Policy Research Working Paper 5932

Green Growth, Technology and Innovation

Mark A. Dutz
Siddharth Sharma

The World Bank
Poverty Reduction and Economic Management Network
Economic Policy and Debt Department
January 2012

Policy Research Working Paper 5932

Abstract

The paper explores existing patterns of green innovation and presents an overview of green innovation policies for developing countries. The key findings from the empirical analysis are: (1) frontier green innovations are concentrated in high-income countries, few in developing countries but growing; (2) the most technologically-sophisticated developing countries are emerging as significant innovators but limited to a few technology fields; (3) there is very little South-South collaboration; (4) there is potential for expanding green production and trade; and (5) there has been little base-of-pyramid green innovation to meet the needs of poor consumers, and it is too early to draw conclusions about its scalability. To promote green innovation, technology and environmental policies work best in tandem, focusing on three complementary areas: (1) to promote frontier innovation, it is advisable to limit local technology-push support to countries with sufficient technological capabilities—but there is also a need to provide global technology-push support for base-of-pyramid and neglected technologies including through a pool of long-term, stable funds supported by demand-pull mechanisms such as prizes; (2) to promote catch-up innovation, it is essential both to facilitate technology access and to stimulate technology absorption by firms—with critical roles played by international trade and foreign direct investment, with firm demand spurred by public procurement, regulations and standards; and (3) to develop absorptive capacity, there is a need to strengthen skills and to improve the prevailing business environment for innovation—to foster increased experimentation, global learning, and talent attraction and retention. There is still considerable progress to be made in ranking green innovation policies as most appropriate for different developing country contexts—based on more impact evaluation studies of innovation policies targeted at green technologies.

This paper is a product of the Economic Policy and Debt Department, Poverty Reduction and Economic Management Network. It is part of a larger effort by the World Bank to provide open access to its research and make a contribution to development policy discussions around the world. Policy Research Working Papers are also posted on the Web at http://econ.worldbank.org. The author may be contacted at mdutz@worldbank.org.

GREEN GROWTH, TECHNOLOGY AND INNOVATION

Mark A. Dutz and Siddharth Sharma[1]

[1] PRMED, The World Bank. The paper benefited from helpful feedback from Natalia Agapitova, Paulo Correa, Marianne Fay, Stephane Hallegatte, Stefano Negri and Michael Toman. We gratefully acknowledge the valuable contributions from Yasin Kursat Onder on the USPTO data and from Ravi Gupta on innovation technology and policy case studies.

1 INTRODUCTION

More rapid green growth is inconceivable without innovation. Frontier innovations shift out production possibilities, allowing the production of more output and newer, more environmentally-friendly outputs with fewer or different inputs. Innovations thereby help to decouple growth from natural capital depletion and environmental pollution, for example towards more resource-efficient and cleaner technologies. Some innovations can directly increase resilience to environmental shocks. Catch-up innovations, that make the use of existing technologies more widespread by adapting them to local contexts, are even more important for all countries. They typically reduce production costs and increase enterprise competitiveness, and are lower risk than frontier innovations. The introduction of new products, processes, business models and other organizational methods, and marketing techniques, whether through frontier or catch-up innovation, in principle contribute to the expansion of existing markets and the creation of new markets, in the process increasing the job content and poverty alleviation of growth.

This paper examines existing patterns of green innovation, to what extent innovation policies should be designed differently to address the green growth agenda, and what policy modifications can best help yield short-run or at least medium-term impact. The paper discusses the implications of the inherent 'double externality' of knowledge-related market failures compounding the traditional environmental externalities. It motivates appropriate policy action in the absence of global agreements, answering the question of why developing countries should undertake green innovation policies, and what types of policies should be pursued depending on existing technological capabilities.

In contrast to most recent empirical analyses that use older patent data to 2005 or at most to 2008 to characterize international patterns of green frontier innovation (OECD 2011a, Dechezleprêtre et al. 2011, Aghion et al. 2011), this paper uses patent data to end-2010 and explores patterns across developing countries in greater detail. This matters since there have been significant increases in green patenting over the 2006-2010 period. The paper also examines different frontier innovation patterns by level of technological sophistication of countries, and by extent of cross-country collaboration. As a proxy for patterns of broader green catch-up innovation, we analyze data on trade in environmental products. And a deeper analysis of trade data allows us to explore the extent to which developing countries export products 'similar' to environmental products in terms of required inputs or technologies, as an indicator of their capability to start producing greener products. Finally, the paper also reports findings from an exhaustive survey of green Base-of-Pyramid (BoP) innovations to meet the needs of poor consumers.

In examining appropriate mixes of policies to foster green innovation, the paper combines insights from the latest relevant policy literature, available data on policy actions and firm-level responses, and selected case studies. These are organized around three complementary policy areas, namely to promote frontier innovation, to promote catch-up innovation, and to develop absorptive capacity. The paper makes the case for a portfolio of green innovation policies that include policy instruments to address the two complementary knowledge and environment-related market failures: both supply-side 'technology-push' elements that reduce costs of knowledge creation and adoption as well as demand-side 'market-pull' elements that increase net revenues from sales of greener products. While it is not premature to put a green twist on generic innovation policies, for instance that prizes are a preferred policy instrument over patents from a number of dimensions to promote the creation and diffusion of green as opposed to non-green technologies, there is clearly still considerable progress to be made in ranking green innovation policies as most appropriate for different developing country contexts. This requires more impact evaluation studies of innovation policies targeted at green technologies.

The next section explores recent data on existing patterns of green innovation. The third section then presents an overview of green innovation policies, discussing the policy rationale and the range of available instruments. A final section provides summary recommendations.

2 GREEN INNOVATIONS – GROWING FROM A SMALL BASE

Innovation in the context of development should be defined broadly as the commercialization of new ways to solve problems through improvements in technology, with a wide interpretation of technology as encompassing product, process, organizational, and marketing improvements. Besides frontier (new-to-the-world) innovations, this definition includes catch-up innovations, namely the diffusion (both across and within countries) and the adaptation to local context of existing green products, processes, organizational and marketing technologies.[2] Green technologies comprise a vast range of fundamentally different technologies that support wealth creation and achieve more resource-efficient, clean and resilient growth:

- Regarding pollution reduction and greater resource efficiency, technologies include improved recycling and energy efficiency in buildings (thermal insulation and new materials, heating, energy-efficient lighting), production processes (new uses of waste and other by-products from firms into production inputs at the same or other firms), agriculture (from GM crops to mechanical irrigation and farming techniques), transport infrastructure, and urban design (including land use).
- Regarding climate change mitigation, technologies include cleaner energy supply (wind, solar, geothermal, marine energy, biomass, hydropower, waste-to-energy, and hydrogen fuels), end-use (electric and hybrid vehicles, climate-friendly cement), and carbon capture and storage (CCS).
- Regarding adaptation, they include more climate-resistant products and processes appropriate for changing environments (such as higher yield seeds for more arid and saline soils together with drought-resistant cultivation practices) and tools to understand and insure against climate risks with improved early-warning system processes (sea-walls, drainage capacity, reductions in environmental burden of disease, and water, forest and biodiversity management).
- They also directly support wealth creation through more sustainable production of plants and livestock, more productive use of biodiversity (natural cosmetics, pharmaceutical products, eco-tourism), and ecosystem protection.

2.1 Frontier innovations concentrated in high-income countries, few in developing countries but growing

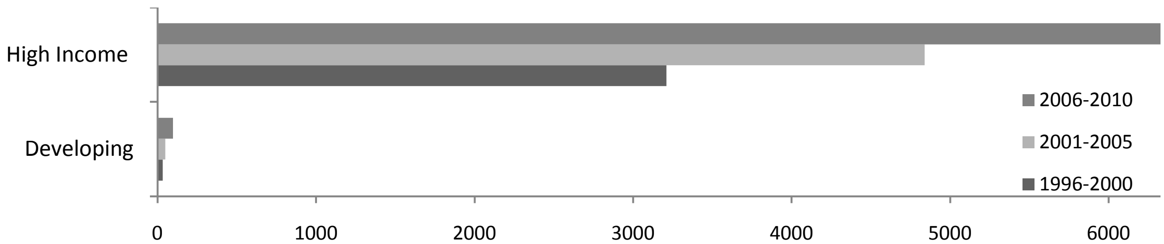
There has been a significant worldwide increase in frontier green innovation since the end of the 1990s. But most of this is taking place in the high-income countries. Indeed, Japan, Germany and the US account for 60 percent of total green innovations worldwide between 2000 and 2005, based on key greenhouse gas (GHG)-mitigation technologies. These three countries plus France and the U.K. are the top five ‘high-

[2] See Canuto et al. (2010) and Dutz (2007) for a broad definition of innovation appropriate for development.

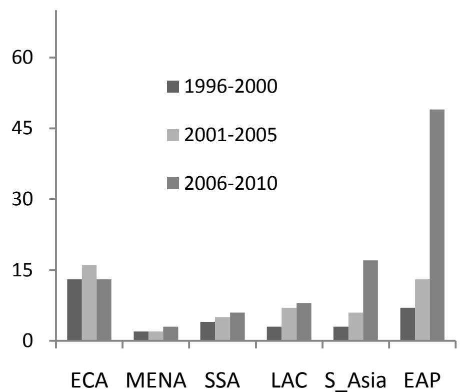
quality' inventor countries, accounting for 64 percent of the world's total high-quality green inventions. China, in tenth place, is the only emerging economy represented among the top ten high-quality innovating countries.[3]

Figure 1: Increasing but Small Fraction of All Green Patents

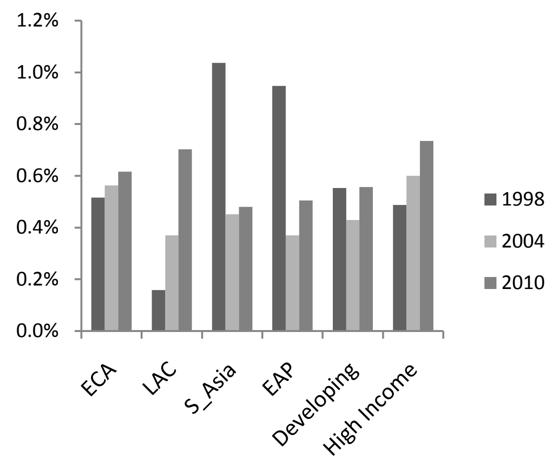
A. Number of Green Patents Granted, Developing vs. High Income countries



B. Number of Green Patents Granted, by Developing Region



C. Green Patents Granted as a Percentage of All Patent Grants, by Region



Panel B: Total USPTO grants in OECD Green Technology Areas. Source: USPTO patents granted in PATSTAT

Panel C: Ratio of 3-yr moving averages of USPTO grants in OECD Green Technology Areas to all USPTO grants (%). Source: USPTO grants in PATSTAT

Other than in China, there are few frontier green inventions in the developing world (Figure 1, Panel A).[4] Over the five year period spanning 2006-2010, countries in the LAC (Latin America and Caribbean), SSA (Sub-Saharan Africa) and MENA (Middle East and North Africa) regions were granted a total of 8, 6 and 3 green US patents, respectively. The EAP (East Asia and Pacific) region, and to a lesser extent S Asia (South Asia) and ECA (Europe and Central Asia) regions have a more sizable output, with 49, 17 and 13

[3] Based on patent applications in 13 GHG-mitigation technology fields filed in 76 countries, with 'high-quality' restricted to patents filed in more than one country ('claimed priorities' rather than 'singulars') by Dechezleprêtre et al. 2011. See the data annex for a description of these 13 technology fields, as we use the same OECD categorization in our patent analysis. Other options for measuring knowledge creation are discussed in Popp (2011), including R&D expenditures as input into the innovation process, scientific publications to measure research at earlier stages of technology development than patents, and surveys (which are particularly useful for certain process innovations).

[4] Details of our estimation are given in the annex, including an explanation for why we focus on US patent grants.

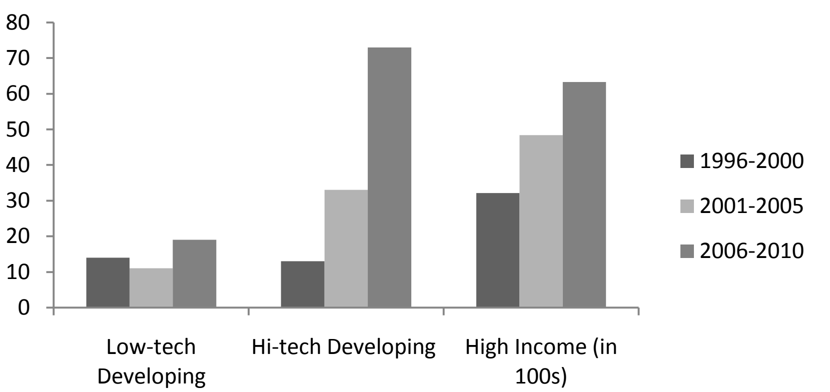
green patents granted. In comparison, high-income countries were granted nearly 1,500 green patents in 2010 alone.

Though small, the 'importance' of green patenting as measured in absolute numbers in developing regions is rising, particularly in EAP and S Asia. This reflects the general rise in patenting by developing countries. Measured by their share in overall patenting per region, green innovations are as prominent in ECA and LAC as in high-income countries, having grown relative to all patents; in this relative sense, green patents have actually declined since the late 1990s in EAP and S Asia and been stagnant across the 2000s (Figure 1, Panel C).[5] But we stress caution in interpreting these trends. For one, these ratios are sensitive to even small changes in the number of patents granted to a few countries. Secondly, scale matters in R&D: even if the relative importance of green patenting is similar to high-income countries, most developing countries have not reached a critical mass of green patenting.

2.2 Technologically-sophisticated countries emerging as significant innovators, but limited to a few technologies

Figure 2: Increasing Patenting in the most Technological Sophisticated Countries

Number of Green Patents Granted



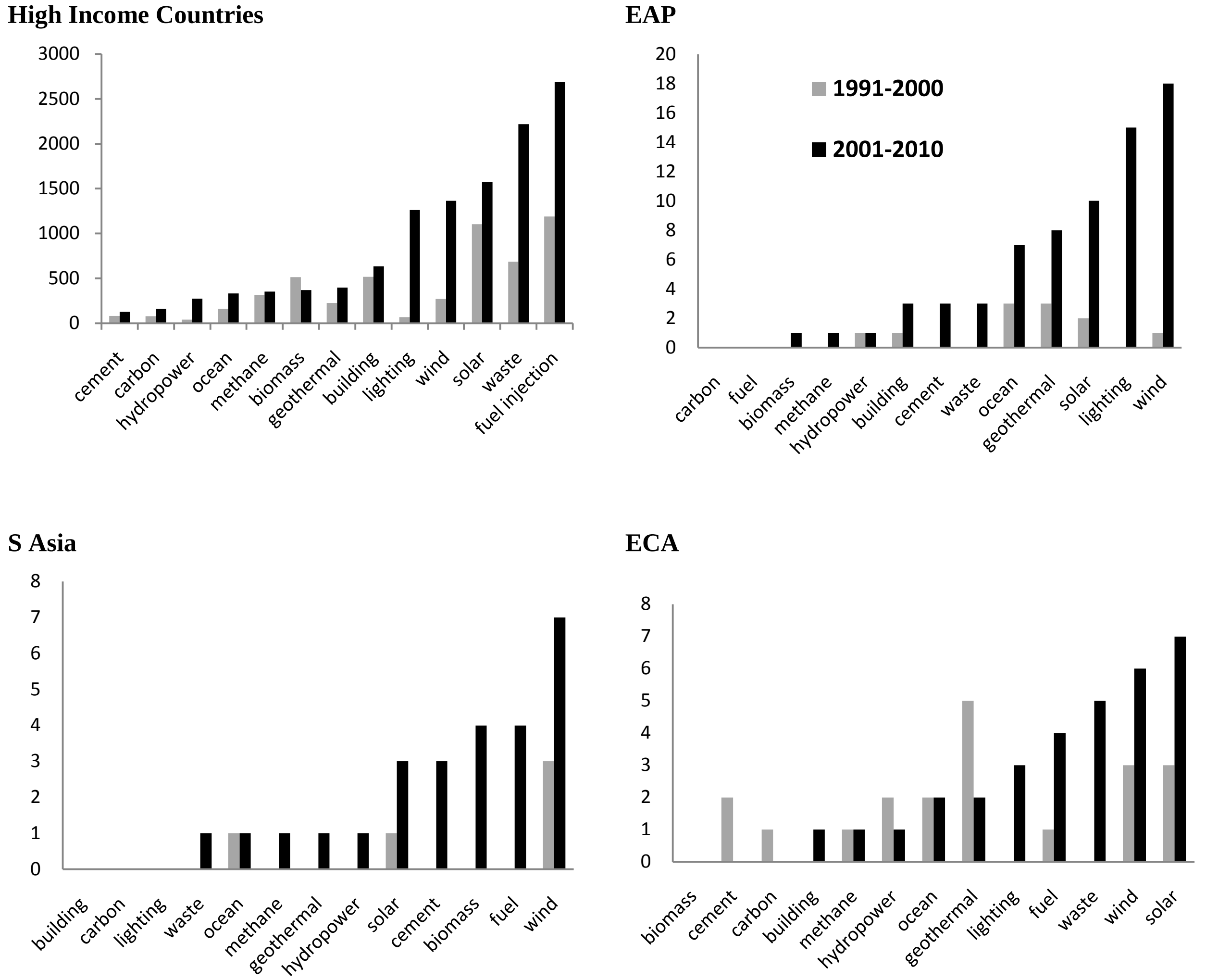
Total USPTO grants in OECD Green Technology Areas for three periods. Patents granted to high-income countries are in 100s. Source: USPTO grants in PATSTAT.

Figure 2 suggests that a significant capacity for frontier green innovation exists in a small group of more technologically-sophisticated developing countries. Hence, appropriate green innovation policy is likely to differ between these and other developing countries (though given substantial differences among the technologically more sophisticated countries, appropriate policy would differ significantly between them as well). A group of nine emerging economies (Argentina, Brazil, China, Hungary, India, Malaysia, Mexico, the Russian Federation and South Africa) account for nearly 80 percent of all US green patent grants to developing countries between 2006 and 2010.[6] Moreover, unlike the technologically less sophisticated countries, these 'emerging' economies display a sharp upward trend in green patenting, with their green patent grants more than doubling between 2000-2005 and 2006-2010.

[5] We have omitted regions where total green patenting is so low that this percentage is a highly volatile, uninformative indicator. Moreover, we have taken 3-year moving averages to smooth out annual fluctuations.

[6] We considered indicators of technological sophistication (R&D personnel per capita) as well as the scale of the R&D sector (total R&D personnel) in making this distinction.

Figure 3: Increasing Patenting in Specific Technological Fields, varying by Developing Regions



Source: USPTO patent grants in green technology areas

Figure 3 highlights that most developing regions 'cluster' in specific green technologies, with the clusters varying by region.[7] In general, wind, solar and fuel injection for engines are major patenting areas common to both high-income and developing countries. But the EAP region is specialized in wind, lighting, solar, geothermal, ocean energy and waste-to-energy technologies, with no or almost no patenting in carbon capture and sequestration, fuel injection, methane destruction, biomass and hydropower. Developing countries have also moved into new technology areas in the last decade. For example, fuel injection, biomass and cement are now major technology areas for S Asia whereas they had no patents in these areas before 2000. Similarly, lighting is a major new area in EAP, and lighting, fuel injection and waste-to-energy for ECA.

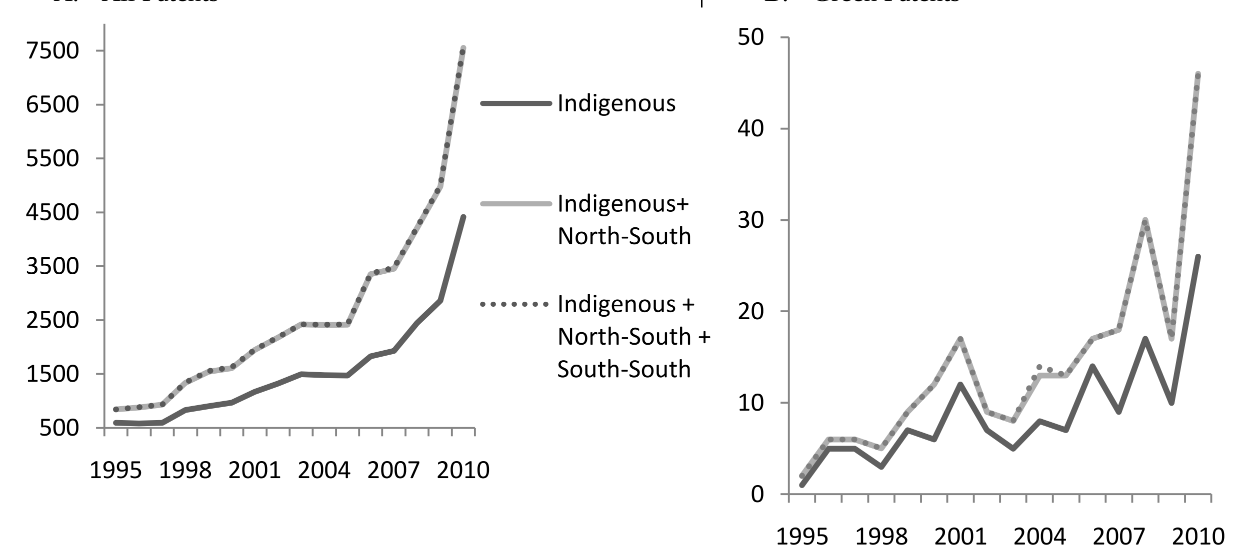
[7] We omit LAC, SSA and MENA regions due to their low levels of green patents.

2.3 Almost no South-South collaboration to-date

The benefits of green technologies spill across national boundaries, so a higher level of international collaboration in green innovation would be the expected norm. But as indicated by the incidence of patents with co-inventors from both developing ('South') and high income ('North') countries, the extent of North-South collaboration is almost identical for green patents as for all patents, with both having increased over time.[8] Across all technology areas, 42% of patents with an inventor from the South also had a co-inventor from the North in 2010 (Figure 4, Panel A). Just for green patents, an almost identical 43% had North collaborators (Panel B). The corresponding figures for 1996 were 35% South-North collaborations across all patents, and 17% collaborations for green patents. Interestingly, these data indicate almost no South-South collaboration: among all green patents granted between 1995 and 2010, there is only one instance of South-South collaboration.[9] Thus, there may be scope for policy to increase international collaboration in green technologies, particularly among developing countries. And even if the benefits from South-South collaboration on frontier innovations are limited, there is a strong case for more collaboration on catch-up innovations when adapted to relatively similar local environments.

Figure 4: Cross-country Collaboration in Patents Granted to Developing Country Inventors

A. All Patents B. Green Patents



Source: USPTO grants in PATSTAT

2.4 Potential for expanding green production and trade

The patent data suggest that there is little capacity for *frontier* green innovation in most developing countries. However, there could be enormous capacity for *catch-up* green -up innovation through new-to-the-firm adoption and adaptation of existing green technologies, and through indigenous base-of-pyramid

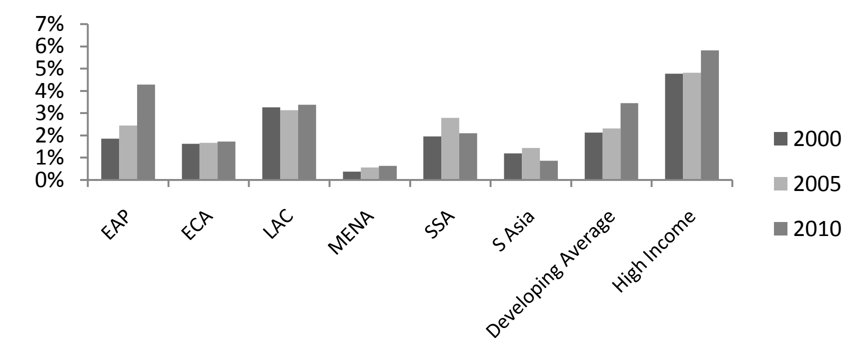
[8] Guellec and Potterie (2001) use patent co-invention to measure international collaboration. Details of our estimation are given in the data annex.

[9] The incidence of South-South collaboration among *all* patents granted to developing country inventors is 0.3%.

innovation. While these are unlikely to be captured in international patent data,[10] they are reflected in the production and trade of 'green' goods and services, to the extent that green technologies are embodied in a good or service.[11]

As shown in Figure 5, environmental goods constitute a non-trivial and rising share of high-income country exports. The share of green exports is slightly lower in most developing regions - but the gap is nowhere near as large as with frontier innovations. However, with the exception of EAP, the share of green exports has not been rising, suggesting that new firms are not entering these sectors.[12] The policy implication of this observation depends on the extent to which this reflects some under-exploited comparative advantages in specific developing countries accounting for lower levels of home production and export of green goods and services. Any policy intervention should be predicated on better information on the sources of this under-exploitation, whether driven by specific market or policy failures. For instance, information on the extent to which the relatively less developed state of environmental regulations in many developing countries may be accounting for these differences could suggest appropriate policies.

Figure 5: Export of Green Goods and Services (as % of all exports)



Source: COMTRADE + OECD List of environmental 6-digit HS categories

Figure 6 shows that green imports are as important (as a share of all imports) in developing regions as they are in high-income countries. This indicates the international transfer of green technology as embodied in green consumption goods. Further, inasmuch as some of these green goods are used as inputs, this also indicates the 'greening' of the input mix, which may reflect adoption and adaptation of

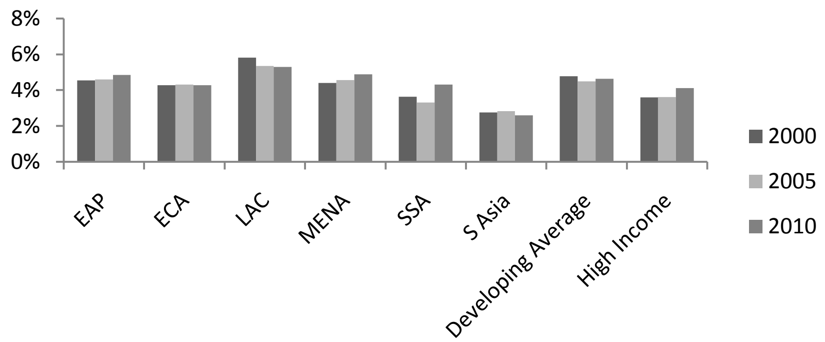
[10] The lack of good data to measure the diffusion of existing green technologies that lack sufficient global novelty for patenting, beyond product-level trade data, is also highlighted by Popp (2011). Dechezleprêtre et al. (2010) use green patent applications data to analyze the international diffusion of patented inventions (the number of patents invented in Country A and filed in Country B) as an indicator of the number of innovations transferred between these countries – an interesting empirical exploration of a small part of diffusion but a poor proxy for broader technology diffusion and adaptation across and within countries.

[11] Details of our measurement of green trade are given in the data annex. Note that the underlying technologies embedded in these green goods and services are much broader than in the patent discussion, which look only at GHG mitigation technologies. These trade-based results are therefore not directly comparable to the patent results. Note also that an increase in a country's aggregate output of a green product does not necessarily reflect an innovation since it could be by firms already producing that good. Nonetheless, changes in aggregate green output are correlated with the introduction of new-to-the-firm green goods.

[12] This is true even when looking at the absolute volume of green exports.

existing technologies by local firms. In addition, the import of green goods may be a response to domestic demand-side green policies in developing countries. However, there is no significant upward trend in any region in particular.

Figure 6: Imports of Green Goods and Services (as % of all imports)



Source: COMTRADE and OECD List of environmental 6-digit HS categories

Even if developing countries are not increasing their exports of green products, they could be increasingly capable of moving into green sectors to the extent that they are producing non-green goods and services that enable them to produce green products because of similarities in the required inputs or technologies. To examine this broader 'capability' for green exports, we utilize the concept of 'proximity' between products.[13] For example, a country with the ability to export apples will probably have most of the conditions suitable to export pears, but not necessarily those for producing electronics. Figure 7 shows in general, the trade in green and 'close-to-green' products is about three to five times that in green products alone. Moreover, some developing regions like EAP and LAC are even comparable to high-income countries in this respect.

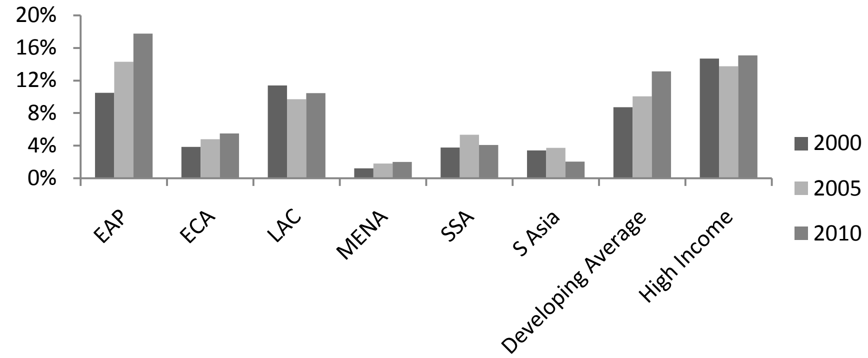
Proximity between two products does not necessarily imply that a country producing one also has comparative advantage in the other. But as described in Hausmann and Klinger (2007), as countries change their export mix –in other words, as comparative advantage *evolves*– there is a strong tendency to move towards proximate goods rather than to goods that are farther away. Thus, Figure 7 suggests that some developing countries have opportunities comparable to developed countries to leap to green products close to products they already export.

Policies targeting the sources of proximity between products could enable such leaps. The pattern of relatedness of products is only partially explained by similarity in broad factor or technological intensities, suggesting that the relevant determinants are much more product-specific, such as product-specific human capital acquired through learning-by-doing (Hausmann and Klinger, 2007). Therefore, any policy intervention should be predicated on better information on the sources of proximity, including crucial technological differences and access to complementary inputs. Further, given the double

[13] Following Hausmann and Klinger (2007), we measure proximity between goods by using an outcome-based method which is based on the hypothesis that similar products are more likely to be exported in tandem. Details are given in the data annex.

externality inherent to green innovation, it may be that demand-side policies are also needed to create sufficient incentives to make the leap to greener products.

Figure 7: Export of Green + Close-to-Green Goods and Services (as % of all exports)



Source: COMTRADE and Proximity Matrix based on 6-digit COMTRADE

2.5 Little BoP green innovation to-date

BoP (Base-of-Pyramid) innovations are defined as innovations to meet the needs of poor consumers. They include formal innovations for the poor, namely innovations by global and local private companies and public institutions, whether fully privately provided, supported by public subsidies, or produced through public-private partnerships (such as medicines for neglected diseases and seeds for 'neglected' soil types and climates). They also include informal innovations by local grassroots inventors largely through improvisation and experimentation.[14] Often facilitated by co-creation with poor consumers themselves, the innovations typically seek to better meet the needs of poor households at dramatically lower costs per unit, aided by significant scale-up in volumes – hence they seek "to create more (products) with less (resources) for more (people)".[15]

An exhaustive survey of green BoP innovations indicates that very few BoP (and related low-tech) green innovations have been sufficiently scaled-up to-date. Whether there may be a need for more focused policy efforts in this area requires a better understanding of the constraints, both on the supply and demand side, impeding scaled-up commercialization, and the benefit-cost of appropriate policies and their implementation to improve market outcomes. Box 1 highlights a few representative green BoP innovations that have been documented.

Box 1. Illustrative BoP innovations

Indoor non-electric cooking stoves: Nearly 3 billion people who don't have easy and/or affordable access to some form of clean, modern energy use indoor cooking stoves burning biomass crop waste, wood, coal or dung. Smoke from the stoves produces black carbon, an important GHG, in addition to indoor air pollution. Patent counts based on inventor country highlight the importance of developing countries as developers of such technologies, with China

[14] See Utz and Dahlman (2007) for examples of BoP innovations across technologies in India.
[15] See, among others, Prahalad and Mashelkar (2010).

the leading source of patents across all four types of listed stoves. And India is the leading source of scientific articles for 3 of the 4 stove technologies, likely driven by research from universities and non-profit foundations, which are less likely to patent and commercialize research findings.

Patent and Publication Counts for Indoor Cooking Stoves, to 2010

	China	India	South Africa	Japan	US	Germany	France	UK	Korea	Total
Patents from 1960s to 2010										
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 / butane stoves	143	0	1	112	21	2	4	2	18	313
Publications 1990-2010										
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 / butane stoves	3	50	2	3	41	4	0	4	1	132

Aakash Ganga ('river from sky'), Rajasthan, India: modernizing an ancient rainwater harvesting system to collect safe drinking water is a low-cost adaptation to arid regions, which has won the 2010 Lemelson-MIT award for sustainability. It spurred additional innovations and thereby generated a range of efficiency and more inclusive growth co-benefits:
-automating the traditional surveying system with satellite imaging shortens design time, minimizes earthwork and reduces material costs
-a numbering plan for reservoirs facilitates co-investments
-induced demand for stretchable roofs has spurred more innovation
-accounting transparency has spurred policy debate on broader inequities in water affordability.

Novel uses of rice husks, one of India's most common waste products: Husk Power Systems (HPS), winner of the 2011 Ashden Awards for sustainable energy, has adapted and converted an existing biomass gasification using diesel technology into a single fuel rice husk gasifier for rural electrification; households stop using dim kerosene lamps when they get HPS electricity, saving on kerosene (with associated reductions in CO_2 emissions) and facilitating evening studying/learning and other productive activities. Tata Consulting Services US$24 *Swach* ('clean' in Hindi) water filter targeted at rural households with no electricity or running water, using ash from rice milling to filter out bacteria, is another example.

Solar irrigation with electric vehicles in Bangladesh: use of lithium-ion batteries (second-hand, recycled from electric cars) that are powered by solar panels allow mobile shallow-tube irrigation systems to meet rural farmer irrigation needs in Bangladesh and other countries that face limited electricity supply and make heavy use of groundwater.

Source: Popp (2011) on cooking stoves (using a combination of keyword and patent classification searches on the Delphion on-line patent database, and using a keyword search of abstracts and titles in the Web of Knowledge database); web searches and interviews for others.

Besides BoP innovation, the adaptation of existing technologies to local conditions is a growing area of green innovation in developing countries. Box 2 provides some recent examples of technology adaptations by innovative developing country companies that solve limitations of resources, labor and infrastructure. They create important co-benefits including more sustainable company cultures.

Box 2. Local innovation companies show what is possible

In principle, the home-grown green ideas of innovative local companies to reduce costs, motivate workers and shape the business environment they operate in should make it easier for their peers in comparable developing country settings to emulate such approaches. Leading examples include:

- ***Equity Bank agricultural financial products, Nairobi, Kenya:*** worked with mobile telecoms provider Safaricom to create a mobile banking system on its M-Pesa platform, offering credit for inputs and supporting farmers throughout the value chain of production, transport, processing and marketing; and has formed an alliance with groups such as The International Fund for Agricultural Development to reduce its risks when lending to smallholders
- ***Broad Group air conditions and construction, Changsha, China:*** adapted non-electric air conditioning technology from US, Japan, Korea and Europe to use the waste heat from buildings to power its machines, with customizable pre-fabricated construction modules reducing electricity consumption up to 80%, using fewer materials and creating less waste; has also developed a miniature device for measuring air pollution that can fit into mobile phones
- ***Natura organic cosmetics, Sao Paulo, Brazil***: worked transparently with rural communities and local governments to tap traditional knowledge about how to extract raw materials sustainably (receiving the Forest Stewardship Council certificate for these raw materials), in turn educating suppliers in sustainable sourcing and production practices (including re-use, refill and recycling of packaging and adoption of a new 'green' plastic derived from sugar cane which is eventually expected to reduce GHG emissions by +70%); also gives bonuses to workers who find ways to reduced the firm's impact on the environment
- ***Jain irrigation systems, Jalgaon, India***: adapted existing drip irrigation systems specifically to meet the needs of smallholder farmers, and works closely with customers to teach 'precision farming' (which optimizes the balance between fertilizers, pesticides, water and energy to increase output); and uses dance and song to explain the benefits of drip irrigation to farmers who can't read

Source: World Economic Forum (2011). WEF and the Boston Consulting Group partnered to review more than 1,000 emerging market-based companies with annual sales ranging from $25 million to $5 billion, coupled with interviews of almost 200 business executives, to identify 16 showcase companies in light of sustainability, innovation and scalability criteria.

Enterprise surveys are another potential source of systematic information on the extent and breadth of such local green innovations. However, most national industrial census efforts and complementary internationally-comparable enterprise surveys have not yet systematically been collecting information on green product, process, organizational and marketing innovations.

3 FOSTERING INNOVATION – POLICIES FOR PROMOTING FRONTIER AND CATCH-UP INNOVATIONS AND FOR DEVELOPING ABSORPTIVE CAPACITY

As with all other technologies, market failures in the creation, dissemination and absorption of knowledge by firms provide a rationale for public policies addressing the development and commercialization of green technologies. In addition, green technologies are also characterized by environmental externalities. The combination of knowledge and environmental market failures require combined policy responses and an even greater emphasis in developing countries on catch-up green innovation relative to developed countries. [16]

There are two gaps between the private and social returns to the production of knowledge that typically result in an under-provision of knowledge absent government intervention. The key market failure is the partial private appropriability of the returns to investment in knowledge due to the public goods attributes of knowledge, in particular that it is non-rivalrous in consumption: once knowledge has been created, it can be consumed by all, and indeed it is efficient for it to be used repeatedly by as many as possible, since its consumption does not subtract from what others know. This raises a tension between static and dynamic efficiency. Although it is most efficient to encourage the use of knowledge as widely as possible once it is invented, without sufficiently high pricing and returns there may not be adequate dynamic incentives for the required investment to generate the knowledge in the first place. Since the firm investing in knowledge creation captures only a portion of the benefits, there will be an under-investment in new knowledge, with the extent of under-investment depending on the extent to which the social returns exceed private returns, which varies across technologies and applications. Analogously, maverick firms adopting an existing technology in a new location (or households for instance adopting solar home electricity systems) will typically not fully take into account the positive demonstration spillovers on later adopters. In addition, there may be no private investment at all if the up-front R&D costs exceed the private ability-to-pay of poorer consumers even though there may be large social returns from the new knowledge.

A second market failure in the creation of knowledge is the information asymmetries between what inventors know and what financiers can gauge before the product is commercialized. The inventor has a better idea than banks and other potential financial intermediaries of the complexities of the underlying technologies to be developed, and of the ability and effort that the inventor will devote to their development. These information asymmetries restrict access to traditional sources of finance and lead to a 'funding gap' or under-investment in innovation projects that may have a high social return.

An additional market size externality can create path dependency, affecting the allocation of innovation effort and leading to a socially undesirable technology lock-in effect – where lock-in is defined as market dominance of an inferior incumbent technology at the expense of a superior contender technology. When there are two or more technologies (some not even invented) that are substitutes, profit-maximizing innovators may focus their efforts on improving productivity of existing technologies ("building on the shoulders of giants") to the extent that the market size for these technologies is large and the return higher. The increase in market size when there are economies of scale, compounded by learning and network effects, can reinforce incentives to continue improving the quality of the initially-selected technology. If this technology is dirty and would lead to an unsustainable growth path, policy intervention may be required to re-direct the economy onto a greener growth path. More than other industries, energy

[16] This paper focuses explicitly on knowledge-related market failures and their interactions with environmental externalities, in contrast to the range of other market failures that motivate green public policy interventions, such as coordination externalities and non-knowledge-related public goods.

markets are prone to these lock-ins because electricity from different technologies is an almost perfect substitute.[17]

Finally –compounding the knowledge-related spillovers and funding gap rationales for policy intervention which are common to all types of technologies— there are the traditional environmental externalities associated with green technologies. To the extent that the social costs to the environment of technologies leading to carbon emissions, other forms of pollution and biodiversity degradation are not reflected in the market through prices or non-price policy interventions, firms and households will under-develop and under-use greener technologies below socially desirable levels.

There is no single green bullet to solve both innovation and environmental challenges: countries should typically use two sets of instruments to address the two complementary knowledge and environment-related market failures. Studies evaluating the effectiveness of policy options find that a dual set of policies involving technology and environmental policies (for instance both research subsidies and carbon taxation) is superior to a policy based only on environmental policies – and that policy neutrality regarding technology is not always possible and even not desirable in certain cases.[18] Policies addressing the knowledge-related market failures can facilitate the creation and diffusion of new environmentally-friendly technologies, while complementary policies correcting the environmental externality provide stronger incentives for their creation and adoption.

Based on a two-sector (initially-dominant dirty and incipient clean inputs representing substitute technologies) growth model of endogenous technical change with environmental constraints, Acemoglu et al. (forthcoming) show that the optimal policy includes both an incentive to stimulate innovation in the green sector (an R&D subsidy directs technical change towards the clean technology) and a separate environmental incentive to internalize the pollution externality (emission taxes or targets). However, they also suggest that, under reasonable discount rates and with sufficient substitutability between inputs, it is optimal to redirect technical change to the cleaner technology immediately without sacrificing much long-run growth. On the other hand, a powerful critique of this model by Hourcade et al. (2011) emphasizes, among others: that the need for quite costly regulation is likely to be relatively longer-term, with a large negative impact on growth; that the substitutability between alternate energy sources may be quite inelastic in practice, at least in the short to medium term, due to the inertia of existing equipments (the capital stock for large sections of the energy system lasts more than 50 years) and to technical constraints

[17] See Acemoglu (2002) on directed technical change, and Acemoglu et al. (forthcoming) for an application to green innovation. Kalkuhl et al. (2012), using an inter-temporal general equilibrium model with two competing low-carbon electricity technologies, show that 'small' market imperfections may trigger a several-decades lasting dominance of an incumbent energy technology over a dynamically more efficient competitor (that is cheaper in the long run). They find that technology quotas and feed-in-tariffs are only insignificantly less efficient than the first-best technology policy of learning subsidies, in addition to a standard environmental policy (carbon pricing).

[18] That technology and environmental policies work best in tandem is a robust conclusion derived by the three last IPCC reports. Del Rio (2008) shows that a combination of a non-neutral technology-prescriptive policy encouraging dynamic cost reductions (such as the creation of niche markets for currently-expensive technologies) and an incentive-based technology-neutral environmental policy aiming at short-term cost-efficiency (such as tradable permits) are needed to address an emissions mitigation objective under conditions of path dependence and lock-in – with technology-neutral policies leading to technology choices by the market that may not be cost-effective in the long term. Azar and Sanden (2011) argue that policy neutrality regarding technology is often an elusive objective that sometimes cannot or should not be prioritized as the main guiding principle. For other contributions, see Popp (2010 and 2011).

(neither gas nor coal can easily substitute for liquid fuels used in internal combustion engines); and that the model relies on very restrictive structural assumptions including a misrepresentation of climate irreversibility and an incomplete endogenous growth model.

Table 1: Innovation policies

Policy areas	**Intended beneficiaries**	**Policy instruments**
1. Promoting frontier innovation (innovation finance and other policies for development and commercialization of new-to-the-world knowledge)	Firms with sufficient technological capabilities; financiers	- government-funded R&D (public labs; matching grants, soft loans and tax credits for private firms) - patents and other intellectual property rights (IPRs) - support for early-stage technology development (ESTD) finance including support for private capital (angels, early stage VC) - prizes and Advance Market Commitments (AMCs)
2. Promoting catch-up innovation (policies to facilitate access to new-to-the-firm knowledge and to stimulate technology absorption)	All firms; public labs & universities; all citizens	- open trade, FDI, IPRs, diaspora and ICT policies - patent buyouts and compulsory licenses - patent pools and open source mechanisms - public procurement, standards and regulations - support for finance to early adopters/demonstrations
3. Developing absorptive capacity (policies to strengthen skills and more broadly spur the accumulation of new knowledge by entrepreneurs/firms)	All firms; workers and managers; researchers; trainers	- education and life-long learning policies - enterprise-based worker training, management and entrepreneurship training, and other technical and vocational education and training (TVET) - facilitating connectivity through global alliances and supplier development linkages to global value chains - rule of law, contract enforcement, competition, bankruptcy & re-entry facilitation; urban policies ('sticky' cities to attract and retain talent)

Note: While some policy instruments like public procurement, standards and regulation are relevant for all three policy areas, they are listed in the area deemed most important to stimulate green innovation in most developing countries.

The following sections discuss in turn policies to support new knowledge creation, to strengthen diffusion and adaptation of existing knowledge to local contexts, and to develop absorptive capacity for innovation, as outlined in Table 1. Beyond the robust desirability of two sets of instruments to address the complementary knowledge and environment-related market failures, what distinguishes green innovation policies as opposed to generic (non-green) innovation policies? While there are still insufficient impact evaluation studies of green innovation policies, both in general and as applied to different developing country contexts, it is not premature to put a green twist on the innovation policies listed in Table 1 by prioritizing certain policy instruments over others based on defining characteristics of most green technologies. One key characteristic of most green technologies is that their broad diffusion and adoption is even more socially desirable than for non-green technologies, given the environmental externality. Another key characteristic is that the efficient use of green technologies requires them to be more heterogeneous than non-green technologies, given the significant variance of the underlying environment by locality (while a state-of-the-art computer chip will be the same whether used in Mexico or Thailand, green technologies require adaptation to local soil, water, air, wind and sun conditions, among others). So prizes, for instance, are typically a preferred policy instrument over patents to promote the creation and diffusion of green as opposed to generic technologies, as patents tend to inhibit both diffusion and the follow-on innovation that builds on the protected technologies, while prize funds can be targeted to meet well-defined objectives, with the developed knowledge widely disseminated and used by all once the prize is awarded. While Advance Market Commitments are a useful complementary demand-pull mechanism to prizes, they are still premature in most countries as there are not yet well-functioning markets for the development of many green technologies that don't require government support in the first place.

The green innovation policy agenda needs to be tailored to countries depending on their local environmental needs, technological sophistication and implementation capabilities. The latter is important, as systemic institutional government failures (including uncoordinated and conflicting policies, unclear responsibilities, and ineffective implementation with excessive rent-seeking) need to be addressed if activist policies to address market failures are to lead to better outcomes than no intervention. Policymakers need to better understand local environmental needs and the innovation ecosystem in their countries, for both firms at the technological frontier and behind it, designing policies that make the ecosystem work better and applying resources at the most appropriate places. They then need to put in place the public-private dialogue processes and capabilities to prioritize and implement policies, and the monitoring and evaluation systems so policies can be continually improved for more effective impact.

3.1 Promoting frontier innovation – different approaches depending on local technological sophistication

A portfolio of policies for frontier innovation can generally be thought of as having both supply-side 'technology-push' elements that reduce costs of knowledge creation in advance of commercialization, and demand-side 'market-pull' elements that enhance net revenue from sales after commercialization. Stimulating appropriate innovations will likely require use of multiple incentives that affect investments on both cost and revenue margins.

New frontier technologies can be created and commercialized even in countries where average technological capabilities are relatively less sophisticated, provided there are one or more agglomerations of firms with sufficient technological capabilities, ideally supported by sufficiently high-quality higher education systems – provided the benefit-cost of public support is sufficiently high to warrant expenditure of scarce public resources relative to alternative uses. This can be achieved by taking advantage of the heterogeneity of public and private capabilities, with the participation in public-private dialogue processes of better-performing firms and parts of the public sector in whatever sector and urban/rural setting they are located within countries.[19]

3.1.1 Limit local technology-push support to countries with sufficient technological capabilities

Direct **government funding** for R&D is an important element of many innovation systems, including funding of public labs and universities, as well as grants, matching grants, soft loans, and R&D tax subsidies to private firms for early-stage, pre-commercialization technology development (for individual firms, and for collaborations between firms, and between firms and public labs/universities). Government-funded R&D of public R&D institutes is the traditional supply-push mechanism, with selection of whom to engage in research projects bureaucratically rather than market-determined, ideally

[19] See Hausmann, Pritchett and Rodrik (2005) on growth accelerations. And see Rodrik (2007) on broader policy lessons from these growth acceleration episodes, including the need for context-specificity and prioritization, sequencing and targeting of reforms on the most binding constraints through a structured process of public-private dialogue.

through a group of independent peers (when the research-awarding process is not captured by rent seekers). One advantage of this approach is that it allows coordination of research efforts with little or no excess duplication. With respect to dissemination, publicly-produced knowledge should generally be made freely available, which is socially desirable to ensure efficient use once produced. A key shortcoming of government-funded R&D is that, as research moves from basic to more applied phases, incentives are not strong to reflect information from markets about what consumers want and are willing to pay for.

As highlighted in Section 1, frontier green (and non-green) innovations that are dependent on significant formal R&D support have to-date largely been concentrated in high-income countries and a few more technologically advanced developing countries, with most developing countries having little such innovations as indicated by patent data. So there is likely a more limited role for formal R&D support for frontier innovations in most developing countries, to the extent that such spending reflects underlying technological capabilities.[20] Box 3 illustrates one such area, the development of smart grids, where major direct government funding for R&D, typically in public-private partnership mode, is taking place in many more technologically-advanced countries, and where the benefits are expected to eventually be reaped by all countries as these technologies diffuse and are absorbed by a broader range of firms.

Box 3. Smart grid R&D and expected green benefits

'Smart grid' means computerizing the electric utility grid, similar to the way today's 'smart phones' have a computer inside. It includes adding two-way digital communication technology to all devices associated with the grid to ensure two-way flow of electricity and information between all power plants and consumers and all points in between, with sensors to gather data on incoming power from wind, solar and other renewable that have constantly varying power outputs, broken equipment and leakages, more intelligent management of generation outages, integration of electric vehicles, and power meter usage in homes and offices. R&D activities advance smart grid functionality by developing next-generation technologies and tools in the areas of transmission, distribution, energy storage, power electronics, cyber-security, and the advancement of precise time-synchronized measures of certain parameters of the grid.

A recent study on whether the smart grid is expected to reduce the intensity of green-house gas emissions in the US concluded that it will likely slow the growth in electric power production by reducing consumption over what would have otherwise been consumed without the smart grid, noting that history has shown that new appliances are typically added to homes as they become available, as the population grows, and as incomes and affordability rise. It emphasized benefits of energy conservation by consumers facilitated by demand-response programs and demand-side management, improvements in transmission and distribution systems that optimize power consumption and reduce the need for electric power, as well as the benefits from electricity storage and management, allowing utilities to smooth renewable generation and use base-load generation sources more effectively.

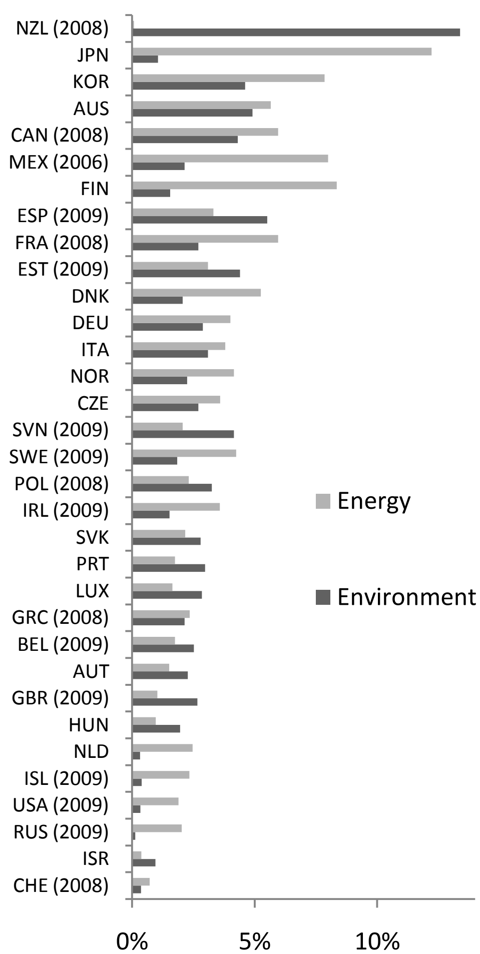
Source: NETL (2011) and http://energy.gov/oe/technology-development/smart-grid

[20] However, even in less developed countries, extending and adapting existing global technologies to local characteristics may justify some investment in basic R&D, including to build technological capacities to define national standards – for instance, solar power technology typically needs to be adjusted to local climate and meteorological conditions, and quality standards for solar panels need to be defined. Public subsidies for basic R&D are subject to the general implementation challenges of focus (which projects to focus on), design (how much subsidy and how best to allocate), and governance structures to mitigate rent-seeking.

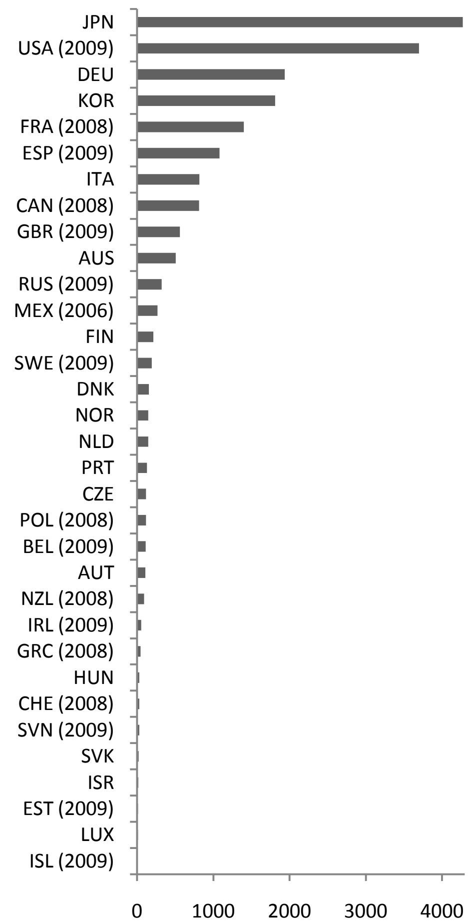
Figure 8 presents data on the absolute central government budget appropriations or outlays for R&D for environmental technologies and for clean energy technologies (a subset of environmental technologies) for 33 countries including 8 developing countries (on the right-hand side, in millions of US$ in PPP terms). The fact that no developing country is in the top 10 absolute funders of energy and environment R&D reflects data availability (China, for instance, is not included presumably due to data comparability issues), but is also consistent with the more limited technological capabilities for formal R&D in most developing countries; the only developing countries included among the top 20 funders for which comparable data were available are the Russian Federation (11), Mexico (12), the Czech Republic (19) and Poland (20).[21]

Figure 8. Government R&D budgets for energy and the environment, 2010

A. *As a percentage of the total government R&D budget*



B. *Total budget on Environment + Energy, Millions USD PPP*



Source: OECD, Research and Development Database, May 2011. Note: Government budget appropriations or outlays for R&D measures the funds committed by the federal/central government for R&D. It can be broken down by various socio-economic objectives, defined on the basis of the primary purpose of the funder, including control and care for the environment as well as energy.

[21] To the extent that the figures in Box 4 are comparable, Brazil with green R&D expenditures of $300 million would be between the Russian Federation and Mexico.

Figure 8 also presents data on publicly-funded research priorities to achieve energy and environment objectives as part of their overall central government R&D budgets. Of available developing countries, Mexico allocates the greatest share of its total R&D budget to environmental technologies, at slightly over 10 percent, with most expenditures in areas other than clean energy technologies. At the other end, the Russian Federation provides the least relative support of available developing countries, with 2% of its R&D budget on environmental technologies. It is noteworthy that other available ECA countries are not at the bottom of the table, with Estonia, Czech Republic, Slovenia, Poland, Slovakia, Belarus and Hungary all devoting a higher share of their R&D budget to energy and the environment than the US and Russia. Box 4 provides a more detailed breakdown of green R&D expenditures in Brazil in 2010, making the case that Brazil's levels of expenditures relative to total R&D are not in line with the comparative advantage of its natural capital, constraining an otherwise more rapid national green growth.

Box 4: Brazil's green R&D expenditures – more than government budget, more than renewable energy

Comparable data to Figure 8 highlight that Brazil's government green R&D budget in 2010 was U$300 million out of a total government R&D budget of $15.8 billion, or 1.9%, placing Brazil in percentage terms at the bottom of the table, below US and Russia and only slightly above Israel. However, government outlays on R&D were only 42% of total green R&D expenditures in 2010, with business outlays (split 56% versus 44% across private and state-owned businesses) accounting for the remaining 58% of total green R&D expenditures of $716 million (which account for 2.6% of total R&D expenditures, in turn accounting for 1.2% of GDP in 2009).

The allocation of total green R&D expenditures is 45% towards renewable energy and 55% towards other environmental areas, with a breakdown of the latter into productive uses of biodiversity and protection of ecosystems (32% of total green R&D expenditures) and 'greener agriculture' (23%). A further disaggregation of R&D expenditures across these three areas reflects underlying comparative advantages, namely: (1) for renewable energy, biofuels account for 82% of the total, with hydro and biomass accounting for a further 6.4 and 4.4%; (2) for biodiversity and ecosystems, natural cosmetics account for 36% of the total, with atmospheric ecosystem protection, sustainable resource extraction and energy efficiency accounting for a further 21.2, 9.5 and 6.9%; (3) for greener agriculture, sustainability of agricultural production and biotechnology account for 30 and 27% of the total, with agricultural zoning and integration of productive value chains accounting for a further 9.0 and 7.8%. But although these expenditures on R&D have yielded impressive research outputs, the link between research outputs and commercializable patents remains weak: while Brazil leads in sugarcane research with 300 scientific articles on Thomson Reuters' ISI Web of Science (with the US almost three times fewer and China at 30 in 2008), China and the US lead Brazil in accumulated sugarcane patents with the EPO over the 2006-2010 period, with 175 for China, 18 for the US, and only 5 for Brazil.

Frischtak claims that these levels of expenditures in R&D and patent results are in stark contrast with the diversity, scale and potential of natural assets available in Brazil. What is needed, according to Frischtak, is a national consensus around the establishment of a clear strategy and work program that finances and creates broader science and technological and regulatory capabilities in Brazil aimed at better stimulating R&D and frontier innovation towards a pattern of growth driven by the sustainable productive use of these green assets. The detailed breakdown of green R&D expenditures data is an essential input into the debate towards achieving such a national consensus.

Source: Frischtak (2011), and an average 2010 exchange rate of 1.76 Reals to the US dollar (IFS, IMF).

In contrast to the supply-push of government R&D funding, **patents** were initially devised as a decentralized demand-pull self-selection mechanism, allowing those who believe they are the most likely to succeed to risk their own resources for the 'prize' of a period of exclusivity during which they can set product prices, with the quid pro quo of full disclosure of the knowledge to other researchers. In practice, significant public funding of R&D, both to public and private entities, typically accompanies the own-resources of the researchers toward the development of patentable ideas. Patents can serve a useful signal for private finance. However, well-known problems with the patent system are that it is distortionary and inequitable in the way funds to support further research are raised, namely by charging monopoly prices, and inefficient in the way usage of new knowledge is restricted. Researchers also face significant litigation risk. Moreover, although innovation incentives are strong in the patent system, they are distorted because there are incentives to engage in research to innovate around existing patents and to spend resources in ways that extend the life of patents. There are also other market distortions such as the largely socially-dissipative advertising and marketing expenditures designed to reduce the elasticity of product market demand in order to raise prices and profits.[22]

Once new commercializable ideas have progressed to the proof of concept stage that demonstrates their feasibility, whether or not protected by one or more patents, further **early-stage technology development (ESTD) finance** is required. The range of ESTD finance options includes both public and private resources, with private sources at this early stage typically restricted to friends and family, angels (affluent individuals, often retired successful entrepreneurs, providing start-up capital and mentoring), venture capital (VC), private equity firms (at later stages), and private corporations (who fund ideas developed in-house and acquire young start-up companies);[23] cheaper sources of financing, such as bank finance, are usually not available for most early-stage ventures as they are too small or young to qualify for traditional loans. Angels and VC investors make money through successful exits based on a sufficient deal flow, with the typical liquidity event being an acquisition or an initial public offering (IPO) on a local or international stock market. If the IPO market is weak with not enough companies going public, then the VC business model is threatened. The challenge facing most developing countries in this area is that these capital market-based, arms-length forms of finance that structure and price each transaction on its merits require deep financial markets underpinned by demanding institutional legal and regulatory frameworks, with monitoring and enforcement mechanisms relying on extensive formal disclosure and corporate governance standards. This is not an area where public interventions such as jump-starting a new VC industry have been successful on average – which is why the recommendation for most governments is that they should focus on "setting the table" rather than "cooking the meal" by ensuring that the basic underpinnings are in place of rule of law, contract enforcement, and broad certainty in legal and regulatory frameworks (Lerner 2009).

[22] See Stiglitz (2008) and Henry and Stiglitz (2010) on the desirability of re-designing the prevailing patent regime to increase its benefits and reduce its costs, and to combine it with government-funded research, prizes and other mechanisms as part of a portfolio of complementary innovation-support instruments. In their review of the relevant literature, Hall and Helmers (2010) also conclude that, given the environmental externality, patents may not be the ideal and cannot be the only policy instrument to encourage green innovation – in light of their tendency to inhibit both diffusion and the follow-on innovation that builds on the protected technologies.

[23] In 2010 in the US, angel investment accounted for almost as much money invested as all VC funds combined ($20.1 billion vs $23.3 billion), but they touched more than 60 times as many companies (61,900 vs 1,012 companies), more than 10% of the roughly 600,000 businesses founded in the US each year, with over 370,000 jobs attributed to angels, widespread across sectors (healthcare, medical devices, biotech, industrial/energy, software, retail, IT services, including green applications). And big private sector corporate like Petrobras (Brazil), ZTE (China), Siemens (Germany), Tata (India), and IBM (US) have set up sizable green tech business lines. See Chatterji (2011).

Box 5: "Pinstripe greens" – Private financiers making millions from clean tech ventures

Although global VC investment in green energy declined with the 2008-09 recession, and shares in clean-tech businesses have underperformed the wider market by a large margin recently, a world of US solar titans, German wind moguls, Brazilian bio-fuel magnates and Chinese battery tycoons has emerged over the past decade. One often hears that "green energy could be the biggest economic opportunity of the 21st century". In 2010, the global clean energy sector (wind farms, solar parks and related technologies) attracted a record $243 billion in new investment, nearly 5 times the volumes six years earlier. And between 2000 and 2010, the global market for solar and wind power rose from $6.5 to $132 billion, the number of hybrid electric car models jumped from 2 to 30, and the number of certified green buildings grew from 3 to 8,138. Examples of private green financing include:

- Khosla Ventures: a venture capital firm founded by Vinod Khosla in 2004 with a clean tech portfolio spanning utility-scale and distributed generation, electrical and mechanical efficiency, batteries, building materials, plastics and chemicals, agriculture, cellulosic alcohol and advanced hydrocarbons, and including investments in a low-emission engine (with Bill Gates) and two-bladed wind turbines (with Goldman Sachs)
- Bloomberg New Energy Finance: a provider of analysis, data and news about clean tech, including on renewable energy, energy smart technologies, carbon, carbon capture and storage, renewable energy certificates, nuclear, power markets and water; founded by Michael Liebreich in 2004 and generating over $1 billion in profits in the last 12 months
- Suntech: Chinese company founded in 2001 by Dr Zhengrong Shi and floated on the NYSE in 2005; the world's largest producer of solar panels, with solar modules installed in over 80 countries (and a low-carbon museum in Wuxi, west of Shanghai, opened by Al Gore)

Source: "How green were their ventures", *Financial Times,* November 5, 2011.

3.1.2 Provide global technology-push support for BoP and neglected technologies

It is not advisable for countries with low technological capabilities and no comparative advantages in creating frontier technologies to be dedicating significant public resources to this objective within their own country. However, given the global nature of the benefits from green innovation, stable, long-term *global* public spending on R&D needs to increase and be channeled into programs that facilitate the development and adoption of technologies applicable to developing country contexts.

Prize funds are one relevant demand-pull mechanism to promote technologies at the global level for the needs of countries with lower technological capabilities, and for BoP and neglected needs. Typically, a pre-announced prize is given to whoever comes up with an innovation that meets defined objectives. Prize funds are most appropriate when objectives can be well defined but the technologies are unknown. The researcher only gets the guaranteed return, in principle more than sufficient to cover time and other resources spent, if the research is successful before that of rivals. Prizes can be designed to be paid out only when specific outcomes are delivered. The size of the prize and the number of prizes can be calibrated by the novelty and magnitude of contribution of the innovation. Like patents which are a form of prize, these more generic prizes are decentralized and based on self-selection. However, once the prize is awarded, developed knowledge can be made freely available, widely disseminated and used by all.[24] A proportional prize makes rewards proportional to the measured impact of any successful innovation, providing incentives to public and private sectors to generate evidence on the results of innovations, measured for instance by the degree of adoption and productivity improvement – though auditing and

[24] If the prize limits post-reward market competition, for example through exclusive marketing arrangements, then the full social benefits of competition that drive prices as close as possible to cost will not be realized.

verification costs can be relatively high.[25] Ideally, the award process should require revelation of information on the innovation so that it can then be broadly disseminated. Such prize funds are particularly relevant for promoting more radical green innovations that are likely to be fostered not through the traditional linear R&D approach but rather through out-of-the-box new knowledge involving co-creation and co-design by scientists, engineers, entrepreneurs, producers and users from different disciplines. Box 6 presents a few of the green prizes that have been set up over the past years.

Box 6. On prizes that seek to stimulate new solutions to green development challenges

Discussion of key lessons to-date of competitions such as:

- ***Ashden Awards for Sustainable Energy:*** annual awards set up in 2001 (linked to the UK Sainsbury Family Charitable Trusts) to reward local sustainable energy projects in the UK and in developing countries (including innovators at the household and local community levels), with currently a top prize of £ 40k and six prizes of £ 20k for developing countries, plus a broadcast-quality film about their work and a substantial post-award business support package
- ***i6 Green Challenge***: a new regionally-driven $12 million competition by the US Department of Commerce in partnership with the National Institutes of Health and National Science Foundation (run in 2010, it supported best ideas for green technology commercialization in six different regions of the US)
- ***Virgin Earth Challenge***: a $25 million prize launched in February 2007 by Virgin boss Richard Branson alongside former US VP Al Gore for an approach “to remove at least one billion tons of carbon per year from the atmosphere”; not yet claimed, highlighting that climate solutions can be both hard to find and verify
- ***Australia Climate Ready***: support for SMEs to develop green technologies through R&D and/or proof of concept and/or early-stage commercialization; features a hybrid policy design associating both prize awards and funding as an efficient way to stimulate innovation in the area of climate change

Advance Market Commitments (AMCs) are another demand-pull mechanism complementary to prizes. AMCs are most appropriate when key characteristics of the desired technology are known and can be specified in a contract. With AMCs or purchase guarantees, sponsoring international financial institutions, governments and/or private foundations make a legally-binding contractual commitment at a pre-specified price to purchase a given quantity of a qualifying product when that product becomes available on the market, without any winner-take-all requirement. According to a proposal by Barder, Kremer and Williams (2006), the AMC could be split; for example, a low-income country could commit some part of the purchase price and donors could make up the difference. The contracts may also include provisions requiring manufacturers to license their technology after the agreed-upon quantity had been purchased, or to sell further units at low prices.

In the first real-world pilot of this mechanism, a group of governments and private foundations in 2007 committed $1.5 billion for a Pneumococcal AMC. The pneumococcal vaccine was chosen because it has a large health impact, suitable vaccines for developing countries are already in development, and the AMC can speed the products to market.[26] Although AMCs have so far been applied to provide affordable

[25] On proportional prizes, see Masters (2008) and Elliott (2010).

[26] The Global Alliance for Vaccines and Immunization (GAVI), the World Bank, WHO, UNICEF, five national governments and the Bill & Melinda Gates Foundation signed the legal documents of the AMC pilot in June 2009. The new vaccine is sold at over $70 per dose but the AMC has set the long-term prices for developing countries at a price no higher than $3.50 per dose for 10 years. In March 2010, the first two manufacturers, GlaxoSmithKline and Pfizer, made commitments to supply new vaccines, and by mid-2011 the vaccine had been introduced in a number of Latin American and Sub-Saharan Africa countries. See Dutta, Dutz and Orszag (2011).

access to healthcare in low-income countries, the approach could be applied in a similar manner to stimulate innovations and widespread access to more affordable green solutions, such as a nutrient-fortified staple food crop or an improved storage technology in contexts of land and water scarcity, climate change, and declining crop yields.[27]

More generally, a strong case exists for a pool of long-term, stable funds for basic research on important frontier green innovation areas for developing countries, whether allocated through prizes, AMCs or other mechanisms.[28] Issues to be addressed include:

- most effective modalities for global research efforts on important topics for developing countries, including total amount of required global resources and resource allocation by areas of need and by geography (including best forms of engagement of R&D networks in developing countries), and how best to capture demand on what is most important to ensure the research is user-relevant;
- lessons from experience with encouraging development of more general purpose technologies (GPTs) such as ICT, materials, nanotech and biotech rather than spending on specific green policy areas, and on stimulating convergence across GPTs;
- the experience with institutional protections to avoid delivering subsidies to favored firms, industries and other organized interests – such as multi-year appropriations, agency independence in making grants, use of peer review with clear criteria for project selection, and payments based on progress and outputs rather than cost recovery;
- the extent of IFI coordination and assistance, given that direct support puts greater demands on government capabilities, which are typically weaker in developing countries.

Box 7. Lessons from ARPA-E, an example of US frontier innovation support that could provide a model for a global green innovation pool

- US Department of Energy's new Advanced Research Project Agency-Energy, authorized by the US Congress in 2007 with an initial funding of $400 million in 2009, is intended to support early stage radical energy technologies that are too high risk for private investors to adequately fund, modeled on DARPA (the central R&D organization for the US Department of Defense established in 1958 and responsible for technological breakthroughs such as stealth aircraft in the 1970s, unmanned aerial drones in the 1980s, and the Internet)
- Key elements of ARPA-E (and DARPA's) management strategy are to invest its funds at external organizations (with opportunities for rebuttal to reviewers' comments prior to funding decisions), primarily universities and industry, bringing in entrepreneurial program managers empowered to make quick decisions about starting, continuing or stopping research; and funding a variety of competing technologies while leaving the private sector to pick winners

3.2 Promoting catch-up innovation – facilitating technology access and stimulating technology absorption

Promotion of green growth for most developing countries is typically more about catch-up innovation and the diffusion of already-existing technologies than about frontier innovation. For all countries, the cost of not adopting, adapting and using existing green technologies can be high in terms of foregone greener

[27] See Elliott (2010) for a comparison of proportional prizes and AMCs, areas of agricultural innovation where AMCs may be useful, and issues involved in choosing a pilot AMC.
[28] See, among others, Arrow et al. (2009) and David (2009).

development. Consequently, facilitating access to environmentally-friendly technologies and stimulating their uptake are essential parts of an effective green growth strategy.[29] In most developing countries, there is significant scope for policy to remove existing distortions and address weaknesses in the business environment that impede private innovation, in particular adaptation and dissemination of technologies from more advanced countries and within developing countries from urban to rural areas, as well as strengthening the absorptive capacity of the domestic economy. Such policy efforts can cover a broad range, including adopting more open foreign trade, investment and technology licensing regimes, strengthening the country's metrology, testing and quality (MSTQ) facilities to support upgrading toward more energy-efficient technologies, improving the quality of and access to mobile phones, Internet and other communications networks, reducing domestic barriers to firm entry and exit, improving access to finance, strengthening skills and capacity development, and implementing more demand-side policies such as public procurement, regulations and standards. The section begins by surveying key policies to facilitate access to existing technologies, then discusses the critical set of supporting policies to stimulate their uptake, and concludes with a discussion of the relative effectiveness of supply-push versus demand-pull policies.

3.2.1 Facilitate access to green technologies

Openness to **international trade and FDI** are among the key factors correlated with adoption rates for technology. Many green technologies are embodied in imported capital goods, machinery and equipment; some are knowledge-based processes or business models and diffuse via movements of people attached to MNCs (multinational corporations) or from the diaspora; and some can be copied by studying imported final goods, or by studying patents (when elapsed) or inventing around them (when still effective). There is evidence that tariffs on renewable energy technologies and subsidies for fossil fuels do more to limit technology transfer of clean technologies than patent protection.[30] A recent study finds that eliminating tariff and non-tariff barriers in the top 18 developing countries ranked by GHG emissions would increase imports by 63 percent for energy-efficient lighting, 23 percent for wind power generation, 14 percent for solar power generation, and 4.6 percent for clean coal technology.[31] In a study of electric power plants in India, Khanna and Zilberman (2001) find that removing import barriers to higher-quality coal would increase the adoption of more energy-efficient technology and potentially decrease carbon emissions.

The **Clean Development Mechanism** (CDM) of the Kyoto Protocol is an explicit mechanism to boost technology transfer and diffusion, as it allows high-income countries to develop or finance GHG emissions reduction projects in developing countries in exchange for emission reduction credits. However, high-income country investments tend to be small when compared to FDI. Based on an analysis of GHG mitigation technology transfers, Dechezleprêtre et al. (2008) show that international transfers have taken place in less than half of the CDM projects, typically combining transfer of equipment with knowledge and operating skills. They also find that most technology transfers concerned end-of-pipe destruction of GHGs in chemical, agricultural and waste management industries (highly specialized, with

[29] See Lanjouw and Mody (1996) and Popp (2006) who both find that access to foreign available knowledge is necessary but not sufficient for local use, with foreign knowledge typically serving as a blueprint and further adaptive R&D required to fit the technology to local markets.
[30] See Copenhagen Economics (2009) and Barton (2007) as cited by Hall and Helmers (2010).
[31] See Table 3.2, World Bank (2008); the assessment is based on first-round approximations rather than full general equilibrium effects.

very little spillover to greening in the broader economy), and wind power. Other projects such as electricity production from biomass or energy-efficiency measures in manufacturing mainly rely on local technologies.[32] In principle, there is an ambiguous relationship between local absorptive capacity and international technology transfer: while high technological capabilities may be required to adopt new technologies, high capabilities also could imply that many technologies are already available locally thereby reducing the likelihood of international transfer. They find that the first effect strongly dominates in the energy and chemical industries, while the second effect dominates for agricultural projects (suggesting that agricultural technologies transferred tend to be simpler). Their findings (2008, 2009) highlight the importance of local capacity building as a means to accelerate technology diffusion – with a strong push by local/municipal governments to strengthen technology capabilities facilitating both the importation of foreign technology and the local diffusion of domestic technologies.

Additional mechanisms to foster increased access to existing technologies include patent buy-outs, compulsory licenses, patent pools and open source approaches. A **patent buy-out**, as outlined by Kremer (1998), is a mechanism to increase access to existing products, or to future products that already benefit from adequate innovation incentives. The idea behind patent buy-outs is that a purchaser –for instance, an international financial institution, government or private foundation– acquires exclusive marketing rights for a patented global green product from the patent owner and offers a non-exclusive, no royalty license to any legitimate generic manufacturer to sell the product in certain target developing country markets. The patent owner is compensated under a buy-out formula. Generic pricing through multiple manufacturers prevails in the target developing countries. Regular patent-based pricing remains in all other countries. The key problems with buy-outs are the development of a mechanism to determine the buy-out price and the availability of a purchaser of the patent at the determined price.[33] Providing more scope for **compulsory licenses** by making it easier for countries to issue them is another complementary way to reduce some of the inefficiencies associated with the current patent system, and ensure more affordable access to patented green innovations by poorer households in low-income countries.[34]

In a **patent pool**, a group of patent holders agree to license a combined set of patents to one another (a closed pool) or to any party (an open pool). Patent pools have been proposed as a solution for inefficiencies that arise in the patent system when too many related fragments of patents are necessary to develop future inventions.[35] As an illustration of a concrete initiative on this front in the context of developing country needs, the international drug-purchasing facility UNITAID agreed to provide funding for a Medicines Patent Pool, which was then established as a Swiss foundation in July 2010 to focus on increasing access to HIV medicines in developing countries. It provides a 'one-stop shop' voluntary licensing service that pools multiple patents and licenses them, with patent holders getting royalties on the

[32] They analyze the 644 CMD projects registered up to May 2007. About 75% of the projects have taken place in Brazil, China, India and Mexico.
[33] Outterson (2006) and others have proposed methods to determine this price.
[34] Henry and Stiglitz (2010) document how the US used the threat of a compulsory license to manufacture Cipro during the anthrax scare following 9/11, and how it overrode patent rights and forced the formation of patent pools to further develop the airplane during WWII, concluding that "what the war against Germany or Japan required, the war against climate change might as well" (p. 245). Canada used compulsory licenses mainly for dealing with health requirements.
[35] See Shapiro (2000) for a discussion on the efficiency-increasing properties of patent pools. Empirical evidence on this issue is provided by Lerner et al (2003), who found that patents were cited more often after being included in a pool, suggesting that patent pools encourage the diffusion of technology.

sales of adapted more affordable generic medicines, and generic manufacturers getting access to broader markets.[36] A similar approach could be used for neglected seeds for drought-prone, saline environments, or for other patented green solutions for lower-income countries.

Generally broader in scope than a patent pool, **patent commons** allow technology holders to pledge their patents for widespread use for no royalty payment. In January 2008, the not-for-profit Eco-Patent Commons initiative was created by a few large MNC patent holders in cooperation with the World Business Council for Sustainable Development. As of mid-2011, over 100 patents have been pledged by 13 participating MNCs, with all pledged patents automatically licensed royalty-free provided they are used in a product or process that produces some environmental benefit. Based on a recent analysis by Hall and Helmers (2011), pledged patents do appear to be climate-change related, though more in the form of environmental clean-up or clean manufacturing. However, evidence to-date suggests that there has been no discernible impact on the diffusion of the knowledge embedded in the protected technologies to other patenting firms. A related development on this front is **open source** innovation, where a body of original information or technology platform is made publicly available for others to use and adapt. The Open Source Drug Discovery (OSDD) initiative launched by India's Council of Scientific and Industrial Research (CSIR) in September 2008 is one such platform. OSDD is a public-private partnership between industry and academia in open source mode, with the purpose of hastening the discovery of drugs for neglected diseases through collaborative exchange of information. Again, a similar approach could be used for neglected green innovation needs for lower-income countries. Box 8 highlights a multilateral mechanism for broader dissemination of biodiversity.

Box 8. Access and Benefit-Sharing and the Nagoya Protocol

Genetic resources (from plants, animals, or micro-organisms) are used in a wide range of activities, either for basic research or for product development. Moreover, the traditional knowledge associated with them and coming from indigenous and local communities provides valuable information for their potential future use in medicines or cosmetics, among others. The "fair and equitable sharing of the benefits arising out of the utilization of genetic resources" or Access and Benefit-Sharing (ABS) is one of the three overarching objectives of the Convention on Biological Biodiversity (CBD), together with the conservation of biodiversity and the sustainable use of its components. However, a lot of uncertainty has always remained as to the practical implementation of ABS.

The Nagoya Protocol (NP) on Access and Benefit-Sharing is an international treaty which aims to develop greater legal certainty as well as transparency for providers and users of genetic resources. The NP covers the use of genetic resources (covered by the CBD) and the traditional knowledge which is associated with it. Its objective is for both parties to acknowledge and respect their reciprocal obligations. Hence, the biodiversity-rich party must facilitate access to its resources on the one hand (through the establishment of clear rules and procedures, the issuance of permits when access is granted, etc.) and reciprocally, the user of genetic resource must commit contractually to ensure an equitable sharing of the benefits accruing from the utilization of this resource, as well as its subsequent utilization. Examples of benefit-sharing include: payment of royalties, preferential access for the provider country to any medicine deriving from the genetic resources (and associated traditional knowledge), joint ownership of intellectual property rights, collaborative research, etc.

Source: http://www.cbd.int/abs/about/

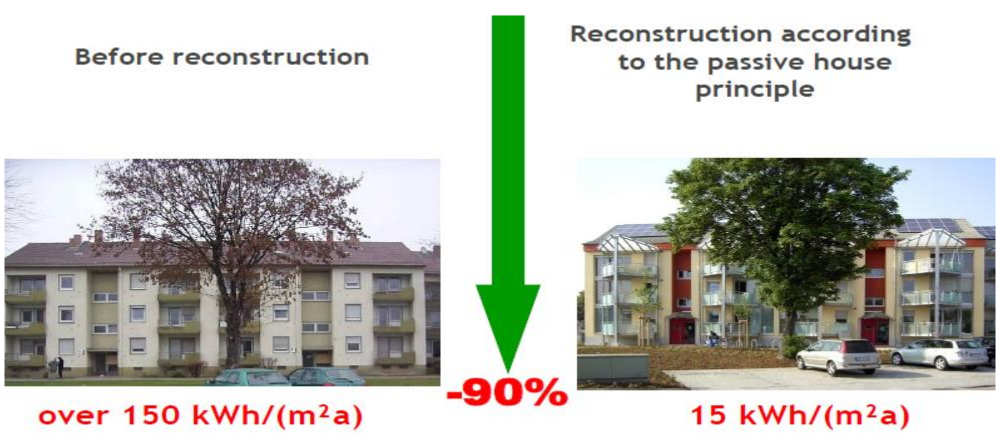
[36] The Medicines Patent Pool secured its first license with the US National Institutes of Health in September 2010, its second license agreement with the pharmaceutical company Gilead Sciences in July 2011, and is in negotiations with six other HIV medicines patent holders.

3.2.2 Stimulate absorption of green technologies

Absent environmental social costs being fully reflected in market prices, demand-side innovation policies including **public procurement, regulations and standards**, together with effective enforcement, are typically needed to stimulate both creation and diffusion of green technologies. They include guaranteed feed-in tariffs for renewables, taxes and tradable permits for emissions pollution, tax credits and rebates for consumers of new technologies (e.g. for compact fluorescent light bulbs), comparison labeling (to inform consumers about the relative efficiency of products), endorsement labeling (e.g. 'CFC-free'), government rules (e.g. limits to polluting emissions from industrial plants), and industry-driven standards (e.g. home and office building insulation). Because they can be such an important pre-condition to the diffusion and absorption of green technologies in developing countries, they are treated in this section. In contrast to most technologies which are adopted because they are inherently cost-reducing or revenue-enhancing to firms, green technologies are often more costly to adopt by firms and not immediately more attractive to end-use customers. Hence these demand-side policies are needed to provide a critical incentive to trigger their adoption. Inventors will not develop and firms will not adopt technologies for which there is insufficient demand. Box 9 provides an illustration of a standard for very low energy building standards in the Czech Republic, with 90 percent energy savings for required combined heating and cooling after reconstruction according to the standards.

Box 9. Energy savings through low energy (passive house) building standards

The concept of passive solar building design dates back to antiquity, reducing a building's ecological footprint. According to the Czech low energy voluntary building standard, and in line with similar standards adopted in Austria, Belgium, Denmark, Finland, France, Germany and the UK (with Luxembourg, Romania, Slovak Republic and Sweden planning to adopt similar standards), the 'passive house' standard requires that the building be designed to have an annual combined heating and cooling demand of not more than 15 kWh per square meter per year. Passive house technologies typically include solar heating to heat and lighten the space naturally, super glazing of windows and an airtight building envelope, without a need for a conventional heating or cooling system; the air is fresh and very clean, and the inside temperature is homogeneous. As of August 2010, there were approximately 25,000 such certified structures of all types in Europe, including residential and office buildings, schools, kindergartens and supermarkets, applying to new buildings and refurbishments. The illustrated refurbished apartment building has achieved 90 percent energy savings by being re-constructed to the standard.



Support policies included:

- Publicly-funded pilot demonstration projects, instrumental in proving technical and economic feasibility so that the private market could then develop; the role of the public sector as early adopter was also crucial.
- Certification/labeling of low energy buildings and trained professionals, to promote confidence of consumers, control costs, and promote the uptake of low-energy buildings.
- The CEPH (Certified European Passive House Designer) project, a pilot training course for certified house designers, already implemented in nine EU countries: architects, construction engineers and building designers received a "train the trainers" course and certificate, in order to then help train all operators in the construction chain, from academia and R&D to builders, contractors, real estate agents, and homeowners.

Several EU countries have already set up long-term strategies and targets for achieving low-energy standards for all new houses:

- in the Netherlands, there is a voluntary agreement with industry to have energy neutral buildings by 2020
- in the UK, the ambition is to have zero carbon homes by 2016
- in France all new buildings should be energy-positive (produce energy) by 2020
- in Germany, soft interest-free loans during the first years up to Euro 75,000 are available both for renovations and new constructions

Source: EU (2009), Barta (2006).

Improving a country's **financial infrastructure** also can have significant effects on green growth by, among others, providing funding for adopting green infrastructure, and enabling farmers to adopt higher-return technologies that both decrease crop losses and decrease vulnerability to the losses (Box 10). Barry et al. (2011) examine the adoption of efficient stoves, biogas plants and tobacco barns by commercial farmers in Malawi, Rwanda and Tanzania; financing was cited as the main stumbling block for all projects because of high start-up costs. Brunschweiler (2010) finds across a range of low-income countries that an increase in financial intermediation has a significant effect on non-hydro renewable energy generation per capita, because investment in renewable energy is constrained in environments where access to long-term loans is limited. And D'Agostino et al. (2011) find that access to financial credit is an important barrier to solar home systems adoption in China.[37] Echoing this theme of the important supporting role of bank financing, Wolf (2011) explains how the largely bank-based, relationship-based financial systems played a key role in supporting the lower-risk technology absorption by firms during the reconstruction of continental Europe after World War II and in the subsequent years when income convergence was the main challenge.

Box 10. Micro-insurance for drought adaptation by subsistence farmers in Malawi

Improving financial insurance instruments by bundling index-based drought insurance with credit has enabled farmers to adopt higher-return technologies, contributing both to climate-change adaptation (reducing crop losses from more frequent drought-flood spells) and to decreasing vulnerability to climate-change impacts.

Malawi farmers face food security threats from their high exposure to weather risk, with about 80% of the population depending on rain-fed subsistence agriculture. A critical obstacle to adopting better technologies is poorly-functioning financial services markets – with banks unable to manage covariant drought and other risks that affect whole regions at the same time. Lack of affordable credit by smallholder farms has prevented access to more expensive, higher-yield seeds.

In contrast to traditional crop insurance, index-based insurance makes pre-specified payouts contingent not on the loss itself but on a physical trigger linked to the event causing the loss, such as rainfall measured at a local weather station. Advantages include: (i) lower administration costs for payouts and less scope for corruption (as

[37] See Popp (2011) for an overview of these three different case studies linking access to finance to successful technology adoption.

payments are triggered by recorded weather data rather than expensive claims-handling of crop damage in multiple small farms); (ii) no moral hazard (as payouts are independent of farmers' practices); (iii) no adverse selection or over-representation of high-risk insured in the pool (as there is a balance of information about the weather on part of insurer and insured). A pilot scheme during the 2005-06 season that bundled bank loans with the insurance (so that farmers could pay for both the premium and high-yield seeds) demonstrated that the scheme could operate without ongoing subsidies (after the mechanism was set in place and start-up expenses were covered by the government). The scheme decreased crop losses by offering incentives to change cultivation practices to become more resistant to drought. And it decreased vulnerability by increasing productivity in good seasons: with a doubling of their cash crop in good seasons, famers were able to save, both raising and smoothing their income over time.

The experience highlights the importance of absorptive capacity at the individual level. A survey revealed that only 55% of farmers reported understanding the scheme before joining it, highlighting the need to substantially improve communication and education. The survey also revealed a lack of trust among farmers in the weather station measurements, highlighting the importance of institutional trust as a challenge in scaling up operations.
Source: Kunreuther and Michel-Kerman (2011) and Suarez and Linnerooth-Bayer (2010).

Finally, three issues are particularly relevant for developing countries. First, as global green technologies improve, the **falling costs of adoption** relative to existing non-green technologies facilitate their adoption by firms. They also lower the costs of adopting the relevant environmental regulation by governments. In their study of the adoption of regulations limiting emissions of nitrogen oxides (NOX) and sulfur dioxide (SO2) at coal-fired plants across 39 developed and developing countries, Lovely and Popp (2011) show that countries adopting these regulations at later dates do so at lower levels of per capita income than adopters who enacted similar regulations earlier. The availability of the technology at lower cost should help shape the regulation that is required as incentive for firms in lower income countries to adopt it.

The second issue concerns the potential **longer-run benefit of well-designed environmental regulation** in enhancing innovation and competitiveness, and the extent to which benefits may more than fully offset the cost of the regulation.[38] Especially in less mature markets characterized by inadequate physical and institutional business infrastructure prevalent in many developing countries, firms may miss profitable green investment opportunities because they are too risky, too costly for the manager, or out of the manager's habits, routines and technical expertise. By making these investments more profitable or requiring them, environmental regulations can help the manager overcome these problems. In line with this view, Alpay et al. (2002) estimate the productivity of the Mexican food-processing industry to be increasing with the pressure of environmental regulation. And in a sample of 17 Quebec manufacturing sectors, Lanoie et al. (2008) have found that stricter regulations led to modest long-term gains in productivity – first reducing productivity in year one, having a slightly positive effect in year two, and then resulting in more positive outcomes in years three and four, more than offsetting the first year's loss. Most empirical studies of the impact of well-designed environmental regulations in high-income countries have found that they stimulate innovation by firms as measured by R&D spending or patents. However, there is relatively little overall evidence to-date that the induced innovation is sufficient to overcome the added costs of regulation, with 10 of 13 studies surveyed by Ambec et al. (2011) finding that the net effect of environment regulation on productivity or profitability is negative. In terms of design of

[38] This view has come to be known as the Porter hypothesis, based on an initial statement that strict environmental regulations do not inevitably hinder competitive advantage against rivals but can often enhance it, at least in the long run (Porter 1991), and a subsequent set of case studies (Porter and van der Linde 1995). See Ambec et al. (2011) for a review of the literature.

environmental regulations, the literature emphasizes that policies should strive to be win-win compatible, in particular focusing on end results rather than means, and be stable and predictable.

A third issue concerns the use of emerging **international sustainability standards** for products and processes as an instrument in helping local firms upgrade their environmental practices, a form of catch-up innovation for business practices.[39] The linking of local firms to the global value chains of MNCs that have adopted sustainability standards helps leverage international market pressures for environmental improvement. Box 11 provides an illustration of how the South African deep-sea hake industry was able to anchor more sustainable local fishing practices through its association with an international standards organization.

Box 11. South African deep-sea fishing

A highly visible and credible product certification that deep-sea hake fishing was sustainably managed by the international non-governmental standards organization, the Marine Stewardship Council (MSC), constrained local regulators in South Africa from allowing excessive entry of fishermen (which would have depleted stocks). It led to restructuring of the equity structures of existing companies to meet Black Economic Empowerment goals.

Other related examples of international sustainability standards include the Forest Stewardship Council (a joint initiative of firms and NGOs with principles for sustainable forestry to which participating firms must adhere, with accredited private auditing agencies to monitor and certify firms' compliance, and compliant firms using the FSC seal to differentiate their products to create a price premium), the Fairtrade Labeling Organizations Alliance (FLO), and the Rainforest Alliance. These four alliances and few others formed the ISEAL Alliance in 2002 as the global association for social and environmental standards, supported by certification and compliance mechanisms.

Source: Levy et al. (2011) and Levy (2011).

3.2.3 The relative effectiveness of supply-push versus demand-pull policies

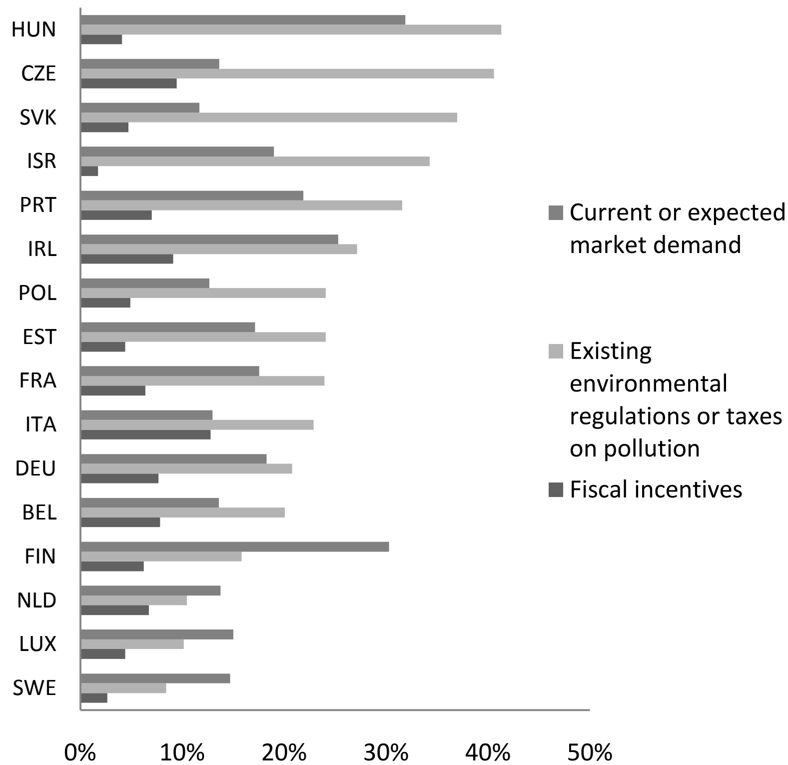
As suggested in Figure 1, different mixes of policy instruments are likely to be effective for countries at different stages of technological sophistication. Some recent empirical evidence suggests that a greater emphasis on targeted supply-push government R&D funding, when local technological capabilities are in place, is more effective than demand-pull policies[40] at generating radical, new-to-the-world frontier innovations. This evidence is based on patent applications filed worldwide from 1994 to 2005 in wind power technology: the marginal million dollars spent on public support to R&D (mostly tax credits on private R&D expenditures received by companies once expenditures have been incurred) generated 0.82 new inventions whereas the same amount spent on demand-pull policies induced at best 0.06 new inventions (Dechezlepretre and Glachant, 2011). A separate case study to assess the extent to which

[39] The Cement Sustainability Initiative, initially created in 2002 by ten of the largest cement manufacturers, has expanded to include 23 major cement producers operating in more than 100 countries. The CSI, among others, identifies actions and facilitates steps for cement companies to accelerate progress towards sustainable development (such as lower GHG-emitting and more energy-efficient processes), and foster greater stakeholder involvement. CSI includes developing country companies such as Argos (Colombia), CEMEX (Mexico), Cimentos Liz, InterCement and Votorantim (Brazil), China Resources Cement Holdings Ltd, CNBM, Sinoma, Tianrui Group and Yatai Group (China), Shree Cement and Ultratech Cement (India), and Siam Cement Group (Thailand).

[40] Namely, deployment policies such as guaranteed feed-in tariffs, production tax credits, and obligations on electricity supply companies to produce a specified fraction of their power from renewable energy sources.

demand-pull policies stimulated non-incremental (radical) change in the California wind power industry in the 1975-1991 period also finds no evidence that demand-side policies alone encouraged more radical frontier-type technical change (Nemet, 2009).

Figure 9. Motivation of firms introducing environmental innovations, 2006-08
(*Firms citing factors as motivations, percentage of innovative firms)*

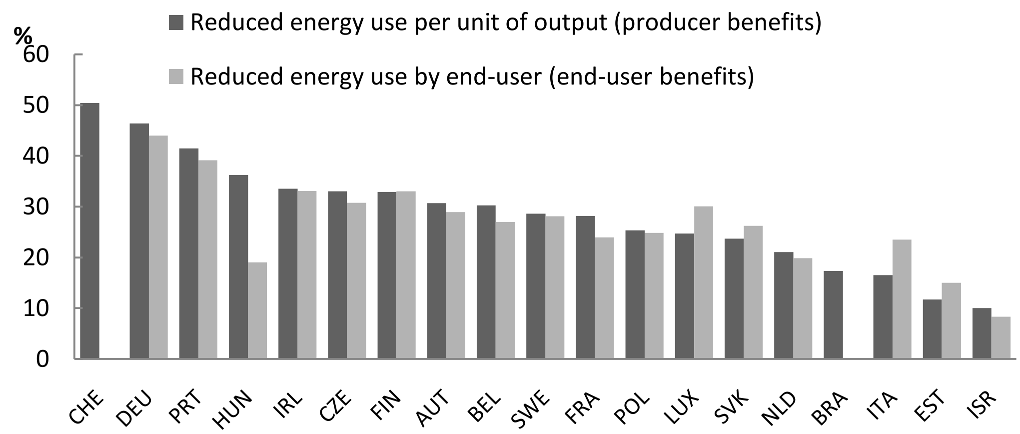


Source: OECD, based on Eurostat (CIS-2008) and national data sources, June 2011.
Note: The Community Innovation Survey (CIS-2008) was the first to introduce a voluntary module on environmental innovation. An 'environmental innovation' is defined as an innovation that leads to more environmental benefits than alternatives. The environmental benefits can be the primary objective or the result of other innovation objectives. 'Innovative firms' refers to firms with any of the four types of innovation (product, process, organizational and marketing).

However, for technologies that are more mature, a greater emphasis on demand-side policies may be more effective in spurring firms to introduce more incremental innovations. Based on firm responses in 16 countries as part of the 2008 EU Community Innovation Surveys, Figure 9 shows that existing or future environmental regulations, followed by market demand from customers, are identified by firms in most countries as the main driver of introducing environmental innovations. The availability of direct public support in the form of fiscal incentives is the least important reported motivation in all countries. Figure 10 highlights the reported benefits of environmental innovations (from the same survey). Interestingly, in most countries surveyed (15 of 19 for this question), a larger percentage of innovative firms perceive the environmental benefits of innovation to be on the cost side (in terms of reduced energy use per unit of output) than on the revenue side (in terms of customers being willing to pay more for new products that reduce energy usage by end-users). This suggests that most of these innovations are likely to be incremental process rather than more radical product innovations.

Thus, it appears that a greater emphasis on supply-side policies may be more effective in stimulating more radical frontier innovation when local capabilities are in place, a greater emphasis on demand-side policies may be more effective in spurring firms to introduce incremental environmental innovations (both frontier and catch-up). The available evidence does not contradict a judicious combination of supply-side and demand-side policies, appropriate to the local context.

Figure 10. Benefits of environmental innovations, 2006-08
(*As a percentage of innovative firms*)



Source: OECD, based on Eurostat (CIS-2008) and national data sources, June 2011.

3.3 Developing absorptive capacity

At the level of the firm, the ability to 'learn' is seen as essential for innovation. Firm learning or 'absorptive capacity' refers to a firm's ability to understand, adapt and use technologies. According to Cohen and Levinthal (1989), a firm's learning capacity is enhanced by its R&D activities, so that R&D has important roles in both frontier and catch-up innovation.

Griffith, Redding, and Van Reenen (2004) find empirical support in a panel of industries across 12 OECD countries for these "two faces of R&D", this notion that R&D, in addition to stimulating the generation of new frontier technologies, also improves the firm's ability to globally search for and adapt existing technologies, and allows firms to more easily understand and assimilate the discoveries of others. Interestingly, they find that countries further from the technological frontier have higher rates of return to R&D than those at the frontier, due to the enhanced learning that R&D facilitates.[41] If returns to R&D rise for countries further from the frontier, then why don't low-income developing countries that are further from the frontier than the OECD countries in the study invest even more in R&D? One explanation of why returns to R&D don't keep rising in developing countries, and in fact fall significantly below those of the frontier countries, is that the business environment worsens typically as countries get further from the frontier, so that the general accumulation of all assets (including intangible knowledge assets) worsens. Faced with worse incentives for productive entrepreneurship, even the best ideas yield lower

[41] While the US, typically at the technological frontier, had a rate of return to R&D of 57% with R&D's contribution to TFP growth largely due to innovation, Finland had a rate of return of 105% with less than half the estimated effect due to innovation and enhanced learning (absorptive capacity) quantitatively more important.

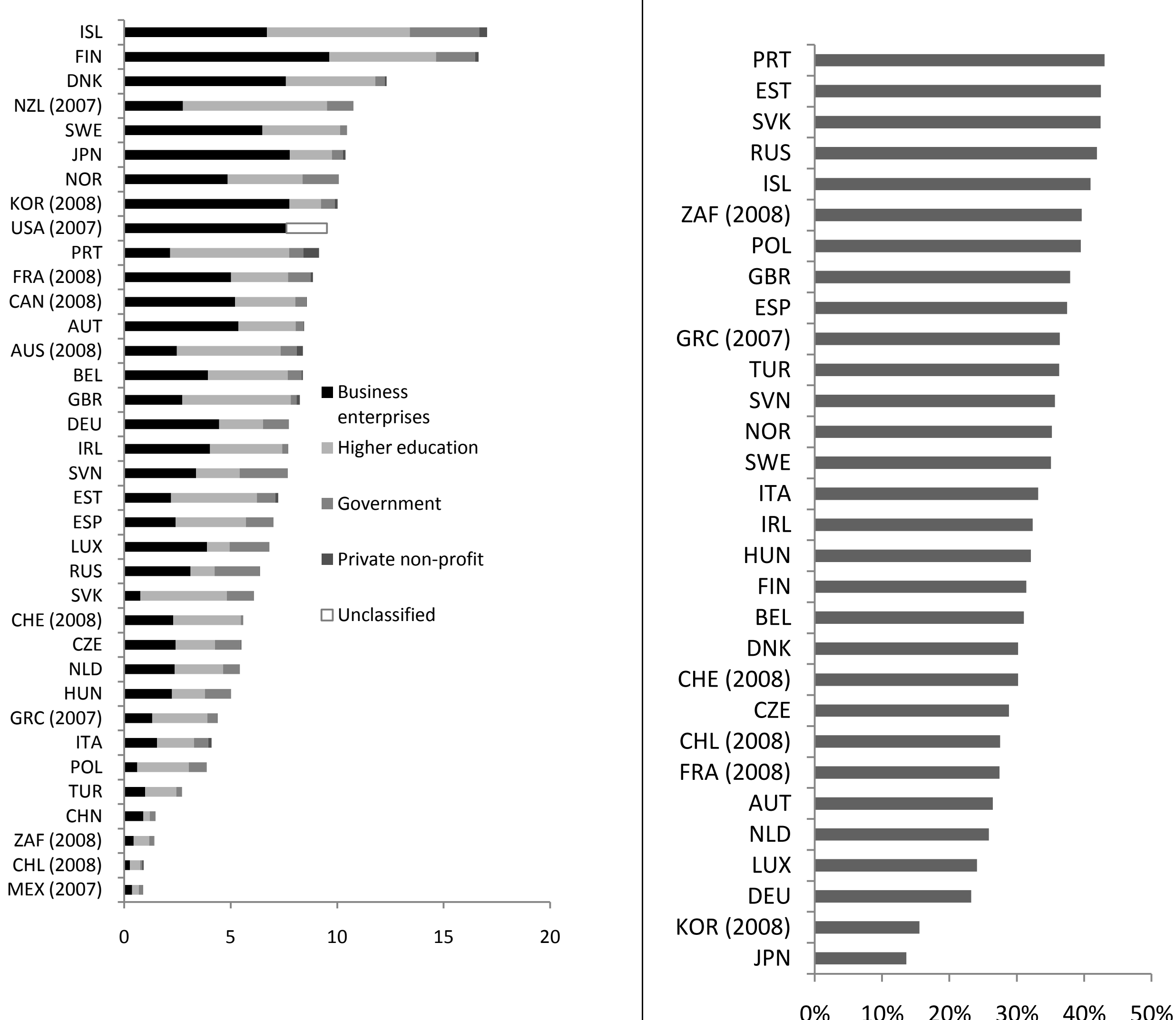
returns – if they are allowed to come to fruition at all. Moreover, progressively weaker human capital in both public and private sectors may result in lower returns (fewer good ideas) from a given amount of R&D investment (Goni, Lederman and Maloney, 2011). The section begins by examining the need for strengthening skills to address this key constraint to the accumulation of knowledge, and then discusses a few policies to address the more general business environment constraints impeding experimentation, global learning, and talent attraction and retention.

3.3.1 Strengthen education and skills for green innovation

Figure 11. Number of Researchers

A. Researchers by R&D performing sector, 2009
(Per thousand total employment in the economy)

B. % Researchers who are Female



Source: OECD, Main Science and Technology Indicators Database, June 2011.

Green innovation, like innovation in general, depends on people who are able to generate and apply knowledge in the workplace and society at large. Required innovation skills include basic skills such as reading and writing, technical skills such as science and engineering, generic skills such as problem solving, multicultural openness and leadership, managerial and entrepreneurial skills, as well as creativity and design skills. It has been recently proposed that the green economy requires a greater emphasis on design and multidisciplinary teamwork, on strategic leadership and adaptability as important generic skills, and on a good knowledge of the sciences (OECD 2011e and CEDEFOP 2009).

Figure 11 highlights how far behind most advanced developing countries are from the more developed countries, based on the relative number of professionals engaged in the creation of knowledge and in the management of research projects. While the five surveyed high-income Nordic countries (Denmark, Finland, Iceland, Norway and Sweden), Japan, Korea and New Zealand each employed more than ten researchers per 1,000 employees, advanced developing countries are at the bottom of the table, with China, South Africa, Chile and Mexico each having less than two researchers per 1,000 employees. It is noteworthy, however, that the 10 developing countries included in these data have a higher average percentage of women researchers (37%) than the 22 high-income countries (31%).

Across countries, the share of business researchers in the national totals varies widely: while in the US four out of five researchers work in businesses, the intensity of business researchers is again lowest in emerging developing countries, with Chile, Mexico, South Africa, Poland, the Slovak Republic, China and Turkey all having less than one researcher per 1,000 employees in industry. In these countries, the business sector plays a much smaller role in the national R&D system than the higher education and government sectors, which is a characteristic of most other developing countries as well. If developing country firms are going to effectively play a greater role in accessing existing green technologies and adapting them for local use, they will need more individuals with research and related creativity skills in the workforce.[42] So a major effort will be required to strengthen market signals so that tertiary education institutions and technical and vocational education and training (TVET) systems are better attuned to the demands of firms and what users need, including through increased involvement of the business sector in curriculum development. Ensuring that skills upgrading costs are shared among students, employers and the government in line with benefits, and adopting periodic national independent and transparent assessments to ensure quality and consistency, will help to signal the merits of different skills development options and promote adaptation in line with evolving market demands (OECD 2009). Box 12 provides an illustration of the challenges of building relevant skills in developing country settings. It highlights the need to have sufficient local capabilities in place to attract back home scientists trained in better-equipped high-income country universities, and the need to ensure sufficient local demand for established scientific and research facilities.

Box 12: African Monsoon Multidisciplinary Analyses (AMMA)

The West Africa region is particularly vulnerable to weather and climate variability due to dependence on rain-fed agriculture on which 80% of Sahel's population depends

To achieve its objective of monitoring West African monsoon variability and society-environment-climate impacts, the AMMA community (an international community established in 2002 of over 600 people from 30

[42] An important unresolved issue here is the extent to which skills are substitutable between green and non-green technologies, as there is an opportunity cost of investing in the skills sets and training for green to the extent that non-green innovations do not occur as a result of skewing capacity building towards greener technologies.

countries, including 250 in Africa with 80 African PhD students, funded by agencies from Africa, the EU, France, UK and US) established local university research programs in climatology, agronomy and related social science fields, and built functional and research teams that built new capacity for improved early-warning systems. These research teams and university programs will in turn continue to train cohorts of African specialists, thereby cultivating a community whose mutual interest in AMMA-related issues will help ensure sustainability.

Although AMMA has been relatively successful in building an international community in partnership with Africans in its first phase (2002-10), the main challenge moving forward in its second phase (2010-20) is to stimulate and ensure sufficient two-way conversations between what users need and what science is capable of doing, in particular generating sufficient downstream demand for improved forecasting and early-warning systems in terms of pull-through of knowledge by users making decisions on the ground: by farmers in terms of when to plan, by hydropower and flood managers in terms of operation of dams, by healthcare side in terms of diseases driven by dust (meningitis) and mosquitoes (malaria, etc.) – in this way, with stronger downstream user demand, the support by politicians for required scientific resources would be more likely.

Source: Thorncroft (2011).

3.3.2 Develop broader absorptive capacities

Three policy areas are discussed here that may be particularly important in most developing countries in affecting the ability of entrepreneurs and firms to learn, namely how the prevailing business environment can facilitate experimentation and quick market re-entry following failure, facilitate collaborative learning by workers and firms from leading global firms, and help attract and retain talent.

Policies to **overcome the stigma of failure** and encourage opportunities for re-entry and renewed experimentation seem to be important drivers of innovation. The US approach to corporate bankruptcy puts economic resources back to productive use as quickly as possible, either saving viable companies from premature liquidation or putting pressure on courts to restructure assets quickly.[43] While closing a terminally ill business takes less than 10 months and allows over 90 cents on the dollar to be recovered in Canada or Singapore, it still takes on average 7 years in Mumbai to recover roughly 16 cents on the dollar (World Bank 2011). Although difficult legal reforms and changes in attitude to debt are involved, making it easier to wind up businesses is one of the best ways to get more people to try out new ideas and start them. In addition, it would probably also be helpful to make existing innovative role models more widely known, such as India’s Tata group awarding an annual prize for the best failed idea.[44] So would policies that reduce the level of sunk costs required to try out a commercializable idea in the first place. This includes improving the depth of resale markets, so that fixed assets such as the machines in a production line that didn’t work out can be quickly and easily resold. And removing impediments for electricity and IT-serviced business premises to be easily leased or rented rather than requiring more significant investments in own assets while the market size for a product is not yet known.

Facilitating **global connectivity** of people through global alliances and insertion of firms into global value chains also is critical for enhanced learning. In both China and India’s rapid development of wind energy capabilities, while licensing agreements with European manufacturers to gain initial access to turbine technology were important, international mobility of workers was as important if not more so: Suzlon, the top Indian wind turbine manufacturer, established R&D facilities in Germany and the

[43] Chrysler and GM were in hands of changed owners in 45 days of filing for bankruptcy.
[44] See the Schumpeter column in The Economist (April 14, 2011).

Netherlands to have its workers learn from global expertise, while Goldwind, the top Chinese manufacturer, sent workers abroad for training.[45] Fibrovent Wind, a Chilean wind turbine blade start-up that was created by inserting itself into a Spanish global value chain, also benefited from international mobility of skilled workers: in addition to South-South transfer of equipment knowledge, there was transfer of management knowledge when a Brazilian wind turbine expert was hired to help set up the company. There was also knowledge transfer about composite materials from the Chilean mining industry, highlighting the importance of local absorptive capacity in effective technology transfer.[46] Learning networks also appear to have been critical in the development of China's photovoltaic (PV) industry: of the top 9 PV producers, only three received FDI while all firms exchanged knowledge with equipment suppliers and benefited from training sessions of engineers and technicians.[47] Finally, a recent public-private partnership program —that uses large MNC 'anchor' companies to solicit SME participation and provides education to increase productivity, competitiveness and environmental performance— appears to offer a promising model for diffusing eco-efficiency techniques to SMEs: during the 2005-07 pilot phase of Mexico's Green Supply Chains Program, 14 MNCs with operations in Mexico participated together with 146 SMEs, with the average SME participant generating environmental improvements of reduced water and electricity usage, carbon dioxide emissions and waste disposal, as well as sizeable economic savings, together with improved supply chain relationships.[48] The impressive results suggest the presence of win-win opportunities for eco-efficiency projects to both save money and reduce environmental damages, no doubt driven by unexploited benefits from improved information dissemination, mentoring and learning.

A final policy area ripe for joint national and local policy reforms in coordination with the private sector is the **urban dimension of entrepreneurship development**, namely enhancement of the livability and "stickiness" of cities, to attract and retain talent.[49] The shift in population as workers move from rural agriculture to urban areas that facilitate face-to-face learning and creative interactions between young entrepreneurs, skilled people, and institutions connected to global knowledge should help unleash innovation (Glaeser, 2011). Dense urban-industrial cluster agglomerations have been vital for

[45] See Popp (2011), who highlights the work of Lewis (2007) documenting how China and India went from no wind turbine manufacturing capacity to almost-complete local production in less than 10 years. Sauter and Watson (2008) present this as a case study of 'environmental leapfrogging', highlighting how the adoption of cutting-edge technologies was facilitated by the creation of learning networks.

[46] See Popp (2011) and the underlying the analysis of technology transfer in the development of the Chilean wind industry in Pueyo et al. (2011).

[47] See Popp (2011) who highlights international mobility of workers as a more important source of information than FDI or licensing, and de la Tour et al. (2011) for the underlying analysis.

[48] The initiative was led by the NAFTA-established Commission for Environmental Cooperation, and included the environmental authority of the state of Queretaro and the Global Environmental Management Initiative non-profit organization of leading US MNCs focused on environmental sustainability. It is a 10-week eco-efficiency educational training program emphasizing learning-by-doing with a commitment by participating SMEs to generate and implement pollution-prevention projects, with recommendations for change made by the participants themselves. Investments related to the implementation of the improvement projects were provided by the individual SMEs, who became convinced of their value. Lyon and van Hoof (2010) found that the average SME participant generated a project with NPV of over $150,000, saved 1,900 cubic meters of water each year, saved 42,000 Kwh/year of electricity, reduced carbon dioxide emissions by 61 tons/year and cut waste disposal by 1,455 tons.

[49] International experience suggests that much of the absorption of existing frontier technologies and the nurturing of technological advances are likely to be concentrated in a few metropolitan regions. Half of the productivity growth recorded by the US between 2000 and 2008 was by 20 metropolitan areas, with these cities accounting for 40% of GDP (McKinsey 2011).

technological upgrading and productivity growth by opening opportunities and stimulating supplies of capital and skills. China's establishment of special economic zones, followed by a range of support by national and local governments for further industrial deepening in its three major urban/industrial agglomerations (the Pearl River Delta centered on Shenzhen, Dongguan and Foshan, the Yangtze River region around the Shanghai-Suzhou axis, and the Bohai region in the vicinity of Beijing and Tianjin) and in a number of inland cities (including the footwear cluster in Chengdu and the Wuhan opto-electronics cluster) highlights how a mix of instruments can be employed together, including support to science parks and extension services, encouragement of local universities to deepen industrial linkages, attracting a major local or foreign anchor firm that can trigger the in-migration of suppliers and imitators, and above all dense transport and communication connectivity infrastructure (Yusuf, Nabeshima and Yamashita 2008).

4 OUTSTANDING ISSUES

Looking forward, there remains an important policy research agenda to better understand both evolving patterns of green innovation and the relative effectiveness of appropriate mixes of policies in different technological and institutional contexts.

Regarding patterns of green innovation, there is need for better data collection on green innovation. In particular, there is no direct evidence on adoption and adaptation of green technologies. There are almost no data measuring BoP green innovations to meet the needs of poor consumers. Firm-level surveys could be a good source to better understand what is taking place on the ground, with the recent EU Community Innovation green module a good starting point for more systematic inquiry across developing countries. More generally, it would be useful to better monitor public and private inputs being devoted to green innovation, starting with a more detailed breakdown of green R&D expenditures (as in Frischtak (2011) for Brazil), and then going beyond R&D investments to measure the broader range of green investments in intangible capital, including other expenditures on innovative property (such as green architectural and engineering designs), on green-related software and databases, and on green-related economic competencies (such as branding, employee training, and organizational improvements).[50]

Regarding policy, almost all evidence on the impact of policies to-date is from high-income countries. And even for high-income countries, the evidence on green innovation policy impact is scant. Not only is there not a lot of good data on angel investing in high-income countries, but there are no cost benefit analyses on angel tax credits or other policies to promote angel investors. Nor is there an impact evaluation study on what Chinese banks have been doing to support their green energy producers. Unfortunately, very few policies have been analyzed to figure out where the bang for the buck is. So there is an urgent need for well-designed impact evaluations of specific policy interventions. Both experimental evaluation with randomized controlled trials and quasi-experimental evaluation of existing interventions are needed, particularly regarding the effectiveness of different policies to promote firm-level absorption of existing green technologies.[51]

[50] See Dutz et al. (2011) for an application of measuring intangible capital to Brazil.

[51] An impact evaluation (IE) of a program or policy seeks to quantitatively measure the impact of the program on specific outcomes of interest, and is distinct from monitoring or evaluation of program activities. Since beneficiary outcomes are affected by a host of factors (besides the program being evaluated), identification of the causal link between program and outcomes is the key challenge for IE. IE tackles this problem by comparing program beneficiaries (the 'treatment' group) to a group of non-beneficiaries (the 'control'). The control group is intended to

REFERENCES

Acemoglu, Daron. 2002. "Directed Technical Change", *Review of Economic Studies,* 69: 781-810.

Acemoglu, Daron, Philippe Aghion, Leonardo Bursztyn, and David Hemous. forthcoming. "The Environment and Directed Technical Change", *American Economic Review*.

Aghion, Philippe, David Hemous and Reihilde Veugelers. 2011. "A framework to think about policy to fight climate change", mimeo, Washington, DC: The World Bank.

Alpay, E., S. Buccola, and J. Kerkvliet. 2002. "Productivity Growth and Environmental Regulation in Mexican and U.S. Food Manufacturing", *American Journal of Agricultural Economics* 84(4): 887–901.

Ambec, Stefan, Mark A. Cohen, Steward Elgie and Paul Lanoie. 2011. "The Porter Hypothesis at 20: Can Environmental Regulation Enhance Innovation and Competitiveness?", Resources for the Future Discussion Paper 11-01, Washington DC: Resources for the Future.

Arrow, Kenneth J., Linda Cohen, Paul A. David, Robert W. Hahn, Charles D. Kolstad, Lee Lane, W. David Montgomery, Richard R. Nelson, Roger G. Noll and Anne E. Smith. 2009. "A Statement on the Appropriate Role for Research and Development in Climate Policy", *Economists' Voice,* February, 1-4.

Azar, C., Sandén, B. A., 2011. "The elusive quest for technology-neutral policies", *Environmental Innovation and Societal Transitions* 1(1): 135-139.

Barry, Marie-Louise, Herman Steyn, and Alan Brent. 2011. "Selection of renewable energy technologies for Africa: Eight case studies in Rwanda, Tanzania and Malawi", *Renewable Energy,* 36: 2845-52.

Barta, Jan. 2006. "Economika pasivniho domu – vyplati se pasivni dum skutecne?" in *Pasivni domy 2006,* EEBW2006, www.pasivnidomy.cz

Barton, J.H. 2007. "Intellectual Property and Access to Clean Energy Technologies in Developing Countries", ICTSD Issue Paper 2.

Brunschweiler, Christa N. 2010. "Finance for renewable energy: An empirical analysis of developing and transition economies", *Environment and Development Economics*, 15: 241-274.

Canuto, Otaviano, Mark A. Dutz and Jose Guilherme Reis. 2010. "Technological Learning and Innovation: Climbing a Tall Ladder", *Economic Premise,* PREM, The World Bank, No 21, July.

CEDEFOP (European Centre for the Development of Vocational Training). 2009. "Future Skill Needs for the Green Economy", research paper. Luxembourg: Publications Office of the European Union.

Chatterji, Aaron. 2011. "On the State of Private Capital and its Future Potential", Panel One of *Can America Get its Entrepreneurial Groove Back? A Discussion about Private Capital's Role in the Economy,* The Brookings Institution, Tuesday, November 15, http://www.brookings.edu/events/2011/1115_private_capital.aspx

Cohen, W. and D. Levinthal. 1989. "Innovation and Learning. The Two Faces of R&D", *The Economic Journal,* 99 (397): 569-596.

measure the *counterfactual*; that is, what would have happened to beneficiary outcomes *in the absence of the program.* A prospective, 'experimental' IE design with randomized assignment to the program is considered the ideal. Randomization of treatment ensures –at the outset— that the treated and the control are 'similar", in the sense that *on average*, their outcomes would have been the same in the absence of the program. Therefore, comparing the change in outcomes across the treatment and control groups will give a correct estimate of the average program impact.

Copeland, Brian R. 2011. "International Trade and Green Growth", mimeo, October, Washington DC: The World Bank.

Copenhagan Economics. 2009. "Are IPRs a Barrier to the Transfer of Climate Change Technology", Report prepared by Copenhagen Economics and the IPR Company.

D'Agostino, Anthony L., Benjamin K. Sovacool, and Malavika Jain Bambawale. 2011. "And then what happened? A retrospective appraisal of China's Renewable Energy Development Project (REDP)", *Renewable Energy,* 36: 3154-3165.

David, Paul A. 2009. "Preparing for the Next, Very Long Crisis: Towards a 'Cool' Science and Technology Policy Agenda for a Globally Warming Economy", UNU-MERIT Working Paper 2009-031, Maastricht: UNU-MERIT

de la Tour, Arnaud, Matthieu Glachant, and Yann Ménière. 2011. "Innovation and international technology transfer: The case of the Chinese photovoltaic industry", *Energy Policy,* 39: 761-770.

Dechezleprêtre, Antoine, Matthieu Glachant, Ivan Hascic, Nick Johnstone, and Yann Ménière. 2011. "Invention and Transfer of Climate Change Mitigation Technologies: A Global Analysis", *Review of Environmental Economics and Policy* 5 (1): 109-130.

Dechezleprêtre, Antoine and Matthieu Glachant. 2011. "Does foreign environmental policy influence domestic innovation? Evidence from the wind industry", mimeo, February.

Dechezleprêtre, Antoine, Matthieu Glachant, and Yann Ménière. 2010. "What drives the international transfer of climate change mitigation technologies? Empirical evidence from patent data", Centre for Climate Change Economics and Policy Working Paper 16, London.

Dechezleprêtre, Antoine, Matthieu Glachant, and Yann Ménière. 2009. "Technology transfer by CDM projects: A comparison of Brazil, China, India and Mexico", *Energy Policy,* 37: 703-11.

Dechezleprêtre, Antoine, Matthieu Glachant, and Yann Ménière. 2008. "The Clean Development Mechanism and the international diffusion of technologies: An empirical study", *Energy Policy,* 36 (4): 1273-83.

Del Rio, Pablo. 2008. "Policy implications of potential conflicts between short-term and long-term efficiency in CO2 emissions abatement", *Ecological Economics* 65 (2): 292-303.

Dernis H., D. Guellec and B. van Pottelsberghe. 2001. "Using Patent Counts for Cross-country Comparisons of Technology Output", *OECD STI Review,* 27 (2): 129-146.

Dutta, Antara, Mark A. Dutz and Jonathan M. Orszag. 2011. "Intellectual Property Rights and Technological Development: Evidence and Unresolved Issues", mimeo, Compass Lexecon.

Dutz, Mark A. 2007. *Unleashing India's Innovation: Toward Sustainable and Inclusive Growth*, Washington, DC: The World Bank.

Dutz, Mark A., Sergio Kannebley Jr, Maira Scarpelli and Siddharth Sharma. 2011. "Measuring intangible capital in an emerging economy: An application to Brazil", mimeo. Washington DC: The World Bank.

Elliott, Kimberly Ann. 2010. "Pulling Agricultural Innovation into the Market", mimeo, March, Washington DC: Center for Global Development.

Enkvist, P.-A., T. Naucler, and J. Rosander. 2007. "A cost curve for greenhouse gas reduction*", The McKinsey Quarterly,* McKinsey & Company.

European Commission. 2009. "Low energy buildings in Europe: Current state of play, definitions and best practice", mimeo, Brussels, ec.europa.eu/energy/efficiency/doc/buildings/info_note.pdf

Frischtak, Claudio. 2011. "Vantagens Comparativas, Inovacao e Economia Verde", September, mimeo.

Glaeser, Edward. 2011. *Triumph of the City: How Our Greatest Invention Makes Us Richer, Smarter, Greener, Healthier and Happier*, New York: The Penguin Press

Goni, E., Daniel Lederman and William F. Maloney. 2011. "Why Don't Poor Countries Invest More in R&D?" mimeo. Washington, DC: The World Bank.

Griffith, Rachel, Stephen Redding, and John Van Reenen. 2004. "Mapping the Two Faces of R&D: Productivity Growth in a Panel of OECD Countries." *Review of Economics and Statistics* 86 (4): 883-895.

Hall, Bronwyn H. and Christian Helmers. 2011. "Innovation and Diffusion of Clean/Green Technology: Can Patent Commons Help?", mimeo, August.

Hall, Bronwyn H. and Christian Helmers. 2010. "The Role of Patent Protection in Clean/Green Technology Transfer", *Santa Clara High Technology Law Journal*, 26 (4): 487-532.

Hausmann, Ricardo, Lant Pritchett and Dani Rodrik. 2005. "Growth Accelerations", *Journal of Economic Growth*, 10: 303-329.

Hausmann, Ricardo and Bailey Klinger. 2006. "Structural Transformation and Patterns of Comparative Advantage in the Product Space", Working Paper Series RWP06-041, Harvard University, John F. Kennedy School of Government.

Henry, Claude and Joseph E. Stiglitz. 2010. "Intellectual Property, Dissemination of Innovation and Sustainable Development", *Global Policy*, 1 (3): 237-251.

Hourcade, Jean-Charles, Antonin Pottier, and Etienne Espagne. 2011. "The environment and directed technical change: comment", mimeo.

Kalkuhl, Matthias, Ottmar Edenhofer, and Kai Lessmann. 2012. "Learning or lock-in: Optimal technology policies to support mitigation", *Resource and Energy Economics* 34: 1-23.

Kunreuther, Howard and Erwann Michel-Kerjan. 2011. "Impact of Behavioral Issues on Green Growth Policies and Weather-Related Disaster Reduction in Developing Countries", mimeo, November 17. Philadelphia, PA: The Wharton School, University of Pennsylvania.

Khanna, M. and D. Zilberman. 2001. "Adoption of energy efficient technologies and carbon abatement: The electricity generating sector in India", *Energy Economics*, 23: 637-658.

Kremer, M. 1998. "Patent Buyouts: A Mechanism for Encouraging Innovation", *The Quarterly Journal of Economics*, 113: 1137-1167.

Lanjouw, J.O. and Ashok Mody.1996. "Innovation and the international diffusion of environmentally responsive technology", *Research Policy*, 25: 549-71.

Lanoie, P., J. Lucchetti, N. Johnstone, and S. Ambec. forthcoming. "Environmental Policy, Innovation and Performance: New Insights on the Porter Hypothesis", *Journal of Economics and Management Strategy*.

Lanoie, P., M. Patry, and R. Lajeunesse. 2008. "Environmental Regulation and Productivity: New Findings on the Porter Hypothesis", *Journal of Productivity Analysis*, 30: 121–128.

Lerner, Josh. 2009. *Boulevard of Broken Dreams: Why Public Efforts to Boost Entrepreneurship and Venture Capital Have Failed--and What to Do About It*. Princeton NJ: Princeton University Press

Lerner, Josh, M. Strojwas and Jean Tirole. 2003. "Cooperative Marketing Agreements between Competitors: Evidence from Patent Pools", NBER Working Paper 9680.

Levy, Brian. 2011. "Innovations in Globalized Regulation: Opportunities and Challenges", mimeo, August, The World Bank.

Levy, Brian, Alex de Jager, and Brendan Meehan, and Tony Leiman. 2011. "Regulatory Efficacy in a Changing Political Environment: The Case of Two South African Fisheries", mimeo, The World Bank.

Lewis, Joanna I. 2007. "Technology Acquisition and Innovation in the Developing World: Wind Turbine Development in China and India", *Studies in Comparative International Development,* 42 (3-4): 16-35.

Lovely, Mary and David Popp. 2011. "Trade, technology and the environment: Does access to technology promote environmental regulation?" *Journal of Environmental Economics and Management,* 61 (1): 16-35.

Lyon, Thomas P. and Bart van Hoof. 2010. "Evaluating Mexico's Green Supply Chains Program", mimeo, September. Ann Arbor: University of Michigan Ross School of Business.

Masters, W.A. and B. Delbecq. 2008. "Accelerating innovation with prize rewards", Discussion Paper 835, Washington, DC: IFPRI.

Nemet, Gregory F. 2009. "Demand-pull, technology-push, and government-led incentives for non-incremental technical change", *Research Policy,* 38: 700-709.

NETL (National Energy Technology Laboratory). 2011. "Environmental Impacts of Smart Grid", January, DOE/NETL-2010/1428. Washington DC: US Department of Energy.

OECD. 2011a. *Fostering Innovation for Green Growth.* Paris: OECD Publishing.

OECD. 2011b. *Invention and Transfer of Environmental Technologies*, OECD Studies on Environmental Innovation, Paris: OECD Publishing.

OECD. 2011c. *Business Innovation Policies: Selected Country Comparisons.* Paris: OECD Publishing.

OECD. 2011d. *Demand-side Innovation Policies.* Paris: OECD Publishing.

OECD. 2011e. *Skills for Innovation and Research.* Paris: OECD Publishing.

OECD. 2009. *Learning for Jobs: OECD Policy Review of Vocational Education and Training: Initial Report.* Paris: OECD.

OECD. 1999. *The Environmental Goods and Service Industry: Manual for Data Collection and Analysis*. Paris: OECD.

Outterson, K. 2006. "Patent Buy-Outs for Global Disease Innovations for Low- and Middle-Income Countries", *American Journal of Law and Medicine*, 32.

Popp, David. 2011. "The Role of Technological Change in Green Growth", mimeo, December, Washington DC: The World Bank.

Popp, David. 2010. "Innovation and Climate Policy", NBER Working Paper 15673, January.

Popp, David. 2006. "International innovation and diffusion of air pollution control technologies: The effects of NOX and SO2 regulation in the US, Japan and Germany", *Journal of Environmental Economics and Management,* 51 (1): 46-71.

Popp, David, Richard G. Newell, and Adam B. Jaffe. 2009. "Energy, the Environment, and Technological Change", NBER Working Paper 14832, April; forthcoming in *Handbook of Economics of Technical Change.*

Porter, M. 1991. "America's Green Strategy". *Scientific American,* 264 (4): 168.

Porter, M., and C. van der Linde. 1995. "Toward a New Conception of the Environment-Competitiveness Relationship," *Journal of Economic Perspectives,* 9: 97–118.

Prahalad, C.K. and R.A. Mashelkar. 2010. "Innovation's Holy Grail", *Harvard Business Review,* July-August, 132-141.

Pueyo, Ana, Rodrigo Garcia, Maria Mediluce and Dario Morales. 2011. "The role of technology transfer for the development of a local wind component industry in Chile", *Energy Policy*, 39: 3064-3075.

Rodrik, Dani. 2007. *One Economics, Many Recipes: Globalization, Institutions and Economic Growth*, Princeton, NJ: Princeton University Press.

Sauter, Raphael and Jim Watson. 2008. "Technology Leapfrogging: A Review of the Evidence", Sussex Energy Group, University of Sussex, 2008.

Shapiro, Carl. 2000. "Navigating the Patent Thicket: Cross Licenses, Patent Pools, and Standard Setting" in A.B. Jaffe, J. Lerner and S. Stern (eds.), *Innovation Policy and the Economy*. National Bureau of Economic Research, vol. 1, Cambridge, MA: The MIT Press.

Stiglitz, Joseph E. 2008. "Economic Foundations of Intellectual Property Rights", *Duke Law Journal,* 57: 1693-1724.

Suarez, Pablo and Joanne Linnerooth-Bayer. 2010. "Micro-insurance for local adaptation", *Wires Climate Change,* 1: 271-78.

Thorncroft, Chris. 2011. "African Monsoon Multidisciplinary Analysis", mimeo, Department of Atmospheric and Environmental Sciences, University of Albany, SUNY.

Trajtenberg, Manuel. 2009. "Innovation Policy for Development: An Overview." In D. Foray, ed., *The New Economics of Technology Policy*. Cheltenham: Edward Elgar Publishing.

Utz, Anuja and Carl J. Dahlman. 2007. "Promoting Inclusive Innovation", Chapter 4 in Dutz, Mark A. 2007. *Unleashing India's Innovation: Toward Sustainable and Inclusive Growth*, Washington, DC: The World Bank.

Wolf, Holger. 2011. "Relationship-Based and Arms-Length Financial Systems: A European Perspective", Policy Research Working Paper 5833, Washington, DC: The World Bank

World Bank. 2011. *Doing Business*. Washington, DC: The World Bank

World Bank. 2010. *World Development Report: Development and Climate Change*. Washington, DC: World Bank.

World Bank. 2008. *International Trade and Climate Change: Economic, Legal and Institutional Perspectives.* Washington, DC: The World Bank.

World Economic Forum. 2011. *Redefining the Future of Growth: The New Sustainability Champions.* Geneva: World Economic Forum.

Yusuf, Shahid, Kaoru Nabeshima and Shoichi Yamashita. 2008. *Growing Industrial Clusters in Asia: Serendipity and Science*. Washington, DC: The World Bank

DATA ANNEX

i. 'Green' Patenting

We use the PATSTAT database to measure patents granted by the US (USPTO) in 'green' technology areas. The technology area of a patent can be identified using the International Patent Classification (IPC) codes. We identify green patents using an exhaustive list of IPC codes pertaining to climate change mitigation technologies which was developed by Dechezleprêtre et al. (2011) and is used by the OECD. A patent in the PATSTAT database is categorized as green if any of its associated IPC codes belongs to this list. The first -named inventor's country of residence is used to assign a patent to a country.

The 13 different classes of technologies with significant global GHG emission abatement potential that are used for our patent analysis include:
7 renewable energy technologies

- **biomass**: solid fuels from animals or plants, and engines operating on such fuels
- **geothermal**: devices for producing mechanical power from geo energy
- **hydropower**: hydraulic turbines, devices for control, hydro power stations
- **ocean** or marine energy: wave power plants, water wheels, ocean thermal energy conversion
- **solar**: solar panels, heat collectors, use for heating and cooling
- **waste**-to-energy: solid fuels, recovery of heat from waste and exhaust gases
- **wind**: motors and devices to control motors

plus 6 additional technologies

- **building**s: heating (heat pumps, air conditioning) and thermal insulation in buildings
- **carbon** (Carbon Capture and Sequestration): extraction, storage and sequestration of CO2
- **cement**: climate-friendly cements, including pozzolana, iron ore, calcium sulfate
- **fuel** injection (electric and hybrid vehicles): also including batteries, control systems
- **lighting**: energy-efficient compact fluorescent lamps, electroluminescent light sources (LED)
- **methane** destruction: anaerobic and biological treatment of waste, collection of fermentation gases

These technologies represent nearly 50% of all GHG abatement opportunities beyond business-as-usual until 2010, excluding forestry, identified by Enkvist et al. (2007).

We look at patent grants rather than applications. Grants are a more conservative measure and a better indicator of innovations closer to being commercialized and having passed through a more thorough review.

Our use of *US* patents, as opposed to those granted by the respective national patent offices, is based largely on comparability concerns, a problem particularly acute in developing countries. The US is also the world's largest unified consumer market, and therefore has a tendency to attract the highest quality patents; and although market-pull type green innovation policy actions have been inadequate at the federal level, there are many instances of such policy action at state and local levels that have created vibrant regional markets for green innovations. Moreover, data on home patenting are not easily available for some developing countries.

A significant drawback of US patent counts is that not all inventions made in other countries are patented in the US. In particular, US patent counts will under-represent inventions that are local to the inventor's country and not intended to be sold elsewhere. Water pollution control technologies, for instance, are less likely to be patented abroad, as local conditions shape the requirements of these technologies (Popp 2011). More generally, since patents are not the only tool available to inventors to protect their invention, patent counts are likely to under-measure inventions. However, there are very few examples of economically significant inventions which have not been patented (Dernis et al. 2001), and patent counts are positively correlated with total inventions. Thus, analysis of US patent counts gives a good sense of broad patterns and trends. Since patents granted to US nationals (that is, home patenting) are not comparable to those granted to other nationals, we analyzed trends for high income countries with and without the US separately. Since these were found to be similar, we present the combined figures.

ii. Collaboration

Following Guellec and Potterie (2001), we measure collaboration using data on the inventors' country of residence in US patent grants. In the estimates given in the text and in Figure 4, the PATSTAT sample of USPTO grants is restricted to patents granted to developing countries (or the 'South'), namely patents in which *at least one* inventor belongs to a developing country. Among these, a patent is classified as indigenous (no cross-country collaboration) if all inventors are from the home country. A patent with inventors belonging to more than one developing country but none to developed countries is classified as South-South. A patent with one or more inventors from high-income countries in addition to the home country is classified as North-South.

iii. Trade in Green Goods and 'Close to Green Goods'

To the extent that green technologies are embodied in specific goods and services, green innovation would be reflected in product-level output and trade data. In an attempt to improve measurement of this 'environmental' industry, the OECD/Eurostat Informal Working Group on the Environment Industry (OECD 1999) started with the following definition:

The environmental goods and services industry consists of activities which produce goods and services to measure, prevent, limit, minimise or correct environmental damage to water, air and soil, as well as problems related to waste, noise and eco-systems. This includes cleaner technologies, products and services that reduce environmental risk and minimise pollution and resource use.

Note that this definition leads to a broader conceptualization of green goods and services as compared to that for green patent technology areas, particularly in that the latter considers only mitigation technologies.

Following this definition, the OECD working group has identified three broad 'environmental segments':

• pollution management, including goods that control air pollution, manage wastewater and solid waste, clean up soil, surface water and groundwater, reduce noise and vibrations, and facilitate environmental monitoring

• cleaner technologies and products, including goods that are more resource-efficient than available alternatives

• resource management, including goods to control pollution, supply water, or manage forests/fisheries sustainably.

Specific goods and services within these categories have been identified at the 6-digit HS commodity classification level. We use this list and the COMTRADE database (at the 6-digit HS level) to measure the volume of trade in green goods.

'Close to Green Goods': Following Hausmann and Klinger (2007), the proximity between a pair of goods is defined as the conditional probability of exporting one given that the other is exported. For instance, the proximity of Good A to Good B is 0.5 if as observed in international trade data, the conditional probability that a country exports Good A given that it exports Good B is 0.5. For every green 6-digit HS category, we measure its proximity to all other 6-digit HS categories using COMTRADE data on international trade, averaged over 2005-08. We classify a product as being 'close' to green if there is some green product with a proximity of 0.9 or higher to it. Thus, the probability that a country exports at least one green product given that it already exports a close-to-green product is 90 percent or higher. We then measure the volume of trade in close to green products using COMTRADE.