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The Role of Technological Change in Green Growth

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Abstract

By reducing the costs of environmental protection, technological change is important for promoting green growth. This entails both the creation of new technologies and more widespread deployment of existing green technologies. This paper reviews the literature on environmentally friendly technological change, with a focus on lessons relevant to developing countries. It begins with a discussion of the data available for measuring the various steps of technological change. It continues with a discussion of sources of environmental innovation. Given that most innovation is concentrated in a few rich countries, this leads to a discussion of the remaining role for lower-income countries, followed by a discussion of technology transfer. Because of the importance of market failures, the paper discusses the role of both technology policy and environmental policy for promoting environmentally friendly technological change. The review concludes with a discussion of what environmental economists can learn from other fields.

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The Role of Technological Change in Green Growth*

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I. Introduction

Recent rapid economic growth of countries such as China and India brings the promise of a better life to much of the world's population. As developing countries grow, attention often turns to the environment. For instance, a recent World Bank report shows that levels of particulate matter (PM) in urban areas are over twice as high in low and lower-middle income countries than in upper-middle and high income countries. As a result, these low and low-middle income countries lose an average of 0.7% of gross national income from PM-related damages, compared to just 0.3% for high income countries (World Bank, 2009). Similarly, Dasgupta *et al*. (2008) provide estimates from a series of World Bank studies in the Middle East and North Africa on the costs of environmental degradation from indoor and outdoor air pollution, inadequate water and sanitation services, land degradation, coastal zone degradation, and solid waste disposal. These costs range from 2% of GDP in Tunisia to 7% of GDP in Iran.[1]

Such costs from pollution suggest that promoting a cleaner environment need not conflict with efforts to promote economic growth. Green growth seeks to encourage economic growth and development in a way that balances concerns about environmental harm with the need for long-term economic growth. Reducing environmental harm can come from end-of-the-pipe solutions that remove pollutants from the waste stream before they enter the environment, or from behavioral changes that reduce the use of resources in production or consumption. Reducing resource usage reduces the pollution that comes from these resources (e.g. reducing fossil fuel consumption reduces greenhouse gas emissions) and reduces stress on the environment from the extraction of natural resources.

[1] These studies consider the costs from indoor and outdoor air pollution, inadequate water and sanitation services, land degradation, coastal zone degradation, and solid waste disposal. Thus, not all of these costs would be measured using conventional definitions of national income.

Technological innovation plays an important role in reducing the costs of both types of environmental protection, and thus promoting green growth. One reason that upper-middle and high income countries have been able to achieve better environmental quality for some pollutants such as local air quality is through their use of advanced pollution abatement techniques.[2] While the use of these technologies often entails initial costs, which can engender debate over near-term gains relative to reduced disposable income, the benefits they provide, which may come in the form of improved health and quality of life as opposed to increased disposable income, are often substantial.[3] Similarly, the development of more efficient appliances, vehicles, and industrial equipment allows for greater energy efficiency and lower cost of resource use. Many of the fixed costs of technology development have already been paid by developed countries. Thus, in many cases, it is the transfer of these technologies to developing countries that is important.

Moreover, the concern is not just for the local environment in developing countries. Global environmental problems are also an issue. While emissions in high-income countries begin to stabilize, the share of emissions coming from developing countries is growing. In 2010, 75% of the growth in CO_2 emissions came from non-OECD countries.[4] CO_2 emissions from non-OECD countries are projected to be nearly double of those from OECD countries by 2035 (Energy Information Administration, 2010). Due to the growth in emissions from developing countries, designing policy that encourages the transfer of clean technologies to developing countries has been a major discussion point in climate negotiations.

This paper reviews the growing literature examining the links between technological change, environmental policy, and economic performance. Technological change proceeds in

[2] See, for example, Dasgupta *et al*. (2002).
[3] For a recent review of such studies in a U.S. context, see Graham (2007).
[4] http://www.iea.org/index_info.asp?id=1959, accessed August 5, 2011.

three stages. At each stage, incentives, in the form of prices or regulations, affect the development and adoption of new technologies:

Invention: an idea must be born.

Innovation: new ideas are then developed into commercially viable products. Often, these two stages of technological change are lumped together under the rubric of research and development (R&D).

Diffusion: to have an effect on the economy, individuals must choose to make use of the innovation.

I use this review to identify gaps in the literature at each of these three stages that merit further study to advance the promotion of green growth. I begin with a discussion of data available for measuring the various steps of technological change. I continue with a discussion of where environmental innovation comes from. Given that most innovation is concentrated in a few rich countries, this leads to a discussion of the remaining role for lower-income countries. I note a growing role for emerging economies, and identify three key questions pertaining to green R&D in developing countries. These questions all focus on the links between innovation and demand: (1) promoting the development of technologies with limited markets in high-income countries, (2) the role of adaptive R&D, and (3) the potential for emerging economies to meet the green technology needs of high-income countries.

Since much R&D occurs in high-income countries, I continue with a discussion of technology transfer. Beginning with diffusion across countries, differences among countries raise important questions, such as (1) understanding how the technological distance between countries affect the transfer of green technologies, (2) whether lessons learned from the recent successes of India and China are generalizable to smaller countries. Similarly, within countries, diffusion of green technologies can be affected by characteristics that are unique to developing countries. For instance, limited access to credit markets may make financing green technology difficult. Research on alternative financing mechanisms should aim to address concerns over access to financing.

Because of the importance of market failures, I then discuss the role of both technology policy and environmental policy for promoting environmentally friendly technological change. Three key questions emerge. First, while there is consensus in the literature that both policies play a role, most of the exiting research focuses on high-income countries that emphasize the creation of new green technologies. Thus, an important knowledge gap is in understanding the balance of policies needed in developing countries, where adaptive R&D and technology transfer will play a larger role. Second, to build stronger support for green innovations even without policy interventions in developing countries, additional research should better quantify the potential of secondary benefits from green technologies. Third, given that the effectiveness of policy depends on good governance, the links between governance and green growth also deserve further study.

The review concludes with a discussion of more general technology issues, such as what environmental economists can learn from other fields. While not exclusive, much of the focus in the paper is on energy use and climate change. This is consistent with general trends in the literature, given recent interest in the climate problem. While not emphasized here, other technologies will also be important for low-income countries, particularly pertaining to resource use (such as water) and agricultural productivity. As noted in the concluding section, future work should also explore the differences that emerge among various technological fields.

II. Data on Technological Change

To begin our review, it is important to know how technology is measured. The knowledge that makes any technology a valuable improvement is an abstract concept. We do not observe knowledge directly. Rather, we observe inputs that create knowledge or outputs that contain knowledge. Similarly, knowledge is rarely given directly to developing countries. Rather, it comes embodied in products bought and sold through international trade, or can be tacit knowledge provided by the education of a worker. It is these indirect inputs and outputs of the knowledge-generation process that are used to measure technological change, both as it pertains to green growth and more generally.

Research and development (R&D) data offer a straightforward measure of innovative activity. R&D is an input into the innovation process. Variations in environmentally-friendly R&D spending tell us the relative importance placed on such innovation. However, as R&D is an input, measures of R&D effort do not reveal information about outcomes of the innovation process. Moreover, detailed information on specific types of R&D is often unavailable. For instance, in a survey of energy R&D activity, Gallagher *et al*. (2011) note that while government spending on energy R&D is widely available for International Energy Agency (IEA) member nations, data on energy R&D efforts from private firms are scarce. As an example of such public R&D data, Table 1 presents public energy R&D budgets for various IEA member countries for selected years. In general, public support for energy R&D has grown in recent years, with the most notable increase coming from energy efficiency and renewable energy research. Moreover, even publicly available R&D data are noisy. Data collection may vary by country. For instance, one country may include basic R&D on semiconductors as investment in photovoltaic research while another may not (Gallagher *et al*. 2011).

Patents offer an alternative measure of inventive activity. Patents provide a detailed record of each invention. From the bibliographic data on a patent, the researcher can learn the identity and home country of the inventor, read a description of the invention, and see references to earlier patents. Using patent data, it is possible for researchers to collect data in highly disaggregated forms. Whereas R&D data are typically available only for specific industries or general applications,[5] patent classifications can be used to distinguish between different types of R&D at great detail, such as air pollution control devices designed to reduce NO_X emissions versus devices designed to control SO_2 emissions.[6] In addition, economists have found that patents, sorted by their date of application, provide a good indicator of R&D activity, as patent applications are usually filed early in the research process (see, for example, Griliches 1990). As a result, patent counts not only serve as a measure of innovative output, but are indicative of the level of innovative activity itself. A recent OECD data collection effort makes data on 37 different types of environmental technologies readily available to researchers.[7]

However, patent data also have drawbacks. While patent counts should be expected to increase as R&D activity increases, the correlation need not be exact. Variations in patent law, both across countries and across time, must be controlled for to properly interpret patent data. Furthermore, the existence of a patent does not mean that the technology has been adopted. Indeed, studies of the economic value of patents find that most patents have little commercial value, suggesting that adoption of most patented inventions is not widespread (see, for example, Lanjouw *et al*. 1998). Moreover, firms are more likely to use patents to protect new products

[5] For example, in the US, private R&D is available from 1972-1994 for air pollution control, but it is not broken down by pollutant.
[6] For example, US patent classes 423/235-423/239 pertain to control of "nitrogen or (a) nitrogenous component", and patent classes 423/242 – 423/244 and 423/569 – 423/570 pertain to control of sulfur compounds. Using patent databases, it is possible to download all patents in these classes.
[7] Accessible at http://stats.oecd.org/index.aspx, accessed September 21, 2011.

than new processes (Levin *et* al. 1987). As such, patent data may understate changes in the nature of innovation as countries shift their environmental policy focus from end-of-the-pipe to integrated solutions leading to modified production process.[8] Despite these caveats, patent data offer several advantages when studying technological change and its effect on the environment, and have been widely used in studies of eco-innovation.[9] For instance, Johnstone *et al*. (2010) show that patenting activity for renewable energy technologies, measured by applications for renewable energy patents submitted to the European Patent Office (EPO), has increased dramatically in recent years, as both national policies and international efforts to combat climate change begin to provide incentives for innovation. Figure 1 illustrates these trends for five technologies: wind, solar, geothermal, ocean power, and electricity from biomass and waste. With the exception of biomass and waste, each technology experiences an increase in innovation after signing of the Kyoto Protocol in December 1997.

Whereas patents represent an innovation that is ready to be commercialized, scientific publications can be used to measure research at earlier stages of technology development. In particular, data on scientific publications can be useful for research carried out by public sector or non-profit organizations that place less emphasis on obtaining patents. As there is no equivalent to a patent classification system for publications, keyword searches of titles and abstracts are often used to identify relevant publications. This search strategy may introduce a biased towards research from English-speaking countries that should be considered when comparing publication trends across countries.

[8] In some cases, process changes may be captured by patent data, particularly when third-party suppliers provide relevant equipment or materials. For an example, see Popp *et al.* (forthcoming), which discusses process changes in pulp and paper production.
[9] Popp (2005) provides an introduction to the use of patent data for studying environmental innovation.

A vast literature in the field of bibliometrics uses data on scientific publications and citations.[10] While peer review has traditionally been the main form of evaluating academic research, quantitative methods have become more important in the past 20 years (Hicks *et al*. 2004). Within the field of economics, until recently most empirical studies of innovation used patent data, rather than publication data, as the measure of research output. While the use of publication data within the economic research community has recently increased, the focus has primarily been on using publication data to measure knowledge flows across institutions, rather than evaluating the effectiveness of research inputs.[11]

Other options for measuring knowledge creation are also available to researchers. Some studies focus on the effects of innovation. For instance, Newell *et al*. (1999) demonstrate a correlation between energy prices and the energy efficiency of home appliances available for sale between 1958 and 1993. Surveys are also used, such as in Lanoie *et al*. (2007). In a survey of firms in seven OECD countries, they find that greater regulatory stringency induces a firm to perform more environmental R&D. Surveys are particularly useful in the case of process innovations, which are more difficult for the researcher to observe with secondary data.

The above data focus primarily on innovative activity. Focusing on the diffusion of technology is more difficult. In some cases, data are available at the macro-level for cross-country comparisons. For instance, studies such as Popp *et al*. (2011) and Brunnschweiler (2010) compare investments in renewable energy capacities across countries. However, for more micro-level studies, detailed data on the adoption of specific technologies is required, such as in Kemp (1997), Blackman and Bannister (1998), or Gallagher and Meuhlegger (2011). Data

[10] Moed, Glänzel, and Schmoch (2004) provide a good introduction and overview of this literature.
[11] Examples of the former include Adams, Clemmons, and Stephan (2004, 2006), Adams and Clemmons (2008), Jones *et al*. (2008), Wuchty *et al*. (2007), and Zucker *et al*. (2007). Doranova *et al*. (2009) provide an example pertaining to green technologies.

collection for such studies can be costly. World Bank support in collecting product-level diffusion data in developing countries would be very useful to the study of green technology diffusion in low-income countries.

Other sources of technology diffusion data include international trade data, which are available at the product level. For example, Sawhney and Kahn (2011) use the harmonized commodity description and coding system of the World Customs Organization to assemble data on U.S. imports of wind and solar energy technology. They find a growing role for emerging economies such as China and India, which they interpret as evidence of increased technology adoption in those countries. Similarly, World Bank (2008a) uses trade data to show that removing trade barriers on alternative energy technologies would increase trade volumes, and hence technology transfer.

III. Green R&D in Developing Countries

As shown in Figure 2, most of the world's R&D occurs in a few high income countries. In 2007, global R&D expenditures were an estimated $1.107 trillion, with OECD nations accounting for 80 percent, and the United States and Japan together accounting for 46 percent. Among non-OECD countries, China performs 9 percent of global R&D. Estimates of R&D from India and Brazil also place them among the top 15 R&D performers worldwide (National Science Board, 2010).

The dominance of high-income countries among the top R&D performers holds true for environmental innovation as well. Using patent data from the US, Japan, Germany, and 14 low- and middle-income countries, Lanjouw and Mody (1996) study technological change for a variety of environmentally-friendly technologies. They find that such innovation increases as pollution abatement expenditures in the country increase. For the US, Japan, and Germany, patents on these innovations are typically domestic patents. In contrast, for developing countries, the majority of these patents come from other countries. This is especially true of air pollution control technologies, which tend to be complex. Water pollution control technologies, on the other hand, are more frequently local innovations, as local conditions shape the requirements of these technologies, and are less likely to be patented elsewhere.

Dechezleprêtre *et al*. (2011) examine climate-friendly innovation using patent data from 1978-2005 for 76 countries and covering a broad range of technologies, including renewable energy technologies, carbon capture and storage, and energy efficiency technologies for buildings, lighting, and cement manufacture. Like Lanjouw and Mody (1996), they find that most climate-friendly innovation occurs in developed countries. In fact, the US, Japan, and Germany together account for two-thirds of the innovations in their sample. Reflecting the role and impact of policy, innovation increases after the Kyoto Protocol in all Annex I countries except the US, which had not ratified Kyoto.[12]

Dechezleprêtre *et al*. (2011) do find some evidence of innovation in emerging economies, as measured by patents. In particular, China, South Korea, Russia and Brazil together accounted for 18.5% of climate-friendly innovations from 2000-2005. However, innovation in emerging economies is often of a different nature. For example, the most prevalent innovations in China, South Korea, Russia, and Brazil include technologies designed primarily for local markets, such as geothermal and cement manufacture. As a result, the share of high-value patents (defined as patent applications filed in multiple countries) from these four countries is just 7.2%. Consistent with Lanjouw and Mody (1996), Dechezleprêtre *et al*. (2011) find that technologies of wider use

[12] Annex I countries include all Annex B countries plus Belarus and Turkey. These are the developed and transitioning economies required to reduce emissions under the Kyoto Protocol. A list of Annex B countries can be found at http://unfccc.int/kyoto_protocol/items/3145.php

globally, measured by the percentage of patents that have corresponding applications in other countries, are nearly all from developed economies.[13]

Most patents are financed via private R&D investments. Data on government-sponsored R&D show that the emerging economies are beginning to ramp up efforts pertaining to energy R&D. Gallagher *et al*. (2011) provide rough estimates of government spending on energy R&D by industrialized economies and six emerging economies: Brazil, Russia, India, Mexico, China, and South Africa (BRIMCS). Industrialized economy governments spent $12 billion on energy R&D in 2008, compared to $13.8 billion by the BRIMCS.[14] In the BRIMCS, government energy R&D spending is a recent phenomenon. However, as in the industrialized world, much of this spending is on traditional energy sources, such as fossil fuels and nuclear. For example, India tripled its nuclear energy R&D budget between 2003 and 2007. Whether such investments can be considered green (e.g. does research on fossil fuels make them cleaner) is unclear.

A. Knowledge Gaps on Green R&D

Because so much green innovation occurs in high income countries, their environmental policies usually shape the development of environmentally-friendly technologies worldwide. This is partially because these countries are typically the first to enact environmental regulations. Because most environmental innovations help to reduce externalities, there is little market for such innovations without policy incentives. By increasing the relative price of pollution, environmental polices provide incentive for green innovation. Drawing on the notion of induced innovation (Hicks 1932, Binswanger and Ruttan 1978, Acemoglu 2002), which recognizes that

[13] Because patents are only valid in the country granting the patent, an inventor must file a patent application in each country for which protection is desired. These related applications are called *patent families*. Economists use these patent families to indicate the importance of an invention (e.g. Lanjouw and Schankerman, 2004).
[14] Both figures are in 2008 US dollars using purchasing power parity. Of the $13.8 billion, $11.8 billion comes from China.

R&D is a profit-motivated investment activity and that the direction of innovation likely responds positively in the direction of increased relative prices, there is a broad literature demonstrating the links between environmental policy and innovation in developed countries (see Popp *et al*. 2010 for a review of this literature).

In contrast, there is less work exploring the potential for additional R&D from developing countries. The technologies needed in developing country markets may differ from those created in high-income countries. Developing countries, particularly emerging economies with demonstrated existing R&D capacity, such as the BRICS, may be able to play a role filling this gap. This suggests three questions for future research.

1. What can be done to encouraging development of technologies with limited markets in high-income countries?

Given that the technologies needed in developing country markets may differ, research is needed on how to encourage innovation on technologies with limited markets in high-income countries. For example, technologies for use off of the main electric grid, such as improved cooking stoves, typically have limited markets in developed countries. However, nearly three billion people in developing nations use indoor stoves burning crop waste, wood, coal, or dung. Indoor air pollution from the burning of these fuels kills 1.9 million people per year (Broder, 2010). Moreover, recent research highlights the potential for improved cookstoves to not only reduce indoor air pollution, but also mitigate climate emissions. Smoke from these stoves produces black carbon, which recent reports list as the second most important pollutant contributing to climate change, responsible for 18 percent of global warming (compared to carbon dioxide's (CO_2) 40%). Ramanathan and Carmichael (2008) first noted the climate change potential of black carbon. They note in particular that China and India alone account for 25-35% of global black carbon emissions. Providing energy efficient and smoke-free cookers, along with reducing soot emissions from coal combustion in small industries, could reduce warming from black carbon in East Asia by 70-80%.

To illustrate the role of developing countries for such off-grid technologies, Table 2 presents total patent counts based on inventor country for four types of cooking stoves whose primary applications are in developing country markets.[15] In all four cases, China is the leading source of patents, ranging from 46% to 89% of the total for each technology. Among developing countries, we also include data for India and South Africa, as these countries are important sources of scientific publications, to be discussed below. However, neither is an important source of patenting. This may be because these countries are doing less commercial work on these technologies, or because intellectual property rights are not seen as valuable in India and South Africa.

Because developed country research on indoor cooking stoves may be led by non-commercial entities such as universities or non-profit foundations, which are less likely to patent successful research outcomes, Table 2 also includes counts of scientific publications. Even here, a developing country is the leading source of articles for three of the four stove technologies.

[15] These patents were identified using a combination of keyword and patent classification searches using the Delphion on-line patent database. Countries are identified using the first inventor listed on the patent. If no inventor country is limited, the first priority country (e.g. the country where the application was first filed) is taken as the source of the invention. Scientific publication data are collected using a keyword search of abstracts and titles in the Web of Knowledge database. Here, the source country comes from author affiliations. For multiple authored papers, affiliations are counted for each country, so that the total number of affiliations may exceed the total number of articles. Appendix A lists the search terms used for each stove type. Note that the use of keyword searches may bias downward counts from countries whose patent abstracts may appear in other languages, such as France and Germany. However, that Chinese patent counts are larger than even the U.S. and Japan, who do the bulk of global R&D, is still notable.

However, in this case, it is India, rather than China, that is the leading source.[16] In both cases, the evidence above suggests that R&D from emerging economies can play a role providing technologies of need throughout the developing world. Their potential needs to be better understood.

2. What adaptive R&D will be needed? What are the potential impacts of adaptive R&D?

Because policies in developed countries have encouraged innovation of emissions-reducing technologies, in many cases technologies are readily available for developing markets. In some cases, the availability of cleaner technologies may even offer developing countries the opportunity to "leapfrog" over developed countries by adopting cleaner technologies before serious harm occurs (see, for example, Dasgupta *et al*. 2002). For example, when China imposed its first fuel economy regulations on passenger vehicles in 2004, they were more stringent than the standards in the United States (Bradsher, 2004).

However, even technology transfer may require some investment in R&D. When adjustments are necessary to fit new technologies to local market conditions, it is the recipient countries that will be best-positioned to do this research. Popp (2006) finds evidence of innovation even in countries that are late to adopt regulations, suggesting that these countries do not simply take advantage of "off the shelf" technologies that have been developed elsewhere. Rather, late adopters often undertake adaptive R&D to fit the technology to local markets, as evidence by the increased likelihood of these later patents to cite earlier foreign rather than earlier domestic inventions. Lanjouw and Mody (1996) find similar evidence that the environmentally-friendly innovations that occur in developing countries are smaller inventive

[16] While illustrative of differences in research trends across income levels (particularly given India's lead over the U.S. in most categories), English language bias is definitely an issue when using publication data, as seen by the large advantage of US publications over countries such as Japan or Germany.

steps, typically done to modify existing technologies to local conditions. Both studies suggest that foreign knowledge serves as a blueprint for further improvements, rather than as a direct source of technology. This suggests that when policymakers consider the potential for technological change to reduce environmental impacts in developing countries, they must make allowances for adaptive R&D to fit technologies to local conditions, or else be prepared for less successful results. As an example of such concerns, Wang (2010) finds that when evaluating potential CDM projects, the Chinese government does not encourage the use of technologies that are new to Chinese conditions because of concern that technologies from abroad may not adapt well to local conditions. The risk of poor adaptation to local conditions would increase the risk to credits generated from the CDM project, thus lowering their value. Similarly, as prevailing wind speeds are lower in India than in Europe, wind turbines need to be adapted to generate electricity at these lower wind speeds to be effective (Kristinsson and Rao 2007).

While these examples provide illustrations of adaptive R&D, more research is needed to fully understand both the magnitude of adaptive R&D needed and the potential impacts of adaptive R&D. For example, the spread of cell phones has had major impacts in developing countries, as they are often used to improve provision of services needed in developing country markets, such as financial services. Developing alternative uses for existing technologies requires fewer resources than traditional R&D, making it within the reach of even lower income countries. Given this, research designed to develop a better understanding of the potential for environmentally friendly alternative uses for traditional technologies would be beneficial. Adapting production processes to fit local conditions is also important. For example, de la Tour *et al*. (2011) note that Chinese photovoltaic manufacturers adapt production processes by replacing capital with labor, which is less expensive in China. Such innovations should require fewer resources than developing processes from scratch. However, process innovations are often more difficult to study, as data are harder to come by. For example, firms are less likely to patent process innovations, as they are easier to keep secret (Levin *et al*. 1987). Thus, studying adaptive process innovation will require a mix of qualitative and quantitative approaches to collect the necessary data.

3. Can emerging economies innovate to meet demands of high-income countries?

A third question of particular importance for emerging economies is whether such adaptive innovation can help them meet the demands of high-income countries. That is, can they be suppliers of advanced green technologies for global markets? A few recent studies provide such evidence for emerging economies. For instance, Medhi (2009) finds that Korean automotive manufacturers first incorporated advanced emission controls into their vehicles to satisfy regulatory requirements in the U.S. and Japanese markets. Only later did the Korean government pass domestic regulations requiring advanced emission controls. While emissions control technologies were produced by foreign suppliers, adaptive R&D was necessary to incorporate them into Korean vehicles. Similarly, Sawhney and Kahn (2011) find that imports of wind and solar equipment from poorer countries have grown faster than those from rich countries, and that emerging economies such as China and India have become important sources of wind and solar equipment, helping to reduce the costs of such equipment. de la Tour *et al*. (2011) note that the Chinese photovoltaic industry produced 35 percent of worldwide capacity in 2008, of which 98 percent was exported.

The potential influence of high-income demand raises several questions. First, will the development of such industries via adaptive innovation eventually provide spillover benefits to the environment in countries? For example, will domestic production of solar and wind equipment hasten the deployment of these technologies in China and India? The Korean automobile case provides a positive example. Can such spillovers to the domestic environment be achieved elsewhere? Second, while nearly the entire current production of solar PV cells from China is exported, and thus has limited impact on emissions in China, these imports also lower the cost of PV electricity in the global market. These price decreases may reduce emissions elsewhere. Quantifying such general equilibrium effects would be beneficial.

IV. Technology Transfer and the Environment

As the last section suggests, promoting green growth within developing countries will often be about the diffusion and adaptation of technology, rather than the creation of new technologies. Having discussed adaptation, we now turn to diffusion. Here two issues are relevant. First is the flow of technology across borders, which is important for getting green technologies to developing countries. Second, even when technologies are introduced in an economy, their spread within the country may be uneven. Moreover, uneven diffusion is often more of an issue in a developing country context. This section discusses both issues in turn.

A. International Technology Transfer and the Environment

While international technology transfer has received much attention in the broader economic literature, research focused specifically on environmental technologies has primarily been recent in nature.[17] Nonetheless, diffusion of environmental technologies, particularly to developing countries, is currently one of the most pressing environmental concerns. Technology transfer may include the exchange of products, equipment, experience and knowledge. The

[17] For a general review of the literature on international technology transfer, see Keller (2004).

benefits of the transfer to the recipient developing country, and thus the potential for technology transfer to improve well-being in the recipient country, depend on the type of transfer.

Embodied technology transfer comes through the importation of equipment into a country (e.g., flows of equipment). In such cases, the technology is *embodied* in the imported equipment.

Disembodied technology transfer involves the flow of know-how or experience. Examples include demonstration projects, training local staff, and local firms hiring away staff from multinational firms operating in a developing country. Disembodied transfers provide additional benefits to recipients, as they enable the recipient to develop skills that can be used in later projects initiated by the recipient country. At the same time, disembodied technology transfers are a concern for private firms, as such benefits may come in the form of knowledge spillovers for which technology suppliers are not fully compensated.

Knowledge spillovers provide benefit to the public as a whole, but not to the innovator. As a result, private firms do not have incentives to provide the socially optimal level of technology transfer. The transfers of disembodied knowledge will typically include knowledge spillovers, as it is nearly impossible for the firm transferring a technology to be fully compensated for the enhanced productivity the recipient will enjoy when employing the newly-received skills in future projects. Indeed, encouraging knowledge spillovers is often a goal of developing country policy. For example, China recently ruled that the Chevrolet Volt electric vehicle would not be eligible for the same tax subsidies available to other hybrid and electric vehicles in China unless General Motors transfers the knowledge necessary for building the Volt to a joint venture with a Chinese partner (Bradsher, 2011).

Technology transfer may come from public or private sources. Public funding includes aid from governments or non-governmental organizations (NGO), typically in the form of official developmental assistance (ODA). Compared to private investment, ODA flows are low, but are important in areas of the world that receive little foreign investment (Gupta *et al*. 2007). Technology transfer from private sources may come via international trade, foreign direct investment, or licensing. Spillovers are possible through private transfers, but depend both on the nature of technology flow (e.g. spillovers are often less likely via FDI, which allows multinational firms to maintain control over their technology) and the absorptive capacity of the country. Absorptive capacity describes a country's ability to do research to understand, implement, and adapt technologies arriving in the country. Absorptive capacity influences the speed at which a newly arriving technology diffuses through a developing country. It depends on the technological literacy and skills of the workforce, and is influenced by education, the strength of governing institutions, and financial markets.[18]

FDI is important for environmental technology transfer, as multinationals are usually the first to bring new environmental technologies to a country (see, for example, Dasgupta *et al*. 2002). In many cases, it is easier for a multinational firm to use the same equipment and processes that it uses at home, rather than develop a dirtier process for use in developing countries. Transfer via FDI is likely to be particularly important for integrated process solutions to reduce pollution. Although currently unexplored, this notion is a fruitful topic for future research.

[18] World Bank (2008b) provides a discussion of the role of absorptive capacity in technology transfer. They use data on education, governance and macroeconomic stability to construct an index of absorptive capacity. In addition to the importance of an educated workforce, they provide evidence that a stable economy and strong business environment improve adaptive capacity.

i. Literature on environmental technology transfer

In the broadest sense, environmental technological change is addressed in literature on trade and the environment. There, economists decompose the effect of international trade on environmental quality in developing countries into three components. First, scale effects account for increased pollution levels due to the greater wealth and increased economic activity that follows international trade. Second, composition effects refer to reductions in pollution resulting from a preference for cleaner goods that develops as countries become richer. Third, technique effects refer to emission reductions that occur because trade expands access to cleaner technologies (Esty 2001, Copeland and Taylor 2003). Attempts to identify this technique effect can be seen as examples of technology transfer.

Fisher-Vanden and Ho (2010) consider the interaction of scale and technique effects in a simulation of increased science and technology (S&T) capabilities and energy use in China. They note that improving S&T capabilities has two offsetting effects. While technological development can lead to the use of cleaner technologies (the technique effect), increases in S&T also lead to larger energy intensive industries (the scale effect). Their paper simulates the effect of S&T growth in China, with R&D intensity reaching 2.5% by 2020, as stated in China's long-term policy goals. They note that China's R&D intensity has already increased from 0.6% in 1996 to 1.3% in 2003. Calibrating their model based on econometric results from 1500 industrial enterprises, they find that the S&T takeoff should have an energy-saving bias, resulting in lower energy prices. However, this leads to more economic growth and greater energy consumption by households, so that the net effect of the S&T takeoff is greater energy use and more carbon emissions. Fisher-Vanden and Sue Wing (2008) develop an analytical model that finds similar results.

Khanna and Zilberman (2001) illustrate the importance of trade to diffusion in a study of the adoption of energy efficient technologies at electric power plants in India. As is typical in adoption models, variations in the adoption of these technologies occur due to differences across heterogeneous plants. Emissions could be reduced by the adoption of high quality coal. However, such coal would need to be imported. In an effort to protect the domestic coal industry, such imports were virtually banned by the Indian government. Khanna and Zilberman find that while an emissions tax is necessary to achieve optimal levels of abatement, simply removing domestic and trade policy distortions would increase adoption of energy efficient technology and potentially decrease carbon emissions. Thus, policies designed to protect specific sectors may have unintended consequences that increase environmental harm, raising political challenges to achieving green growth.

Dechezleprêtre *et al*. (2011) provide a detailed look at technology transfer coming from the Clean Development Mechanism (CDM). The CDM allows polluters in industrialized countries with emission constraints to receive credit for financing projects that reduce emissions in developing countries, which do not face emission constraints under the Kyoto Protocol.[19] Dechezleprêtre *et al*. reviewed 644 CDM projects registered by the Executive Board of the UNFCCC to determine how many projects transfer "hardware", such as equipment or machinery, as opposed to "software", which they define as knowledge, skills, or know-how. Spillovers of software exemplify disembodied technology transfer. Thus, their research helps to identify the settings under which such transfers are likely.

Dechezleprêtre *et al*. (2011) find that 279 projects, or 43%, involve technology transfer. However, these projects are among the most significant CDM projects, accounting for 84% of the expected emissions reductions from registered CDM projects. Of these projects, 57 transfer

[19] Lecocq and Ambrosi (2007) provide a description of the Clean Development Mechanism.

equipment, 101 transfer knowledge, and 121 transfer both equipment and knowledge. Dechezleprêtre *et al.* find that a project is more likely to include technology transfer if it is larger, if the project developer is a subsidiary of a company in a developed country, and if the project includes one or more carbon credit buyers. Before credits for a project can be sold, the emissions reductions must be certified. Because they have an interest in obtaining emissions credits, credit buyers help to facilitate this process. Dechezleprêtre *et al*. (2011) find that technology transfer is more likely if the country is more open to trade. They also find that technology transfer is less likely if there are other similar projects in the country. For instance, countries with greater technological capacity are better able to develop their own innovations in agriculture, reducing the need for technology transfer from abroad for agricultural projects.

Several recent studies explore the role of technology transfer, both through joint ventures with multinational firms and supported by policy, in the development of renewable energy industries in developing countries. Lewis (2007) explores the development of the wind energy in India and China. Both India and China went from having no wind turbine manufacturing capacity to almost complete local production of turbines in less than 10 years' time. In both cases, a combination of local energy policy that created demand for wind energy and efforts of the leading local firms to gain new skills were important. For example, Suzlon, the leading Indian wind turbine manufacturer, established R&D facilities in the Netherlands and Germany to take advantage of the expertise from these countries. In contrast, Goldwind, the leading Chinese wind turbine manufacturer, sends employees abroad for training, but has no overseas facilities. Both firms used licensing agreements with European manufacturers to gain initial access to turbine technology, which they then built upon through their own R&D efforts. In both cases, domestic policies encouraged licensing. India used customs and excise taxes to favor importing wind turbine components over complete turbines, thus providing a market for domestic firms to assemble turbines. China requires that 70% of the content of a wind turbine used in China be produced domestically.

Lewis (2007) also provides examples of the potential constraints faced by developing countries when the promote technology transfer. For example, while foreign-owned wind turbine companies operating in China use China-based manufacturing facilities, they have typically chosen not to transfer intellectual property through licensing agreements. Moreover, in both India and China, the licensing agreements that have been reached have been with smaller companies that had little international presence. In contrast, larger companies avoided licensing agreements so as to avoid helping the development of international competitors.

de la Tour *et al*. (2011) provide a similar analysis of the development of the Chinese photovoltaic (PV) industry. This industry primarily serves international demand, as 98 percent of output is exported. However, these firms are not involved with all facets of PV production. Rather, Chinese production capacity is strongest in downstream segments such as cell production, rather than upstream segments such as silicon purification. These downstream processes require little previous experience, so that Chinese manufacturers are able to take advantage of the low cost of energy to provide PV cells for a global market. As in Lewis (2007), international mobility of workers was a more important source of information than FDI or licensing. Of the top 9 PV producers, only three receive FDI, and all three are late entrants into the market. Chinese firms do exchange knowledge with equipment suppliers. Training sessions of engineers and technicians also allow Chinese firms to adapt the manufacturing process to local conditions, such as substituting cheap labor for equipment. Indeed, to the extent that Chinese PV firms innovate, their innovations appear adaptive. For example, only 1% of Chinese PV patents are also filed abroad, suggesting they primarily target the specific features of the Chinese market.

Extending beyond the BRICs nations, Pueyo *et al*. (2011) examine the role of technology transfer in the development of the wind industry in Chile. The case examines Fibrovent Wind, a start-up company that produces wind turbine blades. The firm was created as a partnership with a Spanish turbine manufacturer. Interestingly, in this case, South-South transfer proved essential, as the firm hired a Brazilian wind turbine expert who helped set up the company. Indeed, the authors conclude that successful technology transfer in this case consisted not only of acquisition of foreign equipment and knowledge, but also to knowledge about management, which helped the firm to assimilate foreign technologies. Moreover, Fibrovent was able to transfer knowledge about composite materials used in the Chilean mining industry to blade production. Both examples further illustrate the importance of absorptive capacity in technology transfer.

ii. Knowledge gaps on environmental technology transfer

Particularly in emerging economies, technology transfer has been a motivating factor in the development of green energy industries. Potential spillovers from technology transfer can enhance the domestic capabilities of recipient countries, thus promoting growth. Technology transfer can also influence innovation, as knowledge spillovers may enhance the recipient country's ability to develop future innovations. Each of the cases discussed above provides examples of successful technology transfer. However, questions remain when considering the connections between technology transfer and green growth.

1. How will the technological distance between countries affect green technologies?

The potential for successful technology transfer depends on a good match between the needs of the recipient and the technologies available from source countries. Using patent citation data to assess the flow of knowledge across borders, Verdonlini and Galeotti (2011) test whether knowledge spillovers from foreign innovations influence domestic energy R&D. They use these data to construct knowledge stocks and show that increases in foreign knowledge have a larger impact on domestic R&D than increases in domestic knowledge. This result suggests that knowledge spillovers across countries are an important driver of innovation. While primarily focused on developed countries, Verdonlini and Galeotti include data from emerging economies such as Brazil and China in their initial analysis of the patent citation data. Importantly for developing countries, they find that greater technological distance, an index measuring the similarity of the patent portfolios of two countries, reduces the flow of knowledge across borders, and that technological distance is more important than geographic distance. Given that technological distance will be greatest between countries of disparate income levels, this further emphasizes the need to focus on technology transfer and adaptation of existing technologies, rather than innovation, for developing countries.

Concerns over technological distance also suggest a potential role for technology transfer *among* developing countries. For instance, one might expect emerging economies to be better positioned to provide technologies specific to developing country needs, as the technological distances will be smaller. The evidence on patents and publications pertaining to cooking stoves presented in section III is an example. However, research must focus not only on the potential of emerging economies to create such technologies, but also on the potential for these economies to supply needed technologies to lower income countries.

Two papers consider flows of technology transfer among developing countries. Brewer (2008) suggests that policy should consider the possibility of South-South or even South-North technology transfers. He gives examples where developing countries play roles as technology leaders, such as biofuels in Brazil and subsidiaries of General Electric developing wind turbines in China. Doranova *et al*. (2009) provide further evidence in a study of 497 CDM projects. They ask whether existing knowledge in the host country shapes technology sourcing patterns, focusing on projects using local technologies. Of the 497 projects studied, 56% use technologies of local origin. Moreover, some technology transfer is South-South. China; Malaysia; Taiwan, China; and South Africa all provided technologies in other developing countries. They use data on patents and publications related to climate friendly technologies to measure the knowledge base of a country. Countries with more publications more likely to use local technologies, but more those with more patents are more likely to use foreign technologies, either alone or combined with local technologies. Countries with more experience with a technology are more likely to use local or combined technologies. While these studies suggest that emerging countries can play a role meeting the research needs of developing country markets for environmental technologies, further research on the potential of emerging economies to close the technology distance gap cited by Verdonlini and Galeotti, would be beneficial. What incentives need to be in place to encourage transfer of needed technologies among developing countries? Similarly, as adaptation to climate change becomes a concern, what lessons can tropical and semi-arid countries provide for warming industrialized nations.[20]

[20] I thank Stephane Hallegatte for this insight.

2. Are the lessons from India and China generalizable?

Much of the literature focuses on successful examples from China and India. Broader comparative studies, particularly of a quantitative nature, could provide additional insights. For instance, Lewis notes the very different strategies used by India and China. Additional work to better understand which strategies are likely to be most successful are needed. Moreover, understanding where these strategies work is important. China offers multinational investors the opportunity to access a market of one billion people. Thus, firms may be willing to accept restrictions on technology transfer to enter the Chinese market that they would not accept to enter smaller markets. Smaller countries may face additional hurdles when attracting technology transfer. Should such countries focus their attention elsewhere? Could a group of smaller countries form partnerships to increase their bargaining power with multinational firms? Moreover, the earlier concerns about technological distance suggest that further study should address whether policy needs may be different for countries at different stages of development. Whereas countries such as India and China may have the absorptive capacity to benefit from the spillovers provided via technology transfer, countries with a greater technological distance may find using technology transfer and adaptive R&D less valuable, either because they lack the skills necessary to adapt the technology or because even an adapted technology wouldn't be appropriate for their market. More comparative studies would thus be of great value to policy makers interested in promoting green technology transfer.

B. Diffusion within Countries

The above studies focus on the flow of knowledge across countries. Also important is the flow of knowledge within countries. The diffusion of a new technology is a gradual, dynamic process. New technologies are not adopted en masse. Rather, adoption usually begins with a few early adopters, followed by a more rapid period of adoption, with the rate of adoption leveling off once most potential users have adopted the technology. This process generates the well-known S-shaped diffusion curve: the rate of adoption rises slowly at first, speeds up, and then levels off as market saturation approaches.

The role of information is important for diffusion in both developed and developing country settings. In one recent developing country example, Rebane and Barham (2011) survey households in Nicaragua about their knowledge and adoption of solar home systems for electricity. These systems are at an early stage of market penetration and are rarely seen in some poorer areas of the country. Rebane and Barham estimate a biprobit model where they first estimate determinants of knowledge about solar home systems and then estimate determinants of adoption of such systems. Not surprisingly, awareness of the technology is important for adoption. Among non-adopters, half were unaware of solar home systems. Of those aware of the systems, most learned about them from a family, friend, or neighbor. The importance of learning from others exemplifies how adoption provides a positive externality to others by increasing awareness of the technology. Rebane and Barham suggest that demonstration projects (e.g. on public buildings) or subsidies for early adopters can thus help spread technology within a market. Moreover, early adopters may also benefit future users by reducing uncertainty about the quality of new technologies.

Recent work also suggests that important differences can be found between adoption rates in developed and developing countries. World Bank (2008b) notes that in industrialized countries, once technologies reach the country, they almost always achieve mass-market scale. In contrast, there is more disparity in developing countries. Of 67 technologies studied by World

Bank (2008b) that reached 5% penetration in developing countries, only 6 reached a 50% market share. Similarly, Winkler *et al*. (2011) note that simply providing access to grid electricity is not sufficient to ensure its use in low-income countries. Affordability is an important constraint. Even after on-grid infrastructure is in place, poor households may be unable to afford appliances that use electricity. Thus, income disparities within countries will lead to uneven diffusion of new technologies.

Two studies by Allan Blackman illustrate differences in adoption of green technologies between developing and developed countries. Blackman and Kildegaard (2003) study the adoption of three clean leather tanning technologies in Mexico. They use original survey data on a cluster of small- and medium-scale leather tanneries in León, Guanajuato, noting that small and medium scale enterprises often dominate pollution intensive industries in developing countries. To explain the adoption of each tanning technique, they estimate a system of multivariate probit models. They find that a firm's human capital and stock of technical information influence adoption. They also find that private-sector trade associations and input suppliers are important sources of technical information about clean technologies. In contrast to results typically found in developed countries, neither firm size nor regulatory pressure is correlated with adoption. In addition to economic incentives, direct regulation, and information provision, some research has emphasized the role that "informal regulation" or community pressure can play in encouraging the adoption of environmentally clean technologies. For example, in an analysis of fuel adoption decisions for traditional brick kilns in Mexico, Blackman and Bannister (1998) suggest that community pressure applied by competing firms and local non-governmental organizations was associated with increased adoption of cleaner fuels, even when those fuels had relatively high variable costs.

Dasgupta *et al*. (2010) study the benefits from integrated pest management (IPM) for Bangladesh farmers. IPM uses natural parasites and predators, rather than chemical pesticides to control agricultural pests. As chemicals are expensive, IPM can potentially increase profits as well as benefit the environment. Dasgupta *et al*. present survey data showing that IPM rice farming is as productive as traditional farming and has lower costs. However, because a neighbor's use of traditional chemical pesticides can kill natural parasites and predators needed for IPM, individual adoption is not rational. Thus, institutional support for collective adoption is needed.

Several recent case studies note the importance of maintenance and access to finance for successful technology adoption in developing countries. Barry *et al*. (2011) study the adoption of efficient stoves, small biogas plants, and efficient tobacco barns for commercial farmers in Rwanda, Tanzania and Malawi. They conclude that maintenance must be planned for (including funding) at the outset of the project, and must be kept simple, so that it does not require much additional training. If not, users will abandon a technology as soon as something goes wrong. Because information is spread by word of mouth, having a local champion for a technology is also important. Because of high start-up costs, financing was cited as the main stumbling block for all projects. Thus, providing aid for financing is also important. Reviewing the success of China's Renewable Energy Development Project, D'Agostino *et al*. (2011) also cite access to financial credit and quality of after-sales service as important barriers to the adoption of solar home systems in China. Finally, Romijn and Caniëls (2011) find that inadequate on-site technical support holds back adoption of small-scale biomass gasification in India.

Exploring the role of financing further, Brunnschweiler (2010) explores the importance of financial sector development in the adoption of renewable energy. Investment in renewable capacity often requires long-term loans. In low-income countries, access to such credit is limited, particularly for small and medium sized companies. Brunnschweiler finds that a one-standard deviation increase in her measure of financial intermediation leads to a 0.3 standard deviation increase in non-hydro renewable energy generation per capita. As such, improving the financial infrastructure of a nation may not only lead to macroeconomic benefits, but also encourage green growth by providing easier funding for green infrastructure.

i. Knowledge gaps on within country diffusion of environmental technology

Many of the questions needing to be addressed regarding within country diffusion of environmental technologies are issues for both developing and developed countries. Even in high income countries, what drives adoption of green technologies is not completely understood.[21] One example is the finding that seemingly cost-effective energy-efficient technologies diffuse slowly, suggesting what has become to be known as an "energy efficiency paradox." Much of the discussion on the energy paradox focuses on whether or not there are market failures that slow adoption or whether people are making seemingly irrational decisions. Incorporating methodology from behavioral economics would contribute to our understanding of why adoption of energy efficiency technologies is slow, and would better inform policy makers' attempts to increase adoption of energy efficient technologies. Given the importance of information for diffusion, such studies could also provide guidance as to what ways information can be provided to best encourage diffusion of green technologies.

Turning specifically to developing countries, the importance of financing suggests that more research is needed to design mechanisms for financing green technology investments. This

[21] Popp, Newell, and Jaffe (2010) provide a detailed review of the literature on diffusion of environmental technologies in developed countries.

is particularly important for efficiency-enhancing technologies. Such technologies require up-front investments, but can provide cost savings that allow the investment to pay for itself over the life of the technology. However, since investors cannot typically borrow on the promise of future cost savings, other forms of financing need to be available to facilitate these investments.

V. The Role of Policy

Public policy plays an important role encouraging both the development and diffusion of green technologies. Market forces provide insufficient incentives for investment in either the development or diffusion of environmentally-friendly technologies. Economists point to two market failures as the explanations for underinvestment in environmental R&D. These market failures provide the motivation for government policy designed to increase such research. In addition, other market failures, such as imperfect credit markets or incomplete information, may slow the diffusion of technology.

One market failure affecting environmental innovation is the traditional problem of environmental externalities. Because pollution is not priced by the market, firms and consumers have no incentive to reduce emissions without policy intervention. Thus, without appropriate policy interventions, the market for technologies that reduce emissions will be limited, reducing incentives to develop such technologies. Similarly, once green technologies are available, diffusion will be slow if market incentives do not properly reflect the environmental benefits offered by such technologies. It is true that there will likely be some incentives to develop clean technologies even without policy interventions, as private benefits may exist. For example, improving energy efficiency in industrial processes not only reduces emissions, but also lowers the costs of production. The market failure problem simply means that individuals do not consider the social benefits of using technologies that reduce emissions, so that not all socially beneficial opportunities for technological change are pursued.

The second market failure pertaining to technological change is the public goods nature of knowledge (see, for example, Geroski 1995). In most cases, new technologies must be made available to the public for the inventor to reap the rewards of invention. However, by making new inventions available, some (if not all) of the knowledge embodied in the invention becomes public knowledge. This public knowledge may lead to additional innovations, or even to copies of the current innovations.[22] As noted earlier, such knowledge spillovers provide benefit to the public as a whole, but not to the innovator. As a result, private firms do not have incentives to provide the socially optimal level of research activity. Because inventors cannot be fully compensated for knowledge spillovers, environmentally friendly R&D will be underprovided by market forces even if environmental policies to correct the environmental externalities of pollution are in place. Similarly, when transferring technologies, multinational firms will attempt to do so in ways that minimize the spillovers that may occur.

As with R&D investments, market failures may affect the diffusion of technology. Externalities are still a concern. For instance, without appropriate accounting for the external benefits from reducing pollution, individual decisions to adopt environmental technologies will be sub-optimal. Thus, environmental regulation is needed to encourage adoption of end-of-pipe solutions to pollution (e.g. Kemp 1998, Kerr and Newell 2003, Snyder *et al*. 2003, and Popp 2010). For efficiency-enhancing investments, such as energy efficiency improvements, there are private incentives to adopt, but even then, adopters will undervalue the social benefits, such as reduced pollution, that come from improving efficiency.

[22] Intellectual property rights, such as patents, are designed to protect inventors from such copies. However, their effectiveness varies depending on the ease in which inventors may "invent around" the patent by making minor modifications to an invention. See, for example, Levin *et al*. (1987).

Uncertainty is another factor that may limit the adoption of new technology (Geroski 2000). Potential adopters may be uncertain both about the quality of a technology and about future market conditions. For example, investing in energy saving technology is less valuable if energy prices fall in the future. As suggested in the previous section, facilitating the provision of information can help to alleviate some concerns about uncertainty.

Because of these market failures, both technology policy and environmental policy will play a role promoting technology transfer of green technologies. Technology policy helps to reward innovators for the public benefits that result from knowledge spillovers. Environmental policy makes polluters accountable for the damages they cause, thus increasing demand for green technologies. This section discusses the role of each of these policy options and suggests questions for future research.

A. Technology Policy

Policy plays a role throughout the innovation process. R&D subsidies and tax credits help promote the development of new technologies. Intellectual property rights protection helps to reward inventors by providing temporary monopoly protection for their invention. However, for developing countries, the goal of technology policy will typically be to attract technology transfer or to encourage adaptive R&D on existing technologies, rather than to promote the development of new technologies. As noted in our literature review, knowledge spillovers from international technology transfer are important for recipient countries. However, these same spillovers may discourage innovators who wish to avoid developing competitors for their own products. For technology transfer, policy must manage a careful balancing act, so as promote knowledge spillovers from technology transfer to the extent possible without discouraging investors from coming into the country at all. Indeed, the literature on technology transfer suggests that a one-size fits all policy is not desirable. As a country's own innovative capacity grows, so should the strength of its intellectual property protection (e.g. Masksu 2002).

Developing country policies can help to promote spillovers. First, policies that improve the absorptive capacity of a country increase the potential of benefiting from knowledge spillovers. Using patent applications as a measure of technology transfer, Hascic and Johnstone (2011) find that absorptive capacity increases wind energy patent applications filed in developing countries by developed country inventors. Indeed, in their study, absorptive capacity proves to be more important than traditional technology transfer policies such as CDM.[23]

By providing access to technology, trade policy can also help to promote spillovers from technology transfer. World Bank (2008a) includes a study of the effect of tariff and non-tariff trade barriers on trade flows of four clean energy technologies: clean coal, wind energy, solar photovoltaic systems, and energy-efficient lighting. Examining imports to the top 18 developing countries ranked by greenhouse gas emissions, they find that eliminating tariff and non-tariff barriers would increase trade volumes by 4.6 percent for clean coal to 63.6 percent for energy-efficient lighting.

Enhancing absorptive capacity or improving access to trade promote spillovers in a way that offer little cost to innovators deciding whether or not to transfer a technology. In contrast, efforts to require technology transfer require a careful balancing act, so as to not discourage multinationals from choosing to participate at all. Wang (2010) illustrates this balancing act in a study on China's policy towards CDM projects. While the Chinese government often acts as a broker to bring parties together when technology transfer is desired, its policies often hamper technology transfer from CDM. Most importantly, China has local content requirements. For

[23] World Bank (2008b) provides a more general discussion of the role of absorptive capacity in technology transfer.

example, by 2004, new wind farms had to have 70% local content. Moreover, regulations on CDM project ownership restrict potential of technology transfer through CDM. Only Chinese companies or Chinese holding companies (requires at least 51% Chinese ownership) are eligible for CDM projects in China. While such restrictions encourage the development of local industry, they limit the ability of local industry to benefit from spillovers from technology transfer partnerships. Certified Emission Reductions (CERs) are viewed as a national asset from which private foreign companies should not profit. Thus, while foreign companies may end up as buyers of CERs, they have limited incentives to finance CDM projects, since they cannot profit from the sale of emission credits. This limits the success of projects where the only benefits are emissions reductions (e.g. reducing landfill gases), as these projects are more likely to need foreign financial support to be viable.

Intellectual property rights provide another example of balancing the need to promote innovation with the need to promote beneficial spillovers. There is rising interest in broader sharing of intellectual property pertaining to environmental technologies. In 2008, the World Business Council for Sustainable Development (WBCSD) created the Eco-Patent Commons to allow free access to patents with environmental benefits. In a 2009 interview, Steven Chu, the U.S. Secretary of Energy, encouraged the sharing of intellectual property, stating that "any area like that (energy efficient buildings), I think, is where we should work very hard in a very collaborative way — by very collaborative I mean share all intellectual property as much as possible."[24]

Intellectual property rights (IPR) provide a tradeoff to both inventors and to society as a whole. The goal of IPR is to reward inventors for the fixed costs of innovation. For

[24] http://dotearth.blogs.nytimes.com/2009/03/26/energy-chief-seeks-global-flow-of-ideas/#more-1775, accessed July 2, 2009.

environmental technologies, patents are the relevant form of IPR. Successful patent applicants are provided a temporary monopoly, lasting twenty years from the initial application date, in return for disclosing information on the innovation in the patent document, which is part of the public record. By granting this market power, IPR helps to mitigate potential losses from knowledge spillovers and encourage innovation. Thus, while it is certainly true that, *conditional on an innovation having taken place*, one would expect technology transfer to be slower when IPR is in place. However, one cannot assume that the level of innovation would be the same if IPR were not available.

While there is still room for more research on the question of IPR and eco-innovation, the role of demand for clean technologies cannot be overstated, and is consistent with results found elsewhere. In an oft-cited study on the role of intellectual property on pharmaceuticals, Attaran and Gillespie-White (2001) ask whether patents constrain access to AIDS treatments in Africa. They find that, even in African countries where patent protection is possible, few AIDS drugs are patented as the markets for such drugs are too small to be of interest to multinational pharmaceutical companies. Rather than patents, they conclude that a lack of income, national regulatory requirements, and insufficient international aid are the main barriers to the spread of AIDS treatments in Africa. Similarly, with green technologies, one would expect demand (or the lack thereof) for clean technologies to be a primary constraint on international technology transfer. The spread of environmental regulation across developing countries is an important pre-condition to the diffusion of eco-innovations. Calls to weaken IPR for eco-innovations will have little impact unless they are packaged in international agreements leading to stronger environmental regulation within the developing world.

B. Environmental Policy

Without environmental policy, polluters do not have incentives to adopt costly technologies that reduce emissions but provide no additional cost savings to the polluter. In fact, in some cases, reducing emissions requires polluters to take costly actions that provide no direct benefits to the polluter itself. For instance, since regulations limiting particulate matter were enacted several years before regulations covering sulfur dioxide (SO_2) and nitrogen oxides (NO_X), most power plants in China have controls for particulate matter, while only the newest plants control NO_X and SO_2 (Lovely and Popp 2011). Similarly, in a study of joint ventures between US and Chinese automobile firms, Gallagher (2006) finds that the emission control technologies transferred to China are not advanced, and, in most cases, the emissions control technologies used on autos in China would not meet standards in developed countries. She notes that "(t)he main reason cleaner and more energy-efficient technologies were not transferred is that there simply were no compelling policy incentives for the US firms to do so, and the foreign firms did not voluntarily transfer better technologies" (Gallagher, 2006, p. 387).

This is important not only for diffusion, but also for innovation, as inventors will not develop technologies for which there is little demand. There is a broad literature, reviewed in Popp *et al*. (2010), linking environmental policy to innovation in the developed world. Because high income countries are typically the first to enact strict environmental regulations, they also take the lead in developing green technologies. Thus, when focusing on links between environmental policy and technological change in developing countries, much of the focus is on the links between policy and diffusion of technology.

Using the Clean Development Mechanism as a policy example, two papers take a qualitative approach to evaluate the potential of CDM for enhancing technology transfer. For example, Schneider *et al*. (2008) suggest four barriers to transfer of environmentally sustainable technology: (1) lack of commercial availability, (2) lack of information, (3), lack of access to capital, and (4) lack of institutional framework (e.g. rule of law, IPR). Using existing empirical studies and expert interviews, they conclude that CDM addresses the first two barriers by creating a market for clean technologies in developing countries and by encouraging sharing of knowledge, such as through the project design process. However, improved access to capital varies depending on how a CDM project is financed. Many unilateral projects must find funds to start a project, with the hope of recouping these costs once CERs are sold. Finally, CDM does nothing to change institutional settings within host countries.

Doukas *et al*. (2009) provide an exploratory analysis of the current developed country status and developing country prospects for five renewable energy technologies: hydropower, wind, solar, geothermal, and ocean energy. Regarding solar energy, they find that it is only economically competitive where grid connection or fuel transport is difficult, costly or impossible, such as remote rural locations. Echoing Schneider *et al*.'s (2008) emphasis on institutional framework, they find that "the nonexistence of the required regulatory framework in most of the developing countries and the very high capital costs usually strangles the interest for (solar energy) projects in developing countries."

Not only do environmental regulations encourage both innovation and adoption of environmental technologies, but the availability of technology itself may help shape regulation. This is important, because since most pollution control technologies are first developed in industrialized countries, and because environmental regulations are needed to provide incentives to adopt these technologies, the decision to enact environmental regulation in developing countries is a key first step in the diffusion of environmental technologies. While the adoption of pollution control technologies within a country responds quickly to environmental regulation, the initial adoption of environmental regulations across countries follows the typical S-shaped pattern noted in studies of technology diffusion, in which a few early adopters, typically technology leaders, are followed by a period of more rapid adoption. A period of slower adoption by the remaining stragglers follows (Lovely and Popp 2011, Jänicke and Jacob 2004).

As a result of these diffusion patterns, over time, countries adopt environmental regulation at lower levels of per capita income. Lovely and Popp (2011) study the adoption of regulations limiting emissions of SO_2 and NO_X at coal-fired power plants in 39 developed and developing countries. They identify access to technology as an important factor influencing the adoption of regulations and find that as pollution control technologies improve, the costs of abatement, and thus the costs of adopting environmental regulation, fall. This enables countries that adopt environmental regulations at later dates to adopt them at lower levels of per capita income than early adopters who enacted similar regulations first. Lovely and Popp suggest that this trend shows that the availability of technologies (produced by those countries that chose to adopt SO_2 regulations first) lowered adoption costs to the point where more countries were able to afford to reduce SO_2 emissions. Moreover, they find that countries that are more open to international trade gain access to new abatement technologies sooner, and thus are able to regulate SO_2 emissions sooner.

C. Knowledge Gaps on the Role of Policy for Green Growth

1. What balance of policies is needed?

Both technology and environmental policies play a role promoting green technologies. Environmental policies create demand for green technologies. However, without technology policy in place, insufficient incentives exist for creating and diffusing new technologies. While there is a large literature demonstrating the need for both policies in developed country settings (see Popp, 2010 for a review), the appropriate balance of environmental and technology policies within developing countries has not received similar attention. However, within developing countries, the focus will be on technology transfer and adaptive R&D, rather than on the creation of new green technologies. Thus, the relative importance of environmental and technology policies may differ in a developing country setting. Moreover, even within developed countries, there is still debate whether it is sufficient to use broad technology policies that correct market failures for all innovations, or whether targeted policies, such as product-specific R&D subsidies or tax credits, are needed.

The appropriate role for intellectual property rights for green innovations provides one example where additional research is needed. While IPR will encourage innovation, it also slows diffusion once innovations exist. For developing countries whose interests are diffusion, rather than the creation, of technology, weaker patent rights may appear to be a panacea. However, empirical evidence to support recent calls for weaker IPR for green technologies is lacking. To date, there has been little work directly studying the effect of intellectual property rights on technology transfer of eco-innovations. A Copenhagen Economics (2009) study on climate change concludes that IPR are not a barrier to the transfer of carbon emission-reducing technologies, and that the high costs of these technologies are due more to the immaturity of the technologies, rather than IPR. Hall and Helmers (2010) provide an extensive review of the literature on patent protection. While they find evidence that stronger IPR encourages innovation in general, this effect is strongest in chemical-related sectors such as pharmaceuticals. Regarding technology transfer, they cite the work by Copenhagen Economics (2009), as well as by Barton (2007), that suggests developing country policies such as tariffs on renewable energy technology and subsidies for fossil fuels do more to limit technology transfer of clean technologies than do IPR. IPR does seem to encourage technology transfer to middle income countries with the appropriate absorptive capacity. They caution that Copenhagen Economics' finding of few climate-related patents in developing countries need not imply that IPR are not a barrier to technology transfer. Rather, it may simply mean that those countries are not yet viewed as favorable markets for climate-related technologies. Moreover, they note that because climate protection is a global public good, wide diffusion of climate-friendly innovations is desirable. Thus, they conclude that additional research is needed to assess the specific implications of IPR for green technologies.

2. What is the role of secondary benefits from green innovation? To what extent can these promote green growth without policy intervention?

Environmental policy encourages the development and deployment of green technologies by making consumers and producers consider the external effects of their actions. However, some green technologies provide benefits that are not externalities. For example, while technologies that increase energy efficiency reduce pollution, thus benefiting the public as a whole, they also provide cost savings to the user. Quantifying and understanding the value of these secondary benefits is important to understanding the extent to which green technologies can be established without the aid of environmental policy. Moreover, clean technologies that provide secondary benefits for the local economy provide an additional boost for green growth.

Such secondary benefits will be particularly important for efforts to foster the adoption of technologies that reduce global pollutants. A willingness to "leapfrog" over dirty technologies to a clean energy system depends not only on the availability of technology, but also on the political will to enact policies supporting more costly forms of energy (Perkins, 2003). For many lower-income countries, such support seems unlikely and undesirable. Documenting potential for both local benefits along with global emissions reductions can help win support for such efforts. For instance, electrification reduces the need to burn wood or waste for heating or cooking, reducing indoor air pollution. It also increases opportunities for economic development (Sathaye *et al*. 2007). Improved cooking stoves could reduce indoor air pollution by as much as 95% (Smith *et al*. 2000, cited in Sathaye *et al*. 2007). Improved energy efficiency brings local economic benefits through lower costs (Sathaye *et al*. 2007). Photovoltaic cells are more costly than traditional electricity sources, but of great value to remote developing regions that are not connected to the electric grid. While the costs of PV energy are typically higher than other forms of electricity, solar PV can be economically competitive where grid connection or fuel transport is difficult, costly or impossible, such as remote rural locations (Doukas *et al*. 2009). As the primary focus of the environmental innovation literature has been on pollution control, these secondary benefits have received less attention. However, they will be important for encouraging expansion of green growth technologies to low-income markets and are deserving of more research.

The links between resource usage and technological change provide another example of secondary benefits worth further study. The focus of the papers cited here, and of much of the research in environmental economics, is on pollution control. However, concerns about access to energy and promoting secure and stable energy supplies often take priority among policymakers. Whether the goal of promoting energy security complements or competes with the goal of providing clean energy depends on the resources available to a country. Lovely and

Popp (2011) find that countries producing larger amounts of coal per capita are less likely to adopt regulations on sulfur dioxide and nitrogen oxide emissions at coal-fired power plants. Cragg and Kahn (2009) show that members of the U.S. Congress representing districts with greater carbon emissions are less likely to support legislation reducing emissions. Relating such findings to innovation, Kim (2011) examines the effect of fossil fuel endowment on the patterns of technology innovation in automobile sector. She finds that countries with larger fossil fuel endowments are less likely to develop alternative fueled vehicle technologies such as electric vehicles or fuel cells. As emerging economies such as China and India increase energy consumption while they grow, more focus on the links between resource endowments and incentives for technological change in such economies is needed. Policies to promote green growth are likely to be most successful when they complement the resource endowments of a country.

A focus on pollution control also ignores the important role of coping with a changing environment. For developing countries, innovation will be particularly important when considering adaptation to climate change. Whereas mitigation of greenhouse gases is a global public good, the benefits of adaptation are local public goods. In some cases, these local public goods may be provided publicly, such as flood control or irrigation projects. In other cases, private actors will undertake adaptive behavior (such as farmers switching to drought-resistant crops). However, while investments in adaptive infrastructure may only have local benefits, knowledge developed research and development that improves adaptive technologies will also have the spillover benefits that result from knowledge being a public good. Given that the types of technologies needed to adapt to climate change are likely to vary depending on local conditions, this suggests a role for developing countries and/or international aid to support R&D designed to improve adaptation options for developing countries.

3. How does governance affect green growth?

Since environmental policy is necessary to create a market for clean technologies, issues of governance are also important. In a developed country framework, recent work by Gennaioli and Tavoni (2011) suggests that rent seeking and corruption may be an issue for clean technologies. Using a difference-in-difference regression strategy across Italian provinces, Gennaioli and Tavoni find evidence of greater criminal activity in provinces with high wind energy potential after the passage of policies favorable to the wind energy sector. They also find evidence that greater corruption leads to faster expansion of wind energy. They conclude that when socio-political institutions are weaker, market-based policies to promote clean technologies may lead to adverse outcomes. While these results are still preliminary and have not been validated in other settings, they raise an important warning signal for countries where institutions may be weak, and suggest that policy options to promote clean technologies must be tailored to fit the broader political context of each country. Extending this work to explore links between governance and environmental policy effectiveness in a developing country setting would be of great value.

VI. Conclusions

This literature review on environmental technological change suggests several lessons for promoting green growth in developing countries. I highlight five of the most important here. First, the fact that high-income countries dominate R&D activities, both for green technologies and more generally, suggests that technology transfer is important. In many cases, the technologies needed to promote green growth will already be available. Second, even when technologies are available, adaptive R&D can improve the fit of new technologies to local market conditions. For example, production processes can be adapted to take advantage of cost savings in local markets. Third, technology transfer will be most likely to promote green growth when it promotes knowledge spillovers. Fourth, financial constraints and ease of use play important roles determining diffusion of green technologies within developing countries. Fifth, policy incentives are important for creating markets for green technologies, as market forces typically do not reward pollution prevention completely.

While not exclusive, much of the focus in the paper is on energy use and climate change. This is consistent with general trends in the literature, given recent interest in the climate problem. Developing countries now play a key role in post-Kyoto negotiations. At the same time, secondary benefits from energy policies (e.g. lower costs from improved energy efficiency, reduced local air pollution) are important for low-income countries. While not emphasized here, other technologies will also be important for low-income countries, particularly pertaining to resource use (such as water) and agricultural productivity. Future work should also explore the differences that emerge among various technological fields.

For instance, advances in agriculture, such as drought resistant crops and more efficient irrigation, are of particular importance to developing countries. In health care, neglected tropical diseases are a prominent issue.[25] These diseases, primarily of an infectious or parasitic nature, occur almost exclusively in developing countries, so that for-profit pharmaceutical companies have had little incentive to invest in new medicines to combat these diseases (Ridley *et al*. 2006). Thus, the same problems of creating demand for innovations needed in developing countries that green technologies face occurs in other fields as well, such as agricultural economics and health

[25] See, for example, http://www.who.int/neglected_diseases/en/, accessed March 17, 2011.

economics.[26] Advance purchase commitments for medicines (Barder *et al*. 2006) provide an example of how researchers in the health care community propose creating demand for innovation on medicines for neglected diseases. Moving forward, environmental economists can learn from existing work in these fields to gain new insights on creating demand for green technology. At the same time, the additional market failure of environmental externalities suggests that simply applying the lessons from other sectors will not be sufficient.

Finally, a focus on pollution control also ignores the important role of coping with a changing environment. For developing countries, innovation will be particularly important when considering adaptation to climate change. Whereas mitigation of greenhouse gases is a global public good, the benefits of adaptation are local public goods. In some cases, these local public goods may be provided publicly, such as flood control or irrigation projects. In other cases, private actors will undertake adaptive behavior (such as farmers switching to drought-resistant crops). However, while investments in adaptive infrastructure may only have local benefits, knowledge developed research and development that improves adaptive technologies will also have the spillover benefits that result from knowledge being a public good. Given that the types of technologies needed to adapt to climate change are likely to vary depending on local conditions, this suggests a role for developing countries and/or international aid to support R&D designed to improve adaptation options for developing countries. A focus on green growth should not only include research designed to improve environmental quality, but also on coping with environmental changes that will inevitably come.

[26] For an example pertaining to pharmaceutical markets in developing countries, see Kremer (2002).

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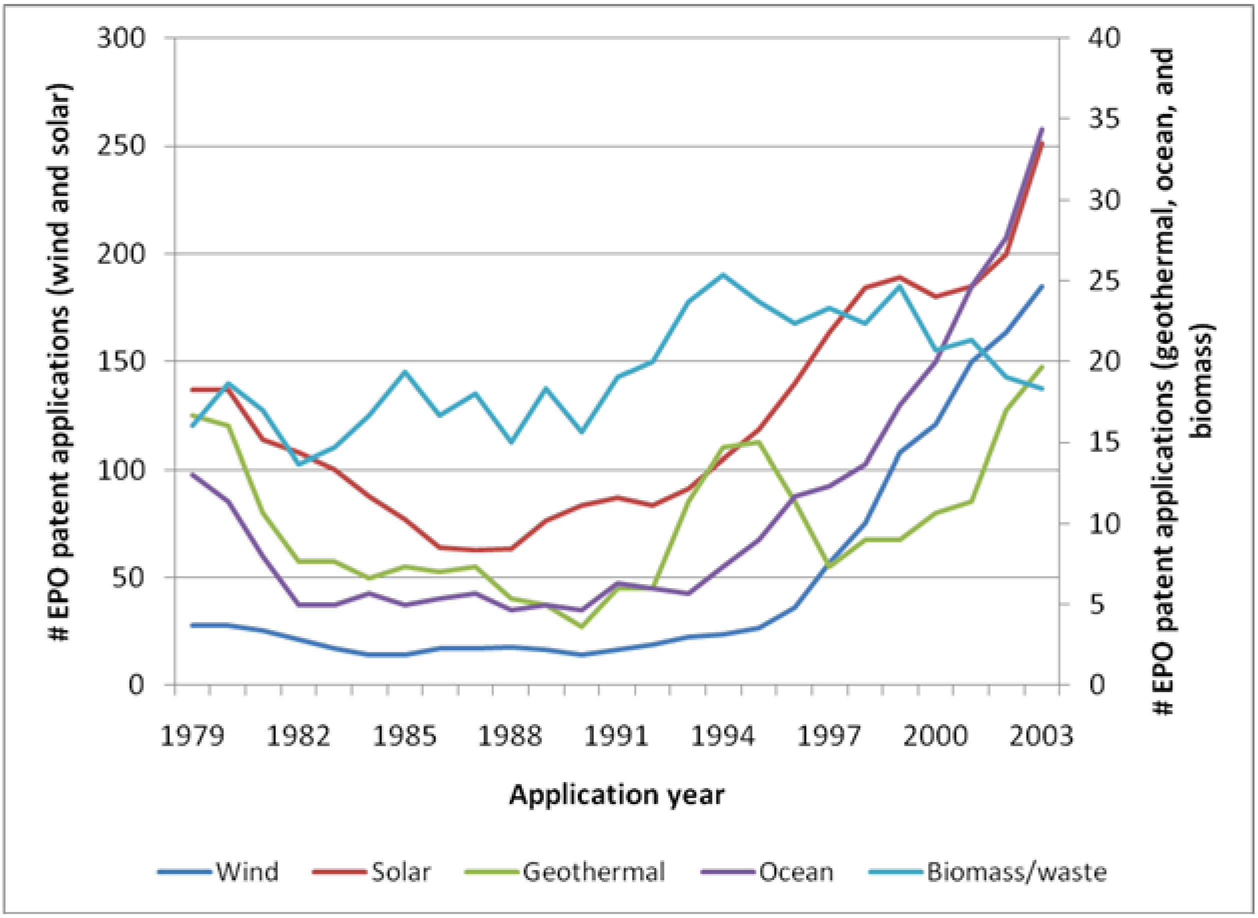
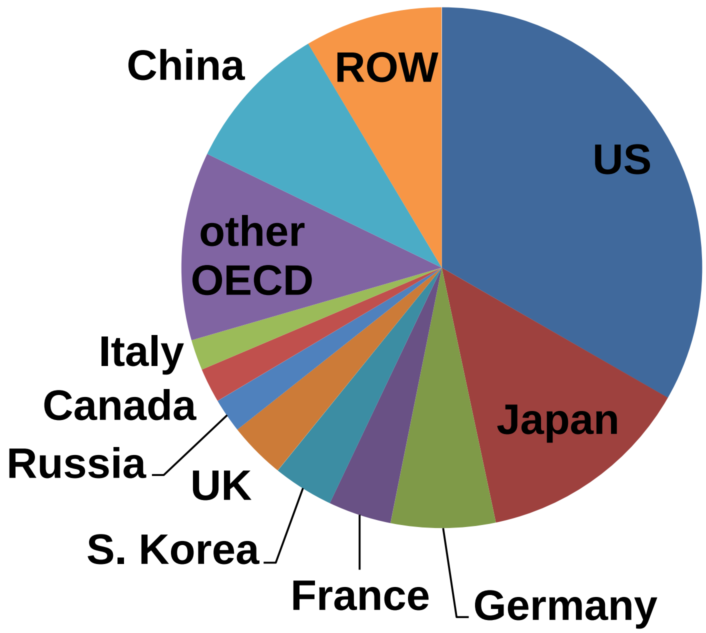
Figure 1. Number of EPO Patent Applications for Renewables by Type of Technology



Source: Based on data from Johnstone *et al*. (2010)

The number of European Patent Office (EPO) applications for patents pertaining to various renewable energy technologies, sorted by the year of application. Patent counts for wind and solar technologies are on the left vertical axis, with counts for the remaining technologies on the right vertical axis.

Figure 2. Share of Global R&D by Country, 2007



Source: Author's calculations using data from National Science Board (2010)

Table 1. Public R&D Spending in International Energy Agency Countries, selected years and topics

Energy Efficiency	**1990**	**1995**	**2000**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
IEA Total	738	1345	1566	1486	1592	1901	2150	3958	3174
IEA Americas	326	746	722	595	522	642	747	2260	1477
IEA Europe	374	324	257	373	502	675	843	1217	1237
IEA Asia Oceania	38	275	587	518	568	584	560	481	460
Fossil Fuels									
IEA Total	2228	1105	663	1249	1356	1474	1562	4636	1838
IEA Americas	1500	483	317	545	567	617	731	3614	830
IEA Europe	321	190	135	320	362	402	371	399	473
IEA Asia Oceania	407	432	211	384	427	455	460	623	535
Renewable Energy									
IEA Total	758	877	826	1159	1253	1688	1664	3775	3119
IEA Americas	182	388	293	320	289	641	533	2351	1456
IEA Europe	440	364	356	525	597	727	794	1067	1188
IEA Asia Oceania	136	125	177	314	367	320	337	357	475
Total Energy R&D Budgets									
IEA Total	11280	9885	9405	11298	11666	12804	13195	19528	14747
IEA Americas	4289	3631	3105	4109	3913	4751	5032	10761	5744
IEA Europe	3783	2547	2524	2918	3307	3588	3813	4452	4736
IEA Asia Oceania	3208	3707	3776	4271	4446	4465	4350	4315	4267

All data are in millions of 2010 US dollars, using PPP

Table 2. Patent and Publication Counts for Indoor Cooking Stoves

	China	India	South Africa	Japan	US	Germany	France	UK	Korea	Total
Patents:										
solar stoves	483	0	0	69	56	8	12	8	2	665
biomass stoves	273	2	0	5	16	3	0	0	0	307
LPG stoves	304	1	0	10	8	0	0	1	5	358
kerosene or butane stoves	143	0	1	112	21	2	4	2	18	313
Publications:										
solar stoves	7	86	12	6	17	9	4	7	0	215
biomass stoves	40	61	3	7	101	8	7	17	4	319
LPG stoves	1	26	2	2	18	2	0	2	2	68
kerosene or butane stoves	3	50	2	3	41	4	0	4	1	132

Source: Author's calculations. Both data sets includes patents and publications through 2010. Patent counts start as early as 1963, although data availability for some countries, such as China, begins later. Publication counts begin in 1990.

Appendix A – Indoor Cooking Stove Search Terms

Patent searches

kerosene or butane stoves
((A47J 027<or>A47J 027??<or>A47J 027???<or>A47J 027????<or>A47J 037<or>A47J 037??<or>A47J 037???<or>A47J 037????<or>F24B*<or>F24C*) <in> IC) <AND> ((kerosene<OR> butane) <in> AB))

liquefied petroleum gas stoves
(((A47J 027<or>A47J 027??<or>A47J 027???<or>A47J 027????<or>A47J 037<or>A47J 037??<or>A47J 037???<or>A47J 037????<or>F24B*<or>F24C*) <in> IC) <AND> (((LPG<OR>"liquefied petroleum gas") <in> AB))

biomass stoves
(((A47J 027<or>A47J 027??<or>A47J 027???<or>A47J 027????<or>A47J 037<or>A47J 037??<or>A47J 037???<or>A47J 037????<or>F24B*<or>F24C*) <in> IC) <AND> (biomass <in> AB))

solar stoves
((solar AND (cooker OR oven OR stove)) <in> AB)

Publication searches

solar stoves
TS=("solar cooker" OR "solar oven" OR "solar stove" OR "solar cookers" OR "solar ovens" OR "solar stoves" OR "solar cooking").[27]

biomass stoves
TS=(biomass SAME (stove OR stoves OR oven OR ovens OR cooker OR cooking))

LPG stoves
TS=((LPG OR ‘’liquefied petroleum gas’’) SAME (stove OR stoves OR oven OR ovens OR cooker OR cooking))

kerosene or butane stoves
TS=((kerosene OR butane) SAME (stove OR stoves OR oven OR ovens OR cooker OR cooking))

NOTES: AB = abstract, IC = International Patent Classification, TS = topic search (includes title, abstract, and keywords)

[27] “TS” represents a “topic search” that looks for the search terms in the title, abstract, or keywords of the article.