropriate spillover benefits of new technologies to other firms, the costs of innovation, environmental benefit functions, and the number of firms producing emissions. The basic model consists of three stages. First, an innovating firm decides how much to invest in R&D by setting its marginal cost of innovation equal to the expected marginal benefits. Second, polluting firms decide whether or not to adopt the new technology, use an (inferior) imitation of it, or do nothing. Finally, firms minimize pollution control expenditures by setting their marginal costs equal to the price of pollution. Policy instruments affect the innovation incentives primarily through three effects: (1) an abatement cost affect, reflecting the extent to which innovation reduces the costs of pollution control; (2) an imitation effect, which weakens innovation incentives due to imperfect appropriability; and (3) an emissions payment effect, which can weaken incentives if innovation reduces firms‘ payments for residual emissions. The relative strength of these effects will vary across policy instruments and particular applications, with no instrument clearly dominating in all applications.

In an analysis that is quite similar in its results to the study by Fischer et al. (2003), Ulph (1998) compares the effects of pollution taxes and command-and-control standards, and finds that increases in the stringency of the standard or tax had ambiguous effects on the level of R&D, because environmental regulations have two competing effects: a direct effect of increasing costs, which increases the incentives to invest in R&D in order to develop cost-saving pollution-abatement methods; and an indirect effect of reducing product output, which reduces the incentive to engage in R&D. Carraro and Soubeyran (1996) compare an emission tax and an R&D subsidy, and found that an R&D subsidy is desirable if the output contractions induced by the tax are small or if the government finds output contractions undesirable for other reasons. Addressing the same trade-off, Katsoulacos and Xepapadeas (1996) find that a simultaneous tax on pollution emissions and subsidy to environmental R&D may be better suited to overcoming the joint market failure (negative externality from pollution and positive externality or spillover effects of R&D).

Addressing a policymaker‘s choice of the level of environmental regulation, Innes and Bial (2002) start with the observation that firms often overcomply with environmental regulation. They explain this behavior using a model in which a successful innovator may prefer stricter environmental standards so as to raise costs for rival firms. An environmental tax that is efficient ex post (e.g., after a new innovation is revealed) also

provides incentives for overinvestment in R&D, as firms hope to gain profits by being the first to invent an environmental technology that will affect regulatory levels and impose costs on other firms. Innes and Bial show that discriminatory standards for technology ―winners‖ and ―losers‖ can offset incentives for overinvestment. For example, regulators can offer non-innovating firms a lower emissions reduction target or additional time to comply with regulatory changes. If the policy levels are optimally set, technology winners still have incentive to overcomply with environmental regulation, as their profits exactly equal the social gains from their innovation.
Noting that the stringency of an optimal policy may change after new abatement technologies become available, Requate (2005) asks when policy adjustments should be made. The model considers a monopolistic provider of environmental technology that performs R&D in response to environmental regulation, and a set of competitive firms that purchase environmental equipment when required by law. The paper considers four policy options: ex post regulation after adoption of new technology, interim regulation after observing R&D success but before adoption, ex ante regulation with different tax rates contingent on R&D success, and ex ante regulation with a single tax rate whether or not R&D is successful. In this model, ex ante commitment with different tax rates dominates all other policies, and tax policies are always superior to permit policies.

Finally, Baker and Adu-Bonnah (2008) show that the way in which technological change affects the shape of the marginal abatement cost curve also affects R&D decisions made under uncertainty. Their model considers both uncertainty about future climate damages (and thus the optimal level of abatement needed) and uncertainty about the likelihood of success for various energy research projects. R&D investment affects the probability that a project will be successful. They consider two types of energy R&D projects: alternative energy that emits no carbon and efficiency improvements for conventional fossil fuel energy sources. For alternative energy R&D, technological improvements unambiguously lower the cost of reducing carbon emissions (e.g., shift marginal abatement costs down). In this case, the socially optimal investment in technologies is higher for riskier projects. However, the opposite is true for research on conventional energy technologies, for which technological change rotates the marginal abatement cost curve. For low levels of abatement, improvements to conventional technologies, such as increased fuel efficiency, lower abatement costs.

However, if high levels of abatement are required, simply improving energy efficiency will not be sufficient—alternative clean energy sources will need to replace traditional fossil fuel sources of energy. In this case, improvements in the efficiency of conventional technologies raise the marginal abatement cost, as they raise the opportunity cost of eliminating fossil fuels. In such a case, optimal R&D investment is higher for less-risky R&D projects. These projects have a higher probability of success, but will only have moderate efficiency gains. However, moderate efficiency gains will have a large impact on the economy, because fossil fuels are widely used. In contrast, the payoff from risky R&D projects with larger efficiency gains is not as high. Efficiency gains are most valuable under low climate damage scenarios. If climate damages are high, energy efficiency gains will have little value, because fossil fuels won't be used. Thus, the need for energy efficiency breakthroughs is not as high as the need for breakthroughs for alternative energy.

Addressing the value of flexible standards, Lanoie et al. (2007) use a survey of firms in seven OECD countries to examine the effect of various environmental policy instruments on environmental R&D. Respondents were asked to describe both the type of environmental policies faced, as well as the stringency of such policies. They find that greater stringency does induce a firm to perform more environmental R&D. More flexible performance standards, which dictate an acceptable level of environmental performance, but do not dictate how that level be achieved, induce more environmental R&D than technology standards, which require the use of a specific technology to meet regulatory targets. Surprisingly, being exposed to market-based environmental policies does not induce greater environmental R&D. One explanation given for this result is that when market-based policies are used, they may be less stringent than other environmental standards. In related work, Johnstone and Hascic (2008) show that flexible environmental regulations lead to higher quality innovation. Using a World Economic Forum survey of business executives, they show that environmental patents have larger family sizes when executives in the inventor‗s home country perceive that there is greater freedom to choose different options in order to achieve compliance with environmental regulations.

There is a more extensive literature on the effects of alternative policy instruments on the innovation of energy-efficiency and alternative energy technologies. The innovation process can be thought of as affecting improvements in the characteristics of products on the market, and the process can be framed as the shifting inward over time of a frontier representing the tradeoffs between different product characteristics for the range of models available on the market. If one axis is the cost of the product and another axis is the energy flow associated with a product, that is, its energy intensity, then innovation is represented by inward shifts of the curve — greater energy efficiency at the same cost, or lower cost for given energy efficiency. With this approach, Newell et al. (1999) assess the effects of changes in energy prices and in energy-efficiency standards in stimulating innovation. Energy price changes induced both commercialization of new models and elimination of old models. Regulations, however, worked largely through energy-inefficient models being dropped—the intended effect of the energy-efficiency standards.

Finally, Johnstone et al. (2008) use a panel of patent data on renewable energy technologies across 25 OECD countries to examine the effect of different policy instruments on innovation. They compare price-based policies such as tax credits and feed-in tariffs to quantity-based policies such as renewable energy mandates. They find important differences across technologies. Quantity-based policies favor development of wind energy. Of the various alternative energy technologies, wind has the lowest cost and is closest to being competitive with traditional energy sources. As such, when faced with a mandate to provide alternative energy, firms focus their innovative efforts on the technology that is closest to market. In contrast, direct investment incentives are effective in supporting innovation in solar and waste-to-energy technologies, which are further from being competitive with traditional energy technologies. These results suggest particular challenges to policymakers who wish to encourage long-run innovation for technologies that have yet to near market competitiveness.

EMPIRICAL RESULTS

One of the challenges of studying the effects of technology indirectly can be found by comparing empirical studies from different eras. Many studies use a time trend to represent technological change, so that the results are interpreted as the net effect of all technological change in a given period. For example, in a study of U.S. industrial energy consumption from 1958 to 1974, Jorgenson and Fraumeni (1981) find that technological change was energy-using—energy use per unit output increased over time. Of course, the time period of their data would not include any of the energy-saving innovations developed after the energy crises of the 1970s. In contrast, more recent work using a time trend to capture technological change finds that technology is energy saving. Examples include Berndt et al. (1993), Mountain et al. (1989) and Sterner (1990).

As an alternative to using a time trend to represent technology, Popp (2001) uses energy patents to estimate the effect of new technology on energy consumption. Popp begins by matching energy patents with the industries that use the inventions by using the Yale Technology Concordance (Evenson et al. 1991, Kortum and Putnam 1989, 1997). Using these patents, Popp creates stocks of energy knowledge, which are used as an explanatory variable in a system of cost functions for 13 energy-intensive industries. The knowledge stocks are defined as a cumulative function of the number of past energy patents used by each industry, adjusted for gradual decay and diffusion. Using these knowledge stocks in a cost function of energy usage, Popp finds that the median patent leads to $14.5 million dollars in long-run energy savings. In comparison, these industries spend an average of $2.25 million of R&D per patent. In addition, using estimates of the elasticity of patenting with respect to energy prices for these technologies, Popp calculates the effect of induced innovation as the combined effect of all new patents induced by a one-percent energy price increase. Interestingly, the estimated elasticities of energy use with respect to price found in that paper are lower than typically found, as they include only the effect of factor substitution, because technological change is controlled for separately. By comparison, re-running the regressions using only a time trend to represent technological change provides energy price elasticities that are consistent with those found in other studies, as such studies include the effect of price-induced innovation in their estimates.

Similarly, Sue Wing (2008) uses patent stocks in a series of industry-level regressions to identify the effects of changing industry composition, disembodied technological change, factor substitution, and induced innovation in response to energy prices on declining U.S. energy intensity. While Popp focuses on energy-intensive industries, Sue Wing‘s data includes 35 industries from 1958-2000. He finds changing composition and disembodied technological change to be the dominant factors. Induced innovation does have an energy-saving effect, but it is the smallest of the four factors studied.

One significant caveat with estimated learning rates is that they typically focus on correlations between energy technology usage and costs, rather than causation. Recent papers by Klaasen et al. (2005), Söderholm and Sundqvist (2007), and Söderholm and

Klaasen (2007) attempt to disentangle the separate contributions of R&D and experience by estimating ―two-factor learning curves for environmental technologies. These two-factor curves model cost reductions as a function of both cumulative capacity (learning-by-doing) and R&D (learning-by-searching, or LBS). To be comparable with the notion of cumulative capacity, in these models R&D is typically aggregated into a stock of R&D capital. Thus, endogeneity is a concern, as we would expect both investments in capacity to be a function of past R&D expenditures and R&D expenditures to be influenced by capacity, which helps determine demand for R&D. Söderholm and Sundqvist address this endogeneity in their paper and find LBD rates around 5 percent, and LBS rates around 15 percent, suggesting that R&D, rather than learning-by-doing, contributes more to cost reductions. However, these results are very sensitive to the model specification, illustrating the difficulty of sorting through the various channels through which costs may fall over time.

POLICY RECOMMENDATION

The abovementioned studies have focused primarily on the incentives faced, and activities conducted, by private firms. However, governments also play an important role in energy R&D. IEA member countries, which together account for about 85 percent of overall global R&D expenditures, spent an estimated $11 billion on publicly funded energy R&D in 2006 (IEA 2007a)—or about 4 percent of overall public R&D spending by these countries in the same year. In the United States, about half of government funding is transferred to universities, other non-profit research institutions, and industry, which perform the associated R&D within a system of contracts, grants, and other arrangements. Government funding tends to focus more on basic and applied research. In addition to creating new knowledge upon which further technological development can draw, university-based R&D supports the production of young researchers. Most of these researchers eventually move into the private sector—thus they represent an important link within the overall innovation system. Ensuring a stream of scientists, engineers, and other research professionals trained in areas relevant to clean-energy technologies can increase the necessary innovative effort and moderate its cost. The capacity of a country‘s workforce to absorb and apply new know-how and technology is also essential for development, and it is one of the main impediments to more rapid technology transfer to developing countries (World Bank 2008). By supporting researchers and graduate students, public funding for research affects an economy‘s capacity to generate and assimilate scientific advances, technology innovations, and productivity improvements. This linkage has made research funding a priority among many who are concerned about the long-term competitiveness of national economies and has led to increased support for expanded R&D spending generally, including in the United States and the European Union. At an international level, programs that facilitate the international exchange of graduate students, post-docs, and more senior scholars in areas relevant to climate-mitigation research can help to expand human-capital-related spillovers.

Government investment plays another important role: it can help to compensate for underinvestment by private firms. Unlike firms, the government is in position to consider social returns when making investment decisions. In addition, government R&D tends to have different objectives than private R&D. Government support of basic R&D is particularly important, as long-term payoffs, greater uncertainty, and the lack of a finished product at the end all make it difficult for private firms to appropriate the returns of basic R&D. Thus, the nature of government R&D is important. For example, Popp (2002) finds that government energy R&D served as a substitute for private energy R&D during the 1970s, but as a complement to private energy R&D afterwards. One explanation given for the change in impact is the changing nature of energy R&D. During the 1970s, much government R&D funding went to applied projects such as the effort to produce synfuels. Beginning with the Reagan administration, government R&D shifted towards a focus on more basic applications.

In addition to correcting for underinvestment by private firms, many government R&D projects aim to improve commercialization of new technologies (referred to as ―transfer from basic to applied research). Such projects typically combine basic and applied research and are often done through government/industry partnerships (National Science Board 2006). For example, the United States passed several policies in the 1980s specifically designed to improve transfer from the more basic research done at government and university laboratories to the applied research done by industry to create marketable products. As such, this technology transfer can be seen as a step between the processes of invention and innovation. Popp (2006c) examines citations made to patents in 11 energy technology categories, such as wind and solar energy. He finds that energy patents spawned by government R&D are cited more frequently than other energy patents. This is consistent with the notion that these patents are more basic. More importantly, after passage of the technology transfer acts in the early 1980s, the children of these patents (that is, privately held patents that cite government patents) are the most frequently cited patents, suggesting that transferring research results from the government to private industry produces valuable research results.

R&D-induced technological change is one of the most common approaches used to endogenize technological change, and a variety of models have been developed along these lines. Several themes resonate throughout the R&D model literature. Two key points are whether R&D-induced technological change is associated with an innovation market imperfection due to spillovers, and whether carbon-saving R&D crowds out R&D in other sectors. There clearly exists a tension between spillovers and crowding out, with the former tending to point to greater cost savings when endogenous technological change is included and the latter dampening or even overturning that effect. In many models, the degree to which spillovers and crowding out arise is a complex interaction among underlying assumptions about model structure and distortions in the R&D market. Yet, these assumptions have important ramifications for the total cost of a climate policy as well as the conclusions drawn about the degree to which estimates based on exogenous technology assumptions are biased.

Including a knowledge stock in the production function does not on its own imply a pathway for inducing carbon-saving technological change. In the simple formulation of a knowledge stock that is most true to the endogenous growth literature, the knowledge stock increases the productivity of all inputs equally. For example, Buonanno et al. (2003)

extend the Nordhaus and Yang (1996) RICE model to implement such a knowledge stock in the endogenous technological change-RICE numerical model. This simple methodology for endogenizing technological change may be useful to capture important aggregate dynamics, but it does not provide a pathway for relative prices to influence energy-saving or carbon-saving innovation.
Smulders and de Nooij (2003) and van Zon and Yetkiner (2003) both build on the endogenous growth literature that includes a continuum of intermediate goods (e.g., Romer [1990]) and apply a variation of this modeling approach to an economy that includes energy as an input to production. In Smulders and de Nooij, endogenous technological change is achieved by improvements in the quality of the continuum of intermediate goods through investment in R&D, while van Zon and Yetkiner achieve endogenous technological change through increases in the variety of the continuum of intermediate goods through R&D investment. Both papers demonstrate the important theoretical point that profit maximization by innovating intermediate goods producers can give rise to a change in the direction of technological change toward energy-saving technological change based on increasing energy prices or constrained energy quantities.

In contrast, van Zon and Yetkiner use a blueprint framework to find that an energy tax that is recycled in the form of an R&D subsidy may increase long-run growth, through R&D-induced technological change. This result stems from two different market imperfections in the R&D market: (1) firms do not consider the effect that current R&D has on increasing the productivity of future R&D investment because it is not captured appropriately in the price of the blueprints and (2) a market imperfection in the supply of intermediates that leads to too low of a demand for those intermediates relative to the social optimum. Effectively, these market imperfections imply an intertemporal spillover for each firm, rather than a spillover from the research of one firm to other firms. Crowding out also plays a less prominent role in the van Zon and Yetkiner model than in Smulders and de Nooij.

Sue Wing (2006) further develops this theory in the context of climate change policy by adding externalities and environmental taxation to Acemoglu‘s (2002) model. Sue Wing shows that an environmental tax always biases production away from the dirty good towards the clean good. However, this does not necessarily mean that the environmental tax also biases innovation towards research on the clean good. Rather, this depends on the substitutability between clean and dirty inputs. If the clean input is not readily substitutable for the more expensive dirty input, the absolute quantity of dirty R&D exhibits a hump-shaped profile, so that it increases under small environmental taxes, but declines under higher environmental taxes. That is, a low environmental tax encourages research to make the dirty input more productive, so as to get more output from each unit of the dirty input. Unfortunately, theoretical models with continuous intermediate goods and abstract representations of blueprints are not well suited to match technological change up to measurable real-world variables or technologies that most numerical models attempt to represent. However, the more general notion of including a Hicks-neutral knowledge stock, as shown above in Buonanno et al. (2003) or factor-augmenting knowledge stock, as in Smulders and de Nooij (2003), is a common choice for numerical models that include an economy-wide production function.

Goulder and Schneider (1999) develop a partial equilibrium analytical framework and then implement some of the resulting insights in a numerical general equilibrium model that endogenizes technological change, with a particular emphasis on spillover effects. The authors find that the presence of endogenous technological change in their model leads to lower costs of achieving a given abatement target, but higher gross costs of a given carbon tax (i.e., costs before netting out climate benefits). In fact, both costs and benefits of a given carbon tax are higher relative to their model with only exogenous technological change, due to more extensive carbon abatement, for the economy responds more elastically to price shocks from the policy. With environmental benefits included, Goulder and Schneider find greater net benefits of this higher abatement level for a given carbon tax when endogenous technological change is present. This outcome can be reinforced or muted if there are prior distortions in R&D markets, depending on the type of distortions.

One important feature underlying these results is a crowding-out effect where expansion of knowledge generation in one sector comes at a cost to other sectors due to the limited pool of knowledge-generating resources (i.e., there is a positive and increasing opportunity cost to R&D in one sector). A carbon-tax policy serves to spur R&D in the alternative energy sector, but discourages R&D in non-energy and conventional energy sectors due both to slower growth of output in those industries and the limited pool of knowledge-generating resources. On the other hand, the knowledge spillover effects, whereby policy-induced R&D has social returns above private returns, provide additional benefits from a climate policy above the environmental benefits. However, the presence of endogenous technological change with spillovers does not imply the possibility of zero-cost carbon abatement, unless the spillovers overwhelm the crowding out effect, a largely empirical question.

Sue Wing (2003) incorporates endogenous technological change into a detailed general equilibrium model, building on several of the concepts in Goulder and Schneider (1999) and others. At the core of Sue Wing‘s model is a recursive, dynamic general equilibrium model in which a representative agent maximizes welfare. A major difference between Sue Wing‘s model and previous models is that Sue Wing further distinguishes several of the factors influencing innovation to gain insight into the general equilibrium effects of inducing innovation in one sector and its consequences for the cost of carbon policies. Conceptually, Sue Wing describes his approach in terms of two commodities: a ―clean‖ commodity and a ―dirty‖ commodity. He finds that a carbon tax reduces aggregate R&D, slowing the rate of technological change and the growth in output. Given the fixed-saving rule and absence of knowledge spillovers in the model, this follows from having a smaller economy due to the carbon tax. However, the relative price effects of a carbon tax lead to considerable reallocation of knowledge services, enabling the economy to adjust to the carbon tax in a more elastic manner, reducing the total costs of the carbon tax.

CONCLUSIONS

Technological change plays an important role in climate change policy. While new technologies can make cleaner production and more efficient resource use possible, markets are unlikely to provide proper incentives for the development of no- or low-carbon technologies, absent public policy. As in other areas of technological change, knowledge spillovers lead to underinvestment in R&D by private firms. However, even if all knowledge market failures were addressed, firms would still underinvest in environmental R&D, as many of the benefits to providing a cleaner environment are external. By addressing the externality problem, environmental policy increases incentives for environmental R&D. While any environmental policy should provide some additional incentive for environmentally oriented R&D, much research has focused on how the proper design of policy will lead to greater innovation. In particular, flexible policy instruments that provide rewards for continual environmental improvement and cost reduction tend to have better dynamic efficiency properties than policies that specify a specific behavior. One such instrument that has received attention lately to encourage R&D is the idea of innovation inducement prizes for climate mitigation The idea is to offer financial or other rewards for achieving specific innovation objectives that have been specified in advance (Newell and Wilson 2005, Kalil 2007, NRC 2007, Brunt et al. 2008).

The positive role of international technology-oriented agreements as part of the architecture of an international climate change policy has become more clear (de Coninck, et al. 2008, Justus and Philibert 2005). Specific activities under such agreements could include knowledge sharing and coordination, joint R&D, technology transfer, and technology deployment mandates, standards, or incentives. These activities can lower the costs of mitigation technologies, resulting in the greater likelihood that countries will implement significant GHG reductions. As outlined by Justus and Philibert, the benefits include ―synergies in research, cost saving and risk mitigation, acceleration of developments, harmonization of standards, and reduced costs of national deployment support policies.

A well-targeted set of climate policies, including those targeted directly at science and innovation, could help lower the overall costs of mitigation. It is important to stress, however, that poorly designed technology policy will *raise* rather than *lower* the societal costs of climate mitigation. To avoid this, policy can create substantial incentives in the form of a market-based price on GHG emissions, and directed government technology support can emphasize areas least likely to be undertaken by a private sector. This would tend to emphasize strategic basic research that advances science in areas critical to climate mitigation. In addition to generating new knowledge and useful tools, such funding also serves the critical function of training the next generation of scientists and engineers for future work in the private sector, at universities, and in other research institutions.

Effective climate technology policy complements rather than substitutes for emissions pricing. On the research side, R&D without market demand for the results is like pushing on a rope, and would ultimately have little impact. On the deployment side, technology-specific mandates and subsidies tend to generate emissions reductions in a relatively expensive, inefficient way relative to an emissions price, and under an economy wide cap-and-trade system will not actually generate any additional reductions. The scale of the climate technology problem and our other energy challenges requires a solution that maximizes the impact of the scarce resources available for addressing these and other critical societal goals. Research suggests that an emissions price coupled with R&D provides the basic framework for such a solution.

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