Executive summary

Technological innovation can lower the cost of achieving environmental objectives, so it is important to understand how environmental policy and technological innovation are linked. This is particularly true in the area of climate change where the economic costs of reducing greenhouse gas emissions are affected greatly by the rate of innovation. While we suspect that public policy can play an important role in accelerating the development and diffusion of climate change mitigation technologies (CCMTs), empirical evidence in this area remains scant.

The evidence presented indicates that the rate of innovation has accelerated in many CCMTs. This is particularly true of those technologies that have come closest to being competitive. While much of the technology transfer and international research co-operation is among Annex I countries, some non-Annex I countries have become significant trade and research partners.

This publication brings together recent work undertaken at the OECD Environment Directorate with respect to innovation in energy and climate change mitigation technologies (CCMTs) and the role played by public policy. It presents data on innovation across OECD countries over the last three decades. We also present work on the international transfer of CCMTs, as well as evidence on the extent of international research co-operation. Much of the data presented here has been constructed using search strategies developed in collaboration with patent examiners at the European Patent Office (EPO). The fields covered in this publication include: *

- *Renewable energy generation*
  - Wind energy
  - Solar energy (thermal and photovoltaic)
  - Geothermal energy
  - Marine energy
  - Hydro energy – tidal, stream or dam-less
  - Hydro energy – conventional

* In addition to the field listed here, the *ENV-Tech indicator* also covers other environment-related technologies such as emissions abatement and fuel efficiency in transportation, energy efficiency in buildings and lighting, etc. Work on climate change adaptation technologies is currently on-going. (For more details, see *www.oecd.org/environment/innovation/indicator*).

- *Energy generation from fuels of non-fossil origin*
  - Biofuels
  - Fuel from waste (e.g. methane)
- *Combustion technologies with mitigation potential*
  - Technologies for improved output efficiency (Combined combustion)
    - Heat utilisation in combustion or incineration of waste
    - Combined heat and power (CHP)
    - Combined cycles (incl. CCPP, CCGT, IGCC, IGCC + CCS)
  - Technologies for improved input efficiency (efficient combustion or heat usage)
- *Technologies specific to climate change mitigation*
  - Capture, storage, sequestration or disposal of greenhouse gases
    - CO_2 capture and storage (CCS)
    - Capture or disposal of greenhouse gases other than carbon dioxide (N_2O, CH_4, PFC, HFC, SF_6)
- *Technologies with potential or indirect contribution to emission mitigation*
  - Energy storage
    - Battery technology
    - Ultra-capacitors, super-capacitors, double-layer capacitors
    - Thermal storage
    - Pressurised fluid storage
    - Mechanical energy storage
    - Pumped storage
  - Hydrogen technology
    - Hydrogen production from non-carbon-containing sources
    - Hydrogen distribution
    - Hydrogen storage
  - Fuel cells
- *Technologies for an efficient electricity transmission or distribution*
  - Flexible AC transmission; Active power filtering; Reactive power compensation; etc.
  - Superconducting electric elements and equipment
  - Efficient management or operation of electric power systems (e.g. smart grids)

In Chapter 1 we present data indicating that the rate of innovation has accelerated in many CCMTs. This is particularly true of those technologies that have come closest to being competitive – such as wind power, some solar power, biofuels, geothermal and hydro. Some technologies showed stagnation in patent activity (e.g. solar thermal), especially in comparison with the rate of patenting in general and with other energy technologies.

With respect to technology diffusion, we find evidence of significant CCMT equipment and knowledge flows across countries. While much of the technology transfer and international research co-operation is amongst Annex I countries, there are non-Annex I countries that have become significant trade and research partners. This is encouraging because international diffusion of environmental technologies and knowledge is key to addressing global environmental problems such as climate change.

A long-term price signal equivalent to oil prices at the upper range of the last oil crisis (2008) would mark a turning point in innovation, triggering a switch away from conventional generation technologies and shifting the focus to renewables.

Following the general overview in Chapter 1, the rest of this book presents outcomes of empirical analyses that try to explain the observed trends in various technological fields. We pay particular attention to factors that help us draw lessons for public policy.

Chapter 2 analyses the role of fossil fuel prices in driving innovation in both conventional electricity generation technologies using fossil fuels and in carbon-free technologies (renewable and nuclear). The study covers a wide cross-section of OECD countries over the period 1978-2008. We show that if oil prices become sufficiently high (similar to the prices observed during the oil crisis in 2008) this will trigger a "switch" in innovation away from fossil fuels to renewable sources.

This is because oil price has different effects across the various technology types. Its effect is positive for renewable energy sources, insignificant for nuclear power technologies, and positive but decreasing over time for fossil fuel technologies. The non-linear effect on fossil fuel technologies indicates that whereas initially a price increase leads to more innovation in efficiency-enhancing fossil-fuel technologies, as price increases even further, this effect becomes weaker and less additional innovation takes place. Therefore, an increase in fossil fuel prices is likely to have a positive impact on the carbon efficiency of energy, as it both leads to an increase in efficiency-enhancing innovation, and to a switching from fossil fuel towards carbon free technologies.

Facilitating international knowledge "spillovers" can contribute to improvements in combustion efficiency of fossil-fuel power plants, with an effect approximately five times greater relative to the case where knowledge does not diffuse across borders.

While it is important to encourage innovation, reduction of pollutant emissions remains the ultimate policy objective. In Chapter 3 we present an analysis of the downstream effects of innovation on the fuel efficiency of fossil-fuel power plants, using data for OECD countries over the last three decades. The analysis takes into account the effects of the fuel mix, the quality of the physical capital stock, the level of capacity utilization, and access to national and international knowledge on mitigation technologies on the level of fuel efficiency of fossil-fuel power plants.

Newer power plants and higher capacity utilization are associated with higher levels of fuel efficiency. Most importantly, the analysis also casts light on the role of past and present innovations, particularly through international knowledge "spillovers" across countries. Taking the two extremes, the estimated effect of a given increase in knowledge stocks on combustion efficiency is approximately five times greater if it is assumed that all countries draw upon a common knowledge pool relative to the case where knowledge is assumed to remain within national borders.

Nevertheless, the decrease in carbon intensity of power plants in OECD countries has not led to overall CO_2 emissions reductions. Indeed, while we find a positive and statistically significant impact of knowledge stock on fuel efficiency, the magnitude of this impact is rather small. Therefore, it is important to keep in mind that additional changes need to occur either on the demand side (energy conservation) or on the supply side (production of electricity from alternative non-carbon sources). This is because increases in the available stock of knowledge will alone not be sufficient to reduce carbon intensity of power generation to such extent that would lead to lower overall level of CO_2 emissions. Clearly, there are limits to what innovation in only one technological field can achieve.

There are important complementarities between targeting public R&D support on innovation in the network infrastructure encouraging increased renewable energy penetration in the electricity supply grid.

A significant barrier to the increased penetration of renewable energy arises from the intermittent nature of the electricity produced. While some renewable energy sources are "dispatchable", that is, can generate energy on-demand (e.g. hydro, geothermal, and biomass), other sources are "intermittent" (e.g. wind, solar and wave/tide power) in that they are subject to varying and unpredictable weather and ecological conditions. The extent to which the power grid as a whole can accommodate such variations is a function of its capacity to adjust to supply and demand shocks; and as the penetration of intermittent renewable sources increases so does the need for such capacity.

System flexibility can be increased through factors such as the inter-connection of grids and trade in electricity services, or the use of a more diverse and dispersed mix of intermittent sources. Another way to introduce flexibility into the system is through increased energy storage capacity and improved grid management, both of which allow for improved matching of electricity supply and demand.

In Chapter 4 we present findings on the importance of various factors in encouraging innovation in advanced energy storage and grid management. The results indicate that a 10% increase in targeted public-sector R&D results in approximately 0.4%-0.5% increase in storage and grid management patents in the base model. This effect is relatively small, and further work is on-going to determine whether such investments result in sizeable increases in the efficiency of storage and grid management technologies, and ultimately increases in renewable energy penetration. Indeed, it is interesting to note that the effect of the introduction of renewable energy support measures is much larger in magnitude.

International technology-oriented agreements have been effective in encouraging research co-operation among countries, allowing for important economies of scale and knowledge diffusion.

In the context of the global climate change debate, increased attention is being paid to international technology-oriented agreements, as a complement to emissions-based agreements. One existing example is the International Energy Agency's "Implementing

Agreements" (IA). Such agreements can play a role in sharing of costs and knowledge. Indeed, results presented in Chapter 5 indicate that researchers in countries which are members of the agreement are much more likely to co-operate with each other in the development of patented climate change mitigation technologies.

This effect varies by technology, with the greatest impact for carbon capture and storage (83%), followed by biofuels and fuel cells (over 70%), wind and solar PV (over 60%), and the lowest effect has been found for energy storage (28%). International technology-oriented agreements do, therefore, have an effect on research co-operation, allowing for important economies of scale and knowledge diffusion. The differences in impacts may be partly due to the nature of technologies but they are also due to the differences in substance and the institutional characteristics of the agreements. Our analysis suggests that, other things held constant, adherence to the IAs would increase co-invention in non-member countries by about 90% in the case of wind and fuel cells, and even more in the case of biofuels, solar PV and CCS.

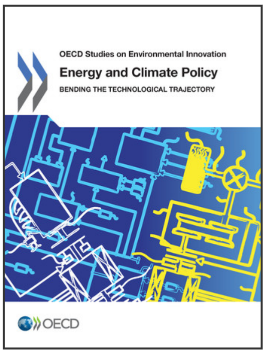
Important avenues for further policy research include the assessment of the drivers of breakthrough innovations, guidance on how to target support for "green" innovation, and the role of international technology and knowledge spillovers.

Further work on the identification of the innovation impacts of alternative policies is required. This will necessarily involve modelling the links between policy regimes, knowledge stocks, capital investment and specific environmental outcomes (e.g., emissions) in a comprehensive manner. The development of commensurable indicators of policy regimes across a variety of emitting sources is perhaps the greatest challenge.

An important additional challenge for the policy research community relates to the provision of solid empirical evidence which helps countries provide targeted support for "green" innovation without running the risk of locking economies into relatively costly mitigation paths. Technology-neutrality is not always an option, but there is little guidance from the empirical literature on how to target support efficiently.

In addition, almost all of the existing work focuses on the effects of policies on technologies that are relatively close-to-market and clearly identifiable as "environmental". Little work has been done on the role of policy on the invention and adoption of breakthrough technologies and more generic technologies with positive (and potentially even more significant) environmental consequences.

A final important avenue for policy research involves the assessment of the value of international research collaboration and technology agreements. Does international research collaboration help economies develop their innovation capacity by giving them greater access to foreign knowledge and expertise? These remain open questions.



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