WORKING PAPER

Innovating for an uncertain market: A literature review of the constraints on environmental innovation

By
Daniel K.N. Johnson and Kristina M. Lybecker

Colorado College Working Paper 2009-06
July, 2009

Department of Economics and Business
Colorado College
Colorado Springs, Colorado 80903-3298
www.coloradocollege.edu/dept/EC

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Daniel K.N. Johnson
Kristina M. Lybecker

Department of Economics and Business
Colorado College
14 E. Cache la Poudre Street
Colorado Springs, CO 80903

July 29, 2009

Daniel K.N. Johnson is the Gerald L. Schlessman Professor of Economics and Director of the Innovative Minds Program at Colorado College, 14 East Cache La Poudre, Colorado Springs, CO 80903, tel 719-389-6654, djohnson@ColoradoCollege.edu.

Kristina M. Lybecker is Assistant Professor of Economics at Colorado College, 14 East Cache La Poudre, Colorado Springs, CO 80903, tel 719-389-6445, kristina.lybecker@ColoradoCollege.edu.

We thank the National Peace Foundation and the United States Chamber of Commerce for their support of this project, and David Popp for his generous and insightful comments.

Executive Summary

This paper aims to summarize the state of academic knowledge surrounding the economics of environmental innovation. Following a definition of environmental technology, the paper enumerates and describes the obstacles or constraints to the development of eco-innovation.

Key Findings:

- Many of the challenges to innovation in general are mirrored and exaggerated in eco-innovation.

- Environmental innovation is fraught with uncertainty: uncertainty about the end-product of a research process, uncertainty about the reception by the market, uncertainty about the ability to appropriate the returns to research while competitors try to produce similar results, and uncertainty about regulatory impacts on the research process and end-result. In addition, there is frequently uncertainty surrounding the pricing of competing as well as complementary goods.

- On the other hand, uncertainty itself often stimulates innovation. Policymakers may very well be conflicted about how much structure to provide for innovators, if they truly thrive on some degree of uncertainty. This is further complicated by the fact that the appropriate policy response undoubtedly differs by industry, by technological problem, and even by time period.

- This review of economic studies reveals five themes which affect the development of eco-innovations: intellectual property rights (e.g. patents), economies of scale, markets and incentives, system complexity and policy choices.

- While developing nations frequently claim that strong intellectual property rights on carbon abatement technologies hinder developing countries' greenhouse gas abatement efforts, it has been shown that IPRs do not constitute as significant a barrier as claimed since a variety of technologies exist for reducing emissions. In many cases, IPR-protected technologies are not necessarily more costly than those not covered.

- Numerous studies have documented the reasons to encourage strong patent law. There is near universal agreement among economists that strong intellectual property rights are an essential prerequisite to the development of environmental technologies. Moreover, most firms indicate that IPRs are essential to the profitability of commercial research, so in its absence they simply will not commit research and development (R&D) funding to the market in question. At the same time, the value of patents, and other forms of protection, varies across industries and across innovations.

- One of the challenges of sequential innovation lies in the difficulty in rewarding early innovators for the technological foundations they develop, while also allowing for the reward of subsequent innovators who improve and extend the original technology to new applications. This is particularly applicable in the context of new technologies, such as environmental technologies.

- The challenge of achieving efficient scale and reducing per-unit production costs is critical to the success of most innovative products and processes. Since most innovations are subject to economies of scale (or increasing returns to scale), in which higher levels of output are associated with lower per-unit costs, larger firms may be better positioned to develop environmental technologies.

- The greater the ease of development and extent to which the innovator will profit from the innovation and appropriate the benefits will both facilitate environmental innovation. However, in the case of eco-innovation, there is uncertainty about actual costs, consumer values, and policy platforms now and in the future. Moreover, the market is complicated by competing technologies (e.g.: fossil fuels) subject to negative externalities in which the user does not bear the full cost of the good. Further, the public goods nature of environmental technology prevents the user (and the innovator) from fully capturing the benefits of the innovation.

- The role of federal regulations is critical to the development of eco-innovation. Environmental regulation might lead to cost-saving innovation if a) the fixed costs of innovation are lower than compliance plus production, or b) spillover effects make innovation strategically a bad idea for the firm but a good idea for society, or c) regulation helps to fix incentive problems between managers and owners, or d) regulation helps to clear information flow.

- Given that knowledge has positive spillovers, benefits to those who bore none of the cost of acquisition, economists conclude that the amount of R&D provided by private markets will be lower than the socially optimal level. As such, questions emerge as to whether the returns to R&D are sufficient to encourage eco-innovation.

- There is an important role for policy in the support or stifling of eco-innovation. Five themes emerge from the papers reviewed.   First, there is a clear portfolio of policy alternatives to stimulate innovation or energy-related investment including taxes, subsidies, permits and standards/regulations. Second, there is strong evidence that regulatory policies can be very effective. Third, policy may serve to create a market for previously uncertain or ill-defined environmental commodities. Fourth, current policymakers are frequently unable to muster the political will to enact legislation that is pro-environmental innovation. Fifth, heterogeneity may be a desirable attribute in policy since many environmental issues are local or regional in nature, and thus require local knowledge and solutions.

- Across numerous studies there are five themes which resonate with all economists as challenges to eco-innovation: intellectual property rights, economies of scale, markets and incentives, complex systems, and policy.

The greatest potential for propelling innovation is usually found in market forces and incentives. Uncertainty, externalities, and subsidies to competing goods undoubtedly hinder the process, but the motivation provided by potential profit is undeniable. However, due to the spillovers associated with eco-innovation and the public goods nature of these technologies, there is a role for government intervention in order to spur an increase in environmental innovation. In this context it is essential for policymakers to find a balance: encouraging competition while guaranteeing a large market for minimum economic scale, reducing uncertainty about future resource prices while keeping alternatives open, offering rights of exclusion to intellectual property holders while not curtailing the ability of sequential innovators to build upon past successes, promoting social goals while respecting market pressures.

<u>Innovating for an uncertain market:</u>
<u>A literature review of the constraints on environmental innovation</u>

This is the first in a series of three literature reviews designed to summarize the state of academic knowledge surrounding the economics of environmental innovation. This first paper concerns broad definitions of environmental innovation (or greenTech or eco-innovation), then proceeds to identify and describe the obstacles or constraints to its development. The subsequent papers in this series consider the challenges to dissemination or diffusion of that technology, and the constraints to financing.

Introduction

"Innovation involves attempts to deal with an extended and rapidly advancing scientific frontier, fragmenting markets flung right across the globe, political uncertainties, regulatory instabilities, and a set of competitors who are increasingly coming from unexpected directions." (Tidd, 2006)

Innovation is an inherently challenging activity. It is fraught with uncertainty: uncertainty about the end-product of a research process, uncertainty about the reception by the market, uncertainty about the ability to appropriate the returns to research while competitors try to produce similar results, and uncertainty about regulatory impacts on the research process and end-result. While the remainder of this paper is devoted to eco-innovation in particular, we remind the reader that many of the challenges to innovation in general are mirrored and exaggerated for this field of eco-innovation. Good reviews of the economics of innovation are available (e.g. Freeman, 1994; Stoneman, 1995; Fagerberg et al., 2005; Shavinina, 2006) and many of the results are applicable here.

However, there are also many areas in which the economics of eco-innovation warrant their own attention, separate from the challenges of innovation in general. For example, many of those uncertainties are greater for environmental innovation than in any other field of innovation. After all, the research problems are enormous. The valuation by the marketplace is far from certain, as frequently consumers do not have the knowledge or tools to evaluate the environmental impact of an innovation. Even with that knowledge of impact, consumers and producers rarely have the ability to 'value' any given environmental impact, as markets provide little of the information needed to do so. Indeed, most activities related environmental processes or products encounter externalities which by definition are not incorporated into any market's price without government intervention. In addition, uncertainty surrounds the pricing of competing as well as complementary goods. Further, the appropriability of returns is open to question, as innovators wonder whether their research will be subject to 'public interest' exclusions to patent law, and perhaps subject to compulsory licensing requirements. Finally, the regulatory landscape is variegated and ever-changing, such that an innovative environmentally-clean process may have enormous value to producers in one location, and zero market value in a nearby jurisdiction. Even worse, that situation may easily reverse, or reduce to zero everywhere. Given those uncertainties and the frequent presence of enormous fixed costs in the research and development stage, it is a marvel that eco-innovation occurs at all.

On the other hand, it is often uncertainty itself that stimulates innovation. In their authoritative work, Jaffe et al. (2001) assert that uncertainty about the future rate and direction of technological change is often the largest single source of differences among predictions in global climate change modeling. It may be that fundamental uncertainty which keeps innovators searching for alternative (and frequently better) solutions to environmental challenges. As Tidd (2006) notes, innovation most often takes place in the context of rules which are clearly understood, but at times the rules are altered to redefine the conditions under which innovation occurs. Sometimes this presents new opportunities, an argument which Porter and van der Linde (1995) champion. Ultimately, uncertainty and changing regulations are factors that both enhance and inhibit eco-innovation, providing policymakers with a critical and challenging role in the process.

Policymakers may very well be conflicted about how much structure to provide for innovators, if they truly thrive on some degree of uncertainty. Unfortunately, economics can offer no panacea, no single answer to this question. Aubert (2004) offers a typology of governments at different levels of science and technology (ST) capacity in Table 1 below, depending upon institutional capabilities, but the appropriate policy response undoubtedly differs by industry, by technological problem, and even by time period. We hope that this series of papers will help to direct the reader to available knowledge and resources, to make the search for effective policy easier.

After clarifying our definition of eco-innovation in the section which follows, we proceed to explore the literature's investigation of five significant challenges facing eco-innovation: intellectual property rights (e.g. patents), economies of scale, markets and incentives, system complexity and policy choices. We then offer some suggestions concerning effective strategies for stimulating eco- innovation, and conclude with policy implications and directions for future research.

Definition(s) of environmental technologies

There are several complementary definitions of environmental technologies, with only slightly different emphases. An early writer on this definition, Shrivastava (1995) defined environmental technologies as

> "production equipment, methods and procedures, product designs, and product delivery mechanisms that conserve energy and natural resources, minimize environmental load of human activities, and protect the natural environment. They include both hardware, such as pollution control equipment, ecological measurement instrumentation, and cleaner production technologies. They also include operating methods, such as waste management practices (materials recycling, waste exchange), and conservation-oriented work arrangements (car pooling, flextime), used to conserve and enhance nature".

Shrivastava considers five thematic approaches for eco-innovation: design for disassembly (e.g. production with an eye towards waste reduction via simpler reusing and recycling), manufacturing for the environment (e.g. innovative cleaner technology using fewer inputs or reducing emissions), total quality environmental management (i.e. adopting a total systems approach to design and manufacturing), industrial ecosystems (i.e. creating inter-organizational

Table 1. Innovation Systems and Policy Agendas (Aubert, 2004)

<table>
<tr><td>Level of institutional and human capital capabilities</td><td>Strong Institutions
(litmus test: business R&D dominate R&D budget)

Decision-making horizon: long-term</td><td>Limited Institutional Capabilities
(litmus test: large stock of export-driven FDI exists yet national innovation system is virtually irrelevant for business)

Decision-making horizon: medium term</td><td>Weak or fragile institutions
little state activist is possible/desirable
(litmus test: investment climate is poor and volatile)

Decision-making horizon: short-term survival</td></tr>
<tr><td>Low ST capabilities

Technology adoption</td><td></td><td>Exports as a springboard agenda:

Developing non-traditional exports as entry point for institutional and technology development
development

Central America (with the exception of Costa Rica)
Traditional urban and rural economics in India and China

Korea in the 60’s
Mexico in the 70’s
Vietnam, Mauritius</td><td>Technology basics agenda:

Creation of demonstration effect to show that innovation does matter, in particular in health, education, agriculture and crafts.

Most of Sub-Saharan Africa

Most Central Asian states</td></tr>
<tr><td rowspan="2">Medium ST capabilities

Technology adoption</td><td colspan="2">‘Turning Point’ Agenda: a need for transition from global sourcing to proprietary technology</td><td rowspan="2"></td></tr>
<tr><td>Increase in R&D Investments

Korea, Ireland in the 90’s
Malaysia
India (IT clusters)</td><td>Increase in business R&D through recombination of S&T capabilities

EU accession countries

Chile
China, Mexico, Brazil
Turkey, South Africa

Korea in the 70’s and 80’s</td></tr>
<tr><td>High ST capabilities

Technology creation</td><td>Innovation leaders agenda:

Development of proprietary technology through promotion of innovation clusters

Korea, Singapore, Taiwan
Finland, Israel</td><td>‘Turning Point’ agenda:

Increase in business R&D through recombination of S&T capabilities

No country currently fits
Russia in the future?</td><td>‘Embedded autonomy’ agenda:

Creating a diversity of autonomous business-led innovation organizations (Foundation Chile Agenda)

Argentina, Russia, Ukraine, Belarus, Armenia

Chile in the 70’s</td></tr>
</table>

linkages like waste exchanges or symbiotic firms), and technology assessment (including technology transfer to areas of greatest marginal impact).

Alternatively, Rennings (1998) cites "Innovation Impacts of Environmental Policy Instruments" (an inter-institutional study commissioned by the German government) as defining the term environmental innovation (short: eco-innovation) as "all measures of relevant actors…which a) develop new ideas, behavior, products and processes, apply or introduce them and b) which contribute to a reduction of environmental burdens or to ecologically specified sustainability targets". Rennings suggests that social and institutional innovations are particularly important in this arena of innovation, but are neglected by neoclassical economics. As such, he so calls for a combination of thought with evolutionary economics to develop new theory for eco-innovation. He points out that this issue calls for a new theoretical effort by economists due to a combination of factors: their double externality (costs and benefits for those who are not decision-makers in either the production of environmentally-related goods, or in the creation of the knowledge needed to change that production in content or process), the importance of the regulatory framework in this sector, and the importance of social/institutional changes as part of the innovative activity. On the other hand, Murphy and Gouldson (2000) argue that organizational innovations usually do no more than facilitate the implementation of process and product environmental innovations. Accordingly, they do not merit anything more than equal consideration alongside more traditional forms of technological change.

Finally, consider Bernauer et al. (2006) which follows OECD (1997b) in defining environmental innovations as "all innovations that have a beneficial effect on the environment regardless of whether this effect was the main objective of the innovation, including process, product, and organizational innovations". They focus primarily on explanations of product and process innovations, defining process innovations as improvements in the production process resulting in reduced environmental impacts. Bernauer et al. argue that the primary environmental impact of many products stems from their use (e.g., emissions by vehicles) and disposal (e.g., heavy metals in batteries) rather than their production process, so product innovations aim at reducing environmental impacts during a product's entire life cycle.

Regardless of which of these definitions one chooses to claim, the following sections are equally useful in the identification and analysis of challenges which face environmental innovators.

The challenges of environmental innovation

This section reviews the literature on five themes which affect the development of eco-innovations: intellectual property rights (e.g. patents), economies of scale, markets and incentives, system complexity and policy choices. Each of these themes is discussed individually in-depth and a variety of studies and resources are cited and may be referenced for specific information. At an overview level, the volume by Kemp (1997) is dedicated to explaining the literature's models of environmental innovation and diffusion, then testing them empirically with case studies. It is good reading for anyone familiar with economics and econometrics, explaining methods and results in a historical (as well as policy-relevant) fashion. In particular, the cases use the same data in competing model formats to highlight the differences in results and interpretation.

a) Role of patents

One of the first themes that arises in most discussions surrounding innovation is also one of the most provocative and emotionally-charged topics, that of intellectual property, specifically patents. As an innovator's legal right to exclude others from an activity, they present a double-edged sword: without some guarantee of repayment for the risk and financial sacrifice of the research process, little innovation will occur, but too great an exclusion right may hamper follow-on innovation or may extract inappropriately large monopoly rents from the consumer. This situation is exacerbated when the innovation is suitable for or desperately needed by developing nations and their impoverished citizens. Naturally, the decision about what repayment for risk and investment is 'appropriate' usually depends upon whether you take the perspective of the producer or the consumer.

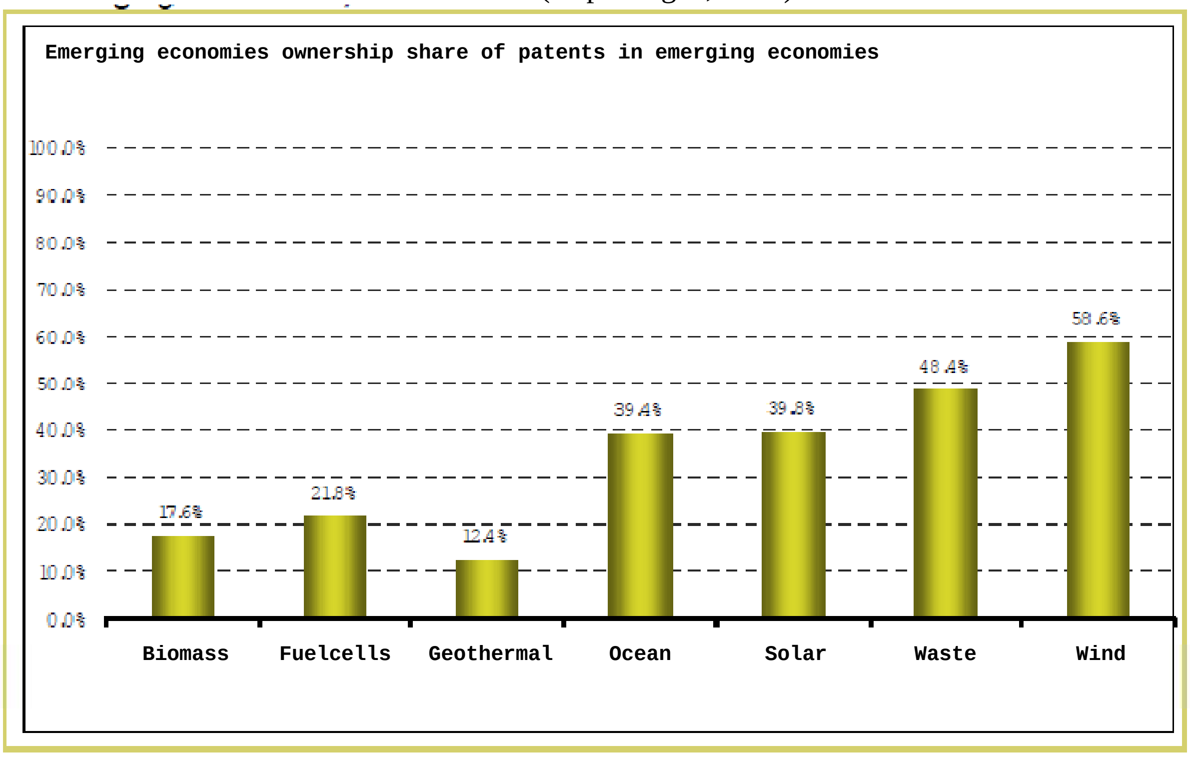
Leading up to the 2009 Copenhagen Summit on Climate Change, the Copenhagen Economics study (2009) examines the claim frequently made by developing nations that strong intellectual property rights on carbon abatement technologies hinder developing countries' greenhouse gas abatement efforts. The study finds that intellectual property rights (IPRs) do not constitute as significant a barrier as claimed since a variety of technologies exist for reducing emissions. Based on the cost-per-unit-of-carbon-emission-reduction, IPR-protected technologies are not necessarily more costly than unprotected alternatives. The authors note that the expense of some innovative carbon abatement technologies stems from the immaturity of the technology rather than patent protection. Moreover, the study finds that while there is a small number of emerging market economies which account for the majority of patents protected in the sample (99.4%), there is a much larger number of low-income nations that protect very few patents (0.6% of the total sample). Given that patents are virtually non-existent for these technologies in most developing countries, it is difficult to argue that IPR protection is a significant barrier to technology transfer.

Further, Copenhagen (2009) presents some intriguing information about the IPR ownership of environmental technologies. The study shows that between 1998 and 2008, a sizeable share of the IPRs for eco-innovations in emerging economies were owned by firms within those economies themselves, rather than by firms in industrialized nations (see Figure 1 below). In their words,

> "The patent count on the relevant technologies covered by this study has indeed increased rapidly. Globally, some 215,000 patent applications were filed worldwide over this period 1998-2008, including some 22,000 in developing countries – out of which about 7,400 were actually owned by developing country residents. When the last four years of the period are compared to the first four years, the global patent count increased by 120%, but by nearly 550% in developing countries. Solar energy and fuel cell patents account for 80% of the count and for most of the growth as well, followed by wind energy as a distant third." (Copenhagen, 2009)

The Copenhagen study also demonstrates that no single country has market dominance in any of the technologies studied, where the largest market shares are held by China (38 percent of solar energy patents) and Japan (28 percent of fuel cell patents). The authors conclude that the price

Figure 1: Share of Patent Protection in Developing Countries,
Owned by Firms in Emerging Economies
1998-2008 (Copenhagen, 2009)



of carbon abatement technology is not driven up by monopoly power since significant competition exists within and between eco-technology markets.

Beyond the evidence that disproves the claim that intellectual property rights constitute a significant barrier for developing nations, there are clearly documented reasons to encourage strong patent law in particular. Levin et al. (1987) is the landmark survey of U.S. firms on the importance of IPRs, a study which launched dozens in its wake. The study finds that the value of patents, and other forms of protection, varies across industries and across innovations. Though patents were important, secrecy, lead times, and learning curve advantages were all considered more effective. The study also confirmed substantial inter-industry variation in the evaluation of different appropriability mechanisms. This suggests that the impact of policy changes should be assessed at the industry level. The authors note that longer patent life would have little impact on innovation in the airline industry, but the effect would be a significant force for additional innovation in the pharmaceutical industry. Beyond industry differences, the results confirm that the value of patents differs across product and process innovations. Notably, for new processes, patents were generally rated the least effective of the appropriability mechanisms. This distinction is important when one considers that pollution can be reduced through either end-of-pipe treatments (e.g. pollution control products) or through changes in production processes. Assuming no third party involvement in the modifications, process changes are less likely to be patented. This point is especially salient when considering whether changes in IP protection would matter for environmental technologies.

Most firms indicate that IPRs are essential to the profitability of commercial research, so in its absence they simply will not commit research and development (R&D) funding to the market in question. That leaves policymakers with a choice of whether to perform the research themselves as a public policy initiative (an option explored below), or to develop patent law that will carefully tread the line or sufficient returns to risky research while protecting consumers and encouraging subsequent research.

Gallini and Scotchmer (2001) describe this challenge succinctly in the language of economists. For economists, efficiency is achieved when the deadweight loss of taxation is minimized, meaning that the unintended distortions to behavior are at their lowest.

> "With intellectual property, projects are funded out of monopoly profits. Monopoly pricing is equivalent to taxing a single market, which is generally thought to impose greater deadweight loss than the broad-based taxation that generates general revenue. Thus, to justify intellectual property, there must be some type of asymmetric information about the costs and benefits of research programs." (Gallini & Scotchmer, 2001)

Indeed, there usually is asymmetric information about research programs, which is the entire reason to bestow IPRs on firms in exchange for public revelation of their research insights. It is this trade, of profits in return for information, which constitutes the heart of any IPR system. As such, policymakers carefully tailor the many dimensions of patents, and scholars analyze and critique the efficiency and equity of existing policy as well as proposed changes.

The potential elements of an effective patent system have been explored in a large and rich literature. As explained by Hopenhayn and Mitchell (2001), a patent is defined by its length, its breadth, and the fees associated with its origination and renewal. Each of these elements has been theoretically modeled, analyzed and evaluated in numerous economic studies. These include the works of Gilbert and Shapiro (1990), Gallini (1992), Gallini and Scotchmer (2001), Green and Scotchmer (1995), Klemperer (1990), Scotchmer (1996), Scotchmer (1999), Yiannaka and Fulton (2001), and Yiannaka and Fulton (2003). Given that patent design is essential to manipulating the incentives that drive innovation, these papers are relevant to the development and dissemination of environmental innovation, but they do not specifically address the unique elements of eco-innovation that distinguish it from other innovation.

In designing an optimal patent system to enforce, policymakers must pay particular attention to technologies that build, one generation to the next generation. Some fields of innovation such as biotechnology, information sciences and technology, and environmental technology face the challenge of sequential, or cumulative, innovation. As pointed out by Green and Scotchmer (1995), the challenge of sequential innovation occurs when innovation happens in separable stages, with the original innovation verging on pure science and having little commercial value but relying on the follow-on stages for the social values based on practical applications. Scotchmer (1991) explores this concern, noting the difficulty in rewarding early innovators for the technological foundations they develop, while also allowing for the reward of subsequent innovators who improve and extend the original technology to new applications. In Scotchmer (1996), she argues that patents are not necessary for the development of second-generation products and that original innovators would collect a larger share of profit if second generation products are not patentable. She notes that this problem is "particularly acute when the entire commercial value is contained in the applications facilitated by the basic research, and when the basic innovation has no commercial value on its own", such as may easily be true for environmental innovations. The first innovator may have insufficient incentive to invest, leading to a potentially large role for public research in basic science.

Some of the concerns surrounding cumulative innovation raised by Scotchmer and Green and Scotchmer are empirically examined in Cohen (2005). Specifically, focusing on the pro-patent movement since 1980 in the US, Cohen explores the claim that the growth of patenting in upstream innovations may constrain critical follow-on research. While the empirical basis for these concerns is limited, he does find evidence that patenting stimulates innovation. Cohen concludes that careful attention should be paid to issues of cumulative innovation as future data become available.

In an empirical investigation of the issues surrounding cumulative technologies, Cahoy and Glenna (2009) collect evidence on patenting around biofuels, to evaluate the concern that IPRs are stifling sequential innovation. They evaluate the evidence that thickets, or the tragedy of the anti-commons, might occur, finding 231 biofuel patents spread among 72 owners. Ownership is therefore markedly less concentrated than genetically modified (GM) patents as a whole (biofuels show 33% by the top three owners, as opposed to 85% by top three owners for GM corn, 70% for non-corn GM). The authors suggest that private ordering, or the collaboration between firms to reach goals of market value, will probably occur as it has done in GM more generally. Private contracts against the background of public enforcement are a key example. Vertical consolidation, joint ventures, cross-licensing, patent pooling, and standard setting are all examples of the private ordering which could solve the potential anti-commons problem. They believe that the a private solution will be more likely in case with a limited number of patents, significant R&D barriers to entry, complementary infrastructure and technology, and long-term market potential. In short, they conclude that the likelihood of a private solution for biofuels is extremely high.

Along this line of thought, it is important to draw a distinction between the roles that patents play in the pharmaceutical sector as compared to the eco-innovation sector. While the underlying principle is the same (to accord a limited degree of market power, limited by both time and the entrance of competitors, in return for the research and creative process as well as the public sharing of information sufficient to replicate the innovation), Barton (2007) summarizes a key difference particularly well. In the case of eco-innovation, most fundamental technologies have long ago been absorbed into popular technical knowledge, having been off-patent in many cases for decades. Thus, current patents primarily protect amendments or improvements to those fundamentals, encouraging competition among alternative models which serve the same general purpose. Pharmaceutical compounds, on the other hand, are usually the result of completely new biochemical research, facing much higher research costs to recover and fewer short-run competitors in the IPR-protected marketplace. In summary, while patents serve to encourage innovators in both sectors, it would be extremely simplistic (and probably dangerously incorrect) to make an argument about eco-innovation on the basis of conclusions made for pharmaceuticals.

Beyond the economic literature that explores the importance of patents in the innovative process is the legal literature on patents. While this review is largely focused on the economics of eco-innovation, it is important to recognize the complementary nature of the (unexplored, at least here) legal literature.

Mandel (2005) presents a very readable review of the role of patent law in encouraging eco-innovations in particular, discussing the possibility of alterations to patent law for environmental technologies in particular. He considers and dismisses the merits of two possible changes: extended patent terms on eco-innovations (which should alter incentives only marginally) and accelerating patent prosecution (which already exists on special terms in the US and is rarely used). Instead, he suggests a patent reward system in parallel with the current legal framework, giving extra value to eco-innovations out of the public purse, to align social value with private market values. Naturally, this poses the administrative challenge of valuing innovations without market signals, but it poses little risk. The US already has a patent reward system in place for atomic energy innovations (42 U.S.C. § 2181. 81, 42 U.S.C. § 2187). Mandel considers and responds to four major criticisms of patent rewards:

a) rewards fail to incentivize commercialization (but that could be a separate issue, under government authority in this case)
b) rewards based on marginal costs do not compensate for fixed costs (but in this case we could calculate social value rather than marginal private value)
c) rewards do not screen out invalid patents (but the evaluative board could summarily reject awards)
d) rewards are costly to administer (which may be true, but we have a template in place. Costs are in payment and administration, and should pale next to costs of under-provision of eco-innovations, not to mention that they can be offset against other costs like environmental protection and mitigation costs).

In short, Mandel suggests that the current legal system is entirely compatible with supplementary efforts to encourage specific types of innovation. There need not be any special consideration of eco-innovation within IP law, but encouragement could take the form of public funding to augment the incentives provided by market forces, thus minimizing the opportunity for distortion of private economic activity.

In the specific case of developing nations, Park and Lippoldt (2008) empirically analyze the impact of strengthened IPRs in the developing world on local innovation and technology transfer, and discover a positive relationship in both cases. Strengthened IPRs are significantly and positively associated with: developing country patent applications and expenditure on R&D as a share of GDP, inward FDI, merchandise imports, service imports and the inflow of high-tech products. The study also includes case studies of Brazil, Russia, India and China. Specifically the case studies reinforce the finding that technology transfer and FDI are among the most important factors contributing to the development of indigenous technological capacity. These results are reinforced by the findings of Kanwar (2007). Utilizing country-level data for 44 developing and developed countries, between 1981 and 2000, Kanwar (2007) examines the influence of intellectual property protection on innovation per se. The study analyzes the relationship between R&D investment (a proxy for innovation) and an index of patent protection (a proxy for IP protection). The study concludes that the strength of intellectual property rights exerts a strong, positive impact on innovation.

Given the importance of intellectual property rights to innovation, it is essential to learn more about the differences that exist in IP regimes between developing and industrialized nations. Kanwar and Evenson (2001, 2009) examine the claim that the technology-haves (developed nations) provide relatively stronger IP protection, while the technology-have-nots (developing nations) opt for weaker protection. Utilizing cross-national data for 1981-2000, the studies find only weak support for this claim, noting that weak IP protection is more likely due to the lack of financial resources and human capital, and their inward-looking trade-orientation.

In conclusion, there is virtually unanimous consent among economists that strong intellectual property rights are an essential prerequisite to the development of environmental technologies. The dissenting voices (e.g. Hutchinson, 2006) make the valid claim that patent law increases the cost of technology acquisition by consumers or intermediary producers, but do not explain how technology arrives more cheaply by another means. Given that innovation is costly and risky, there is quite simply no alternative to IPRs proposed in the literature that will adequately encourage eco-innovation. Given that IPRs are necessary, there are potential alterations that we should consider to make IPRs work more effectively for eco-innovation in particular. Financial awards, or the clearer distinction between primary research and cumulative / application research could both be avenues for policy consideration.

b) Role of economies of scale

For most innovative products and processes, one of the challenges is how to scale up production in order to lower costs. In other words, most innovations are subject to economies of scale (or increasing returns to scale), in which higher levels of output are associated with lower per-unit costs. Eco-innovations are no exception, and evidence of this output-cost relationship is documented universally (see for example Cowan 1990; Cowan and Gunby 1996; Cowan and Hulten, 1996; Cowan and Kline, 1996; Islas 1997; Kemp, 1997). For example, Kemp (1997) reviews the case of CFCs and the shift by DuPont to less destructive HCFCs. DuPont estimated the cost of retooling production at roughly $1.25 billion, for a more expensive product at a higher 'minimum economic size'. While producing 2.5 kilotons of CFC-11 costs $10 per ton, the costs of HCFC only reach $10 per ton if 25 kilotons are produced. Even at production of 5 kilotons, costs of HCFC are just under $25 per ton, five times that of CFC-11.

The same is true for learning curves, which is another way of relating scale of production to costs, over time as opposed to simultaneously. Evidence on the ability to lower costs for eco-innovation as more units are produced can be found in Joskow and Rozanski (1979), Zimmerman (1982), Sharp and Price (1990), Lester and McCabe (1993), Nakicenovic (1996), Neij (1997), Grübler and Messner (1999), and Grübler et al. (1999).

Friedman (2006) quotes General Electric's CEO Jeffrey Immelt as noting 'the big energy players are not going to make a multibillion-dollar, forty-year bet on a fifteen-minute market signal'. In short, they need a promise of a long-term market for whatever they develop. To illustrate, he cites the case study of First Solar, an Ohio company which produces exclusively in Germany because they guaranteed the buy-back price of solar energy from consumers for 20 years after installation.

The prevalence of economics of scale and significant learning curves may also be linked to another characteristic of successful eco-innovation firms, specifically firm size and resources. Baylis et al. (1998b) and Clayton et al. (1999) argue that environmental activities go along with a higher amount of financial and human resources, which is why larger firms have better opportunities and abilities to reduce environmental impacts. Several empirical studies show that, by and large, firm size has a positive influence on environmental innovation (e.g., Cleff and Rennings, 1999; Rehfeld et al., 2006; Arimura et al., 2007).

In a similar vein, Berrone et al. (2007) proposes that firms with more available resources, or organizational slack, have a better ability to evaluate outside influences and to adapt to internal pressures. They use an unbalanced panel of 340 firms drawn from the 20 most polluting industries, firms listed in CompuStat 1997-2001 and firms listing more than 40 patents in USPTO. Utilizing regression analysis, they find that larger, more R&D-intensive, capital-intensive, EPA-litigated firms have more eco-innovations. Interestingly, Cainelli et al. (2007) use an Italian census of 773 firms 1993-95 to test the opposite causality, namely the impact of eco-innovation strategies on employment, turnover and labor productivity. They find a negative relationship on employment and turnover, with no significant effect on productivity.

Friedman (2006) argues that the US role in eco-innovation development is to provide the upfront investment, just as it did for PCs, DVDs, iPods. Then the global community can draw on India's low service costs and China's low manufacturing costs to produce at a scale and price that will make it accessible to all. Without massive investment in the development phase, we'll simply chip away at a large problem with a small tool.

Clearly there are several effects at play, effects which change over time. Teece (1998) points out that "with increasing returns, that which is ahead tends to stay ahead… mechanisms of positive feedback reinforce the winners and challenge the losers." On the other hand, global markets have become increasingly liberalized, so restrictions on knowledge transfers have evaporated. Given this, firms are no longer able to earn extra-normal returns by capitalizing on trade restrictions. While lower transportation costs have facilitated large scale production, competition has increased and information about market opportunities diffuses virtually instantaneously. Paradoxically, this might mean that competition keeps individual innovators from profiting much from their work, because competitive forces slow any one firm from reaching sufficient scale to achieve minimum economic size.

The challenge of achieving this efficient scale and reducing per-unit production costs is critical to the success of most innovative products and processes. Economic evidence indicates that successful firms are those that more quickly achieve economies of scale and quickly move along technological learning curves. Though no guarantee, larger firms with more resources seem better poised to exploit the output-cost relationship.

c) Role of markets and incentives

Innovation is the response of market-based firms to profit potential and other market-based incentives. The evidence is overwhelming on this point (see Mansfield et al, 1977; Mowery and Rosenberg, 1979 for early evidence but the literature sprawls outward from there). Within the immense body of work on incentives and innovation, there is a branch of literature dedicated to the empirical testing of 'induced innovation', or the suggestion that higher prices lead consumers to search for alternatives, at least partly in the form of new products and processes.

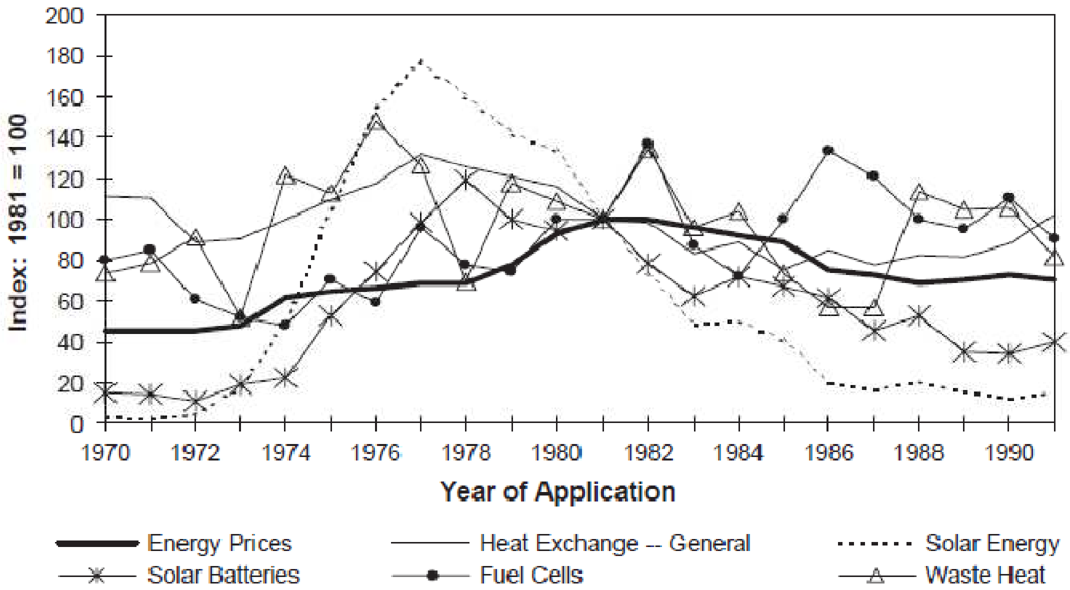
Kemp and Soete (2000) point out that there are several factors auguring against environmental innovation. On the supply side, technological opportunity and appropriability affect this field of innovation in a fashion similar to other fields of innovation. The greater the ease of development and extent to which the innovator will profit from the innovation and appropriate the benefits will both facilitate environmental innovation. On the demand side, innovation faces much higher hurdles here. First, there are problems related to knowledge and information, including who is responsible for costs, and how to price damage. Second, there is uncertainty about actual costs, consumer values, and policy platforms now and in the future. Third, many eco-innovations are process in nature, but aim to market to the end consumer without necessarily lowering costs, making them a strange commodity. In addition, the market is complicated by competing technologies (e.g.: fossil fuels) subject to negative externalities in which the user does not bear the full cost of the good. Further, the public goods nature of environmental technology prevents the user (and the innovator) from fully capturing the benefits of the innovation.

Popp (2006) examines government subsidies for innovation in the context of addressing the two market failures that characterize green technology. The first is the public goods nature of knowledge, which leads to knowledge spillovers. This is where policies such as intellectual property rights protection and R&D subsidies play an important role. Popp finds that while R&D subsidies do lead to increases in climate-friendly R&D, they address only the public good problem. Notably, this market failure characterizes all forms of innovation. The second market failure, environmental externalities, is unique to environmental innovation. The market does not reward, or allow for complete appropriation of the benefits of, innovations that increase costs but reduce pollution. Since the environmental externality problem is not addressed, there are no additional incentives to adopt the new technologies. In this case, environmental regulation provides the incentives for innovation. As such, policies that directly impact the environmental externality result in greater gains in terms of both atmospheric temperature and economic welfare. This illustrates the importance of putting environmental policy in place as a first step, and also demonstrates that expectations about future policy are a key component of the uncertainty surrounding eco-innovation.

In a similar vein, Arrow et al.(2004) refer to three reasons that natural resources may be underpriced: unclear property rights, externalities and government subsidies. They refer to the 1992 World Development Report by the World Bank which showed that in 29 of 32 LDCs surveyed, subsidies had caused the price of electricity, water and fossil fuels to fall below cost (not even including externality costs). The similarly report that the International Energy Agency (1999) "has estimated that in India, China and the Russian Federation, full-cost pricing would reduce energy consumption by 7, 9 and 16 percent, respectively… where most of the departure from social cost pricing is attributed to energy subsidies".

Nevertheless, there is a strong literature that finds a statistical linkage between energy prices and the development of environmental technology. Newell et al.(1999) tested the effect of energy prices on innovation in home appliances, while controlling for regulatory effects. Popp (2002) is a seminal piece linking environmentally-related innovations in industrial energy-using equipment to energy prices, controlling for the supply of available knowledge. Perhaps the most striking of Popp's findings is the speed at which innovation responds to incentives. For example, Figure 2 below demonstrates how energy technology patenting responds to changes in energy prices.

Figure 2: Induced innovation and Energy Prices (Popp 2002)



In another paper, Popp (2005) describes the key lessons from empirical studies on policy and environmentally-friendly innovation. He enumerates the lessons as follows: innovation responds quickly to incentives; innovation in a given field experiences diminishing returns over time; the social returns to environmental research are high; and the type of policy used affects the nature of new innovations. These results hold across industries and time. As evidence, consider the evidence in the automotive industry.

A host of studies of the automotive industry (Ohta and Griliches, 1976; Goodman, 1983; Atkinson and Halvorsen, 1984; Wilcox, 1984; Greene, 1990; Pakes 1993; Berry et al., 1996; Goldberg, 1999; Crabb and Johnson, 2010) have found similar results of both prices and regulation affecting fuel efficiency. The results are case-sensitive, and method-dependent, but all show separate effects of both factors. Most find that much of the improvement over time was autonomous or exogenous, with very strong effects of both price and policy. For example, Crabb and Johnson (2010) describe policy as a ratchet, to keep the impacts of price on innovation from backsliding during periods of lower energy prices. They calculate that a $5 per barrel increase in the price of crude oil (roughly 12 cents a gallon for gas at the pump) translates into a 4% increase in granted patents dealing with energy-efficiency in automobiles (36 per year in the US).

On the other hand, Jaffe et al.(2001) point out that it is more difficult to test induced innovation in eco-innovation because the prices are frequently not explicit, but rather shadow prices felt differentially by each industry. They briefly review the large literature on the impact of environmental regulation on productivity, a result which is clearly case-specific. Nordhaus (2000) calibrates his DICE model of the economics of climate change, and finds that induced innovation has very little effect on emissions. This is largely due to the nature of his model which features a fixed factor production function, though partially due to the fact that new innovation completely crowds out innovation in other sectors. Nordhaus' paper is the most extreme negative result in the induced innovation literature. Bernauer et al. (2006) further recommends nine studies on markets for green products, studies which are not reviewed here, but which clearly show case-specific results.

There is a strong theme in the literature encouraging policymakers to help to create markets for eco-innovation, although some minor disagreements on how that should be done. Cahoy and Glenna (2009) encourage the use of the Coase Theorem, to enable private solutions to pursue eco-innovation. They suggest encouraging information dissemination as early and fully as possible, to avoid duplicative research and to maximize collaborative potential. Regulation probably will not accomplish this, so they encourage federal incentives (e.g. in alternative energy via agriculture) to be tied to information disclosure. The suggestion parallels the disclosure in the pharmaceutical industry via the Orange Book, tied to incentives under the Hatch-Waxman Act.

Beyond federal incentives, there is a large literature on the role of federal regulations. Porter and van der Linde (1995) recommend strong regulation, which will itself create new markets for environmental technology. Their article provoked a deluge of commentary and exploration into the conditions under which increased regulation could or could not stimulate greater profits (e.g. Jaffe et al., 1995; Palmer et al., 1995; Gabel and Sinclair-Desgagne, 1998; Bonato and Schmutzler, 2000; Schmutzler, 2001; Mohr, 2002; Roediger-Schluga, 2004). While possible, the mathematical conditions are unlikely, but could indeed easily divert research activity to a more desirable end-goal in eco-innovation compared to their current goals elsewhere in industry. For example, Bonato and Schumutzler (2000) build a theoretical model to test the Porter hypothesis and find that it holds only under fairly strict mathematical (although theoretically possible) conditions. Environmental regulation might lead to cost-saving innovation if a) the fixed costs of innovation are lower than compliance plus production, or b) spillover effects make innovation strategically a bad idea for the firm but a good idea for society, or c) regulation helps to fix incentive problems between managers and owners, or d) regulation helps to clear information flow. However, the compliance costs must be low and there must be initial underinvestment for the arguments to hold in a mathematical model.

Desrochers (2008) places the Porter hypothesis within the larger framework of a literature on the incentive to create by-products for profit out of industrial waste. He argues that the profit motive generates the activity, not regulation. Regulation might simply help to set the property rights in place for a new market to develop more easily. The three variants of the Porter Hypothesis presented in Jaffe and Palmer (1997) are empirically tested in Lanoie et al. (2007).

- Weak version: environmental innovations will be stimulated by environmental regulation.
- Narrow version: flexible environmental policy regimes give firms greater incentive to innovate than prescriptive regulations.
- Strong version: properly designed regulation may induce cost-saving innovation that more than compensates for the cost of compliance.

The authors find qualified to strong support for each with data from 4200 facilities across seven OECD nations. The greatest support emerges for the weak variant. Most significantly, environmental policy induces innovation (as proxied by R&D expenditures).

Additional evidence comes from Costantini and Crespi (2007) who test the hypothesis that stronger environmental regulation creates a comparative advantage in those nations in the production of eco-innovation. They posit that the ‘pollution haven’ hypothesis is the opposite, where low regulation areas become low cost producers of all goods (but what about comparative advantage?). Using a 1996-2004 sample of 20 OECD exporting nations and their trade flows with 148 importing nations, they use a gravity model augmented with environmental policy variables to test the impact of regulation on trade flows in goods related to energy and energy savings alone. Environmental policy is proxied by CO_2 emissions, current environmental protection expenditures both of the public and the private sectors, the percentage of revenues from environmental taxes on total revenues, and public investments on environmental protection. Innovation is alternatively measured as the number of patents in the energy sector, the number of total patents from residents, or the percentage of research and development expenditures. The model general results show the expected signs and significance.

Cahoy and Glenna (2009) consider the impact of the imperfectly competitive agribusiness industry, and the consolidation of market power there in a few firms. The danger is that the horizontal integration is 'necessary' for economies of scale, but reduces competition and limits the gains flowing back to the small-scale producer. The same may occur in eco-innovation, particularly since there are efficiency advantages to local production (rather than shipping biomass to a central facility for energy conversion, thereby losing the energy content advantage over traditional fuels). In short, the oligopolistic nature of the distribution or even production system must be taken into account when forming policy.

There is also a theme in the literature questioning whether the returns to R&D are sufficient to encourage eco-innovation. Since knowledge has positive spillovers (benefits to those who bore none of the cost of acquisition), economists usually conclude that the amount of R&D provided by private markets will be lower than the socially optimal level. That is, if we all paid what research is truly worth to us, more would be provided by the firms involved. Evidence is provided in the literature surrounding Hall (1996) and Jones and Williams (1998). However, Goolsbee (1998) provides a convincing counterargument, namely that although the social return to R&D is higher than the private return, thus warranting public investment, the supply of researchers is inelastic so an increase in public funding often serves as a return to human capital investment rather than as a spur to innovation. In fact, public funding may crowd out private investment.

Friedman (2006) suggests that there are two kinds of innovation, namely the big laboratory moments and the smaller adaptation moments. The US focuses on the first, neglecting the crucial role of the second. The second is enhanced by quicker and more widespread diffusion, along with regulatory incentives to adopt at large scale. He argues that one role of government should be to fund basic research, since from 100 lines of inquiry only one might merit commercialization. That one might be commercialized by venture capital, but initial funding has to be done using basic science without a profit motive.

Unfortunately, it is unclear that markets for eco-innovations will develop on their own. Roberts (1996) shows that demographics explains less ecologically-conscious consumer behavior now than it did in the past. Instead, it is an attitudinal emphasis that matters, with the belief in environmental impact of individual behavior explaining most effectively whether consumers buy eco-innovative products or not. Straughan and Roberts (1999) confirms that result with college students. This opacity makes it extremely difficult for potential innovators to gauge the size, depth or even location of their potential market before they engage in costly product research.

Finally, it is unclear that eco-innovation is beneficial to a firm. As noted earlier, Cainelli et al. (2007) use an Italian census of 773 firms 1993-95 to carefully estimate the impact of eco-innovation strategies on employment, turnover and labor productivity. They find a negative relationship on employment and turnover, with no significant effect on productivity. Mazzanti et al.(2008) use the same firms to confirm a negative link between environmental motivations and growth in employment. Mazzanti et al.(2009) follows up using a larger sample of 61,219 Italian manufacturing firms 2000-2004, with results showing a trade-off of lower environmentally efficiency in the recent past which allows slightly faster growth in the short and medium term, although there are some possibly complicated nonlinearities in that relationship involving policy types. Bernauer et al. (2006) further recommends nine studies on markets for green products, studies which are not reviewed here, but which clearly show case-specific results.

A great deal of clarifying empirical work could still be done here. There is a small literature (following Pakes, 1985) which attempts to link patent grants with stock market valuation, but we are unaware of any work specific to eco-innovation. Similarly, there is work to evaluate the characteristics of patents which contribute to their value at auction (e.g. Sneed and Johnson 2009), but nothing specific to environmental technologies.

In sum, the greatest potential for propelling innovation is frequently found in market forces and incentives. Uncertainty, externalities, and subsidies to competing goods undoubtedly hinder the process, but the motivation provided by potential profit is undeniable. Economic studies show that the innovative process may be enhanced (or inhibited) by appropriate government incentives or regulations. Given the spillovers associated with eco-innovation and the public goods nature of these technologies, there is a role for government intervention in order to spur an increase in environmental innovation.

d) Role of system complexity

System complexity is a serious problem for any policy to consider. Not only is the modeling of the economic-environmental system complex, but each policy decision has both direct and indirect impacts on multiple sectors of the economy. As a simple example, Goolsbee (1998) and Jaffe et al. (2001) raise the question of the elasticity of supply of R&D inputs, so that if innovation is pursued actively in environmental areas, there may be a deterioration of innovation in other fields.

Models of the economic-environmental system abound, and none are simple. The Dynamic Integrated model of Climate and the Economy (DICE; Nordhaus 1994), arguably the first and simplest of the models, includes 74 variables, most of which vary over time and with the state of the model's development, and 32 equations, many of which dynamically fix the relationships between constraints and objectives. Extensions of the DICE model (e.g. in Nordhaus and Boyer 2000) run to 36 pages of appendices outlining the programming of the constraints and functions. Further extensions or alternatives, each excelling in one particular nuance of theory or another, can be found in a spectrum of sources (Nordhaus and Boyer, 2000; Buonanno et al., 2003; Gerlagh and van der Zwaan, 2003; Bosetti et al. , 2006a and 2006b). As a result, it would be futile here to try to summarize the results. Instead, we merely point the reader to those sources for advanced mathematical models to evaluate most policy considerations.

Cahoy and Glenna (2009) consider the impact of the imperfectly competitive agribusiness industry, and the consolidation of market power there in a few firms. The danger is that the horizontal integration is 'necessary' for economies of scale, but reduces competition and limits the gains flowing back to the small-scale producer. The same may occur in eco-innovation, particularly since there are efficiency advantages to local production (rather than shipping biomass to a central facility for energy conversion, thereby losing the energy content advantage over traditional fuels). In short, the oligopolistic nature of the distribution or even production system must be taken into account when forming policy.

Karl et al.(2005) examine thirteen case studies of eco-innovation in Italy, and find that the challenges vary considerably by sector. In all cases, they point to the underlying challenge of coordination/cooperation between firms, as innovation invariably means spillovers to other agents. They find very positive effects attributable to intermediary organizations, to the degree of trust between agents, and to specific policy initiatives that facilitated cooperation and information exchange.

Uncertainty, as outlined in the introduction, clearly contributes to the complexity of the situation. Tidd (2006) points out that technological discontinuity leads to extremely challenging problems that emerge in a complex system. Innovative and production players, as well as regulators and government agencies, may be faced with a new environment or uncertainty stemming from the extent of system complexity. Chandrashekar and Basvarajappa (2001) propose that creating a network of working relationships, comprised of industry, academia and government entities, across industries with key technological inputs is one of the greatest challenges to technology policy. However, they note that creating networks in different key industries with technology inputs may accelerate the process of change in these industries through organizational, institutional and personal relationships that ameliorate the risk and disruption associated with technological change.

Interestingly, less developed nations may have an advantage in eco-innovation where their systems are less developed. Larson (2001) analyzes fuel cell technology, suggesting that it may be adopted in less developed nations before developed nations, since the need is greater in the absence of a well-developed power distribution grid. In the absence of an existing reliable power infrastructure, fuel cells could follow the path of cell phones, leapfrogging the challenges of fixed distribution lines and moving ahead to a decentralized model. As the least capital-intensive system (compared to stringing transmission lines from a central generation plant to remote areas), it may very well win based purely on lower upfront costs.

Along similar lines, less developed nations may also have the advantage of less techno-economic certainty, resulting in less resistance to new complex eco-innovative systems, since they have fewer effective institutionalized systems currently in place for energy provision, manufacturing, waste disposal and other environmentally-sensitive sectors. Craig et al. (2006) look at survey responses from 278 Australian family-owned businesses, and find that higher techno-economic uncertainty and better information flows both work in favor of innovation.

e) Role of policy

The literature is unanimous in asserting that policy clearly has a tremendous role to play in the support (or stifling) of eco-innovation. Press (2007) is a good review of the literature on the impact of regulation on environmental protection, but also on competitiveness and innovation and capital movements. There are several key themes upon which virtually all economists agree.

First, there is a clear portfolio of policy alternatives to stimulate innovation or energy-related investment including taxes, subsidies, permits and standards/regulations. Unfortunately, Requate (1998) shows that comparing taxes and permits depends critically on the parameters, so the social preference on policy should be situation-specific. Montero (2000) finds that standards and taxes yield higher incentives for R&D in a Cournot environment (where firms compete based on quantity), but yield the worst results in a Bertrand market (where firms compete based on price). Parry (1998) presents model simulations showing that the welfare gain of policies encouraging innovation may be limited, depending on the type of spillover externalities. In short, economists agree that the details of the policy matter more than the overall degree or intent of the policy (Kemp 1997; Cleff and Rennings, 1999; Hemmelskamp, 1999; Klemmer et al., 1999; Jaenicke et al., 2000; Frondel et al., 2004; Jaffe et al., 2004; Jacob et al., 2005; Johnstone et al., 2005; Johnstone et al., 2007; Johnstone, Hascis and Popp (2008); Bernauer et al., 2006; Rehfeld et al., 2006).

Second, there is strong evidence that regulatory policies can be very effective. For example, Popp (2001, 2003) empirically shows that regulations requiring plants to install SO_2 scrubbers created an incentive for eco-innovation, distinctly different from the pre-regulation period. While patenting rates fell, the nature of innovation was shifted to pollution-limiting goals from other private cost-reducing goals. Rehfeld et al. (2006) analyze firm-level data in the EU to show that the certification of environmental management systems has a significantly positive effect on environmental product innovations. Jaffe and Palmer (1997) find a less inspirational result, namely that lagged environmental compliance expenditures have a significant positive effect on R&D expenditures, but they do not find that successful patent applications are related to compliance costs. Berrone et al. (2007) confirm unsurprisingly that in the U.S., firms with a history of more litigation by the Environmental Protection Agency have more eco-innovations, holding other factors equal. Work by a host of others (e.g. Bonifant et al., 1995; Shrivastava, 1995; Hemmelskamp, 1999; Klemmer et al., 1999; Jaenicke et al., 2000; Brunnermeier and Cohen, 2003; Jacob et al., 2005; Johnstone et al., 2005; Johnstone et al., 2007; and Johnstone, Hascic and Popp, 2008) all document the empirical effects of environmental regulation. However, the costs are substantial: Brunnermeier and Cohen (2003) conclude that firms spend $170-185 billion per year complying with environmental regulations, up 50% from 1990.

Arimura et al. (2007) use 4200 firm-level observations across the OECD to study the propensity for firms to do environmentally-related R&D. In a simple Tobit estimation, they find that subjective perception of the stringency of environmental regulation is a strong predictor of environmentally-related R&D. Firms with an environmental accounting system, or access to technical assistance programs, are likewise more likely to do more R&D. There is also a strong nation-specific, and perhaps cultural, effect. In a similar study drawing on the same data, Lanoie et al. (2007) find that environmental policy induces innovation.

A worthwhile and readable account of this sensitivity to location and culture is presented by Calef and Goble (2005) as they compare the policy encouragement during the 1990s of electric vehicle diffusion by California and France. They argue that California's stringent regulation spurred the development of innovative hybrid and fuel cell vehicles more effectively than the French approach, calling it "technology-forcing". On the other hand, there is mixed evidence about the impact of regulatory policy on automobile fuel efficiency standards (see Crabb and Johnson, 2010 for a recent review and evidence).

In a larger empirical study on the impact of regulation, Cleff and Rennings (1999) used the Mannheim Innovation Panel survey of 2264 companies with follow-up for 929 eco-innovative firms in the survey. The data are only summarized, but generally show that a combination of regulation and public image drove the majority of innovations, rather than stated green goals. These data would be very interesting to analyze again with a more rigorous model and statistical toolkit.

Ulph (1998) correctly concludes that increases in the stringency of a regulatory standard has 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”. Others, like Carraro and Siniscalco (1994), show that innovation subsidies could be used instead of pollution abatement taxes, achieving the same goal without the output drag of a tax or regulation.

However, the evidence on the effectiveness of financial policy measures (taxes and subsidies) is ambiguous at best, and negative in many cases. Kemp (1997) argues that they have been largely ineffective, a result largely upheld by the literature review of Hall and van Reenen (2000). Carraro and Soubeyran (1996) found an R&D subsidy preferable to an emissions tax only if the output contractions induced by the tax are small or if the government finds output contractions desirable for other reasons. Katsoulacos and Xepapadeas (1996) confirmed that a simultaneous tax on pollution emissions and subsidy to environmental R&D may work best of all in overcoming the joint market failure (negative externality from pollution and positive externality or spillover effects of R&D). Goulder and Mathai (1994) and Jaffe et al. (2001) note that in many cases, in the presence of eco-innovation subsidies, the optimal rate of pollution taxes will be lower, even though the desired level of abatement is higher, resulting in a worse government budget situation.

Johnstone, et.al. (2007) and Johnstone, Hascic and Popp (2008) study the impact of environmental policies on renewable energy technology using panel data from 26 countries from 1978 to 2003. The study finds that public policy has a significant impact on the development of new technologies. Utilizing a composite policy variable (including production tax credits, mandatory production quotas, differentiated tariff systems and tradable certificates) the authors find that the policy instruments are statistically significant for all renewable energy sources. Notably, the study found that only tax incentives have wide influence on renewable energy innovation.

Tradeable permits markets for pollution have almost universal support from economists, as they encourage the efficient distribution of costs from a regulatory measure. By requiring and enforcing a maximum aggregate amount of pollutant, such markets ensure that standards are upheld. By encouraging firms to trade permits, markets distribute benefits to firms capable of low-cost reductions in emissions, thus encouraging the aggregate reduction of pollution in a least-cost manner. Laffont and Tirole (1996) utilize a theoretical model to reorganize tradable permits markets with an attached futures market to encourage eco-innovation for the next generation of standards. In a related proposal, Driesen (2003) suggests an “Environmental Competition Statute” to authorize those who achieve low emissions to collect the cost of achieving low emissions plus a premium from competitors with higher emissions.

Third, policy may serve to create a market for previously uncertain or ill-defined environmental commodities. Porter and van der Linde (1995) presented this forcefully as the assertion that environmental regulation can be good for industry by pointing out, or even forcing, unseen opportunities, and Desrochers (2008) restates it as part of a larger literature on the incentive to create by-products out of industrial waste. Ricci (2004) builds a model in which environmental regulation can improve productivity and economic growth, i.e. supporting the Porter hypothesis via increased productivity of inputs, better education, economies of scale in abatement, expectations of a better environment encouraging greater household savings and therefore cheaper investment, and stimulated overall R&D because it is a clean activity.

Bonato and Schumutzler (2000) build a theoretical model and find that the Porter hypothesis holds only under fairly strict mathematical (although theoretically possible) conditions. Environmental regulation might lead to cost-saving innovation if a) the fixed costs of innovation are lower than compliance plus production, or b) spillover effects make innovation strategically a bad idea for the firm but a good idea for society, or c) regulation helps to fix incentive problems between managers and owners, or d) regulation helps to clear information flow. However, the compliance costs must be low and there must be initial underinvestment for the arguments to hold in a mathematical model.

Jaffe et al. (2001) summarizes five ways in which regulation may focus the ability of markets to create profit from environmental concerns: they focus attention on the issue, they create information useful in developing solutions, they reduce uncertainty, they create first-mover advantages if other regions follow in regulation, and they create pressure to overcome inertia by polluters. The empirical evidence is thin on each side of this hypothesis.

Fourth, current policymakers are frequently unable to muster the political will to enact legislation that is pro-environmental innovation. Arrow et al. (2004) point to government subsidies as one of the three most important threats to eco-innovation. They refer to the 1992 World Development Report by the World Bank which showed that in 29 of 32 LDCs surveyed, subsidies had caused the price of electricity, water and fossil fuels to fall below cost (not even including externality costs). They similarly report that the International Energy Agency (1999) "has estimated that in India, China and the Russian Federation, full-cost pricing would reduce energy consumption by 7, 9 and 16 percent, respectively… where most of the departure from social cost pricing is attributed to energy subsidies". Friedman (2006) argues that China has one political advantage over the US, that it can make decisions against special interests and all bureaucratic obstacles or worries about voter backlash and simply order a change. If the US could do that for one day, to institute responsible regulations, standards, education, infrastructure and prices, he argues, then our system would make sure that they are enforced via legal action if necessary.

Fifth, heterogeneity may be a desirable attribute in policy. Adler (2001) advocates "competitive federalism as a promising alternative to rigid, inefficient national regulation and regimentation". He asserts that many environmental issues are local or regional in nature, so require local knowledge and solutions. He advocates a national policy of "ecological forbearance", where states would petition the EPA for waivers of particular requirements in order to pursue state-level innovation and experimentation. Rather than rely on a patchwork system of prescriptive policies which may slow innovation and impose non-trivial costs, a new system might encourage (or at least permit) states to deviate from the national norm in pursuit of better solutions. Kemp (1997) even goes so far as to argue that uncertainty about regulation may spur innovation, and in fact simultaneous innovation and regulation discussions may offer the best path. While both are fairly dramatic positions for mainstream economists to espouse, most would indeed agree that a variety of approaches is wise, in order to encourage the widest possible base of knowledge to tackle problems common to us all. The comprehensive survey of alternative energy technologies by Hoffert et al. (2002) concludes that a portfolio approach for simultaneous development is the only realistic strategy for success.

Strategies for effective innovation

There are several key lessons in this literature review for the effective policymaker. First, economics has effective tools, many of them highly mathematical and difficult to summarize, that permit policymakers to simulate policy choices and their effects on the environment and related innovation. None are perfect, nor do they pretend to be. However, they all work from a common set of assumptions that empirical studies have proven to be reasonable. Naturally, the future is unpredictable and innovation is doubly so by its creative nature. There are economic models freely available to offer best estimates, and we impartially recommend comparison between them. In fact, a direct comparison of their predictions would be a valuable contribution to the literature. For alternative models, see Kaufman (1997), Messner (1997), Goulder and Schneider (1999), Goulder and Mathai (2000), Van der Zwaan et al. (2002), Buonnano et al. (2003), Bosetti et al. (2006a, b), Popp (2004, 2006b). Keeping in mind that results are often sensitive not only to the underlying parameters, but to specifications of the functions in the model (see Soderholm and Sundqvist, 2007 on the fragility of modeling results based on alternative specifications of a learning function), parallel analyses are warranted.

Second, we have pointed to five themes which resonate with all economists as challenges to eco-innovation: intellectual property rights, economies of scale, markets and incentives, complex systems, and policy. Economists are virtually unanimous in pointing to intellectual property rights as an essential precondition, not a constraint to innovation, but there are some suggestions in the literature about ways in which the existing system could be improved for the stimulation of eco-innovation specifically. Economies of scale are undeniably important, raising the question of how to present a sufficiently sized market to drive costs per unit down to levels permitting widespread access. The market has a clear role to play, but when the systemic effects are complex and uncertainty is high, the role of policy becomes disproportionate.

Aubert (2004) identifies a number of features that characterize successful innovation in less developed nations in particular: motivated individuals or groups, assistance from foreign partners in financing or market networks, support from local politicians to overcome administrative barriers, and concentration in a well-defined locality or industry. Market forces will shape some of these factors, but there is a clear role for effective policymaking in order to foster these conditions and facilitate environmental innovation in the nations that most require, and perhaps can least afford, these technologies.

Conclusions and policy implications

The challenge to policymakers is one of balance: encouraging competition while guaranteeing a large market for minimum economic scale, reducing uncertainty about future resource prices while keeping alternatives open, offering rights of exclusion to intellectual property holders while not curtailing the ability of sequential innovators to build upon past successes, promoting social goals while respecting market pressures. This is no doubt complicated by the policy distortions and market failures that characterize the markets for competing and complementary goods. The exercise is one of structuring the future but permitting innovators to creatively fill in the frame and to build out in unpredictable directions. The unenviable challenge requires flexibility and vigilance by policymakers, but the challenge is only commensurate with the stakes.

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