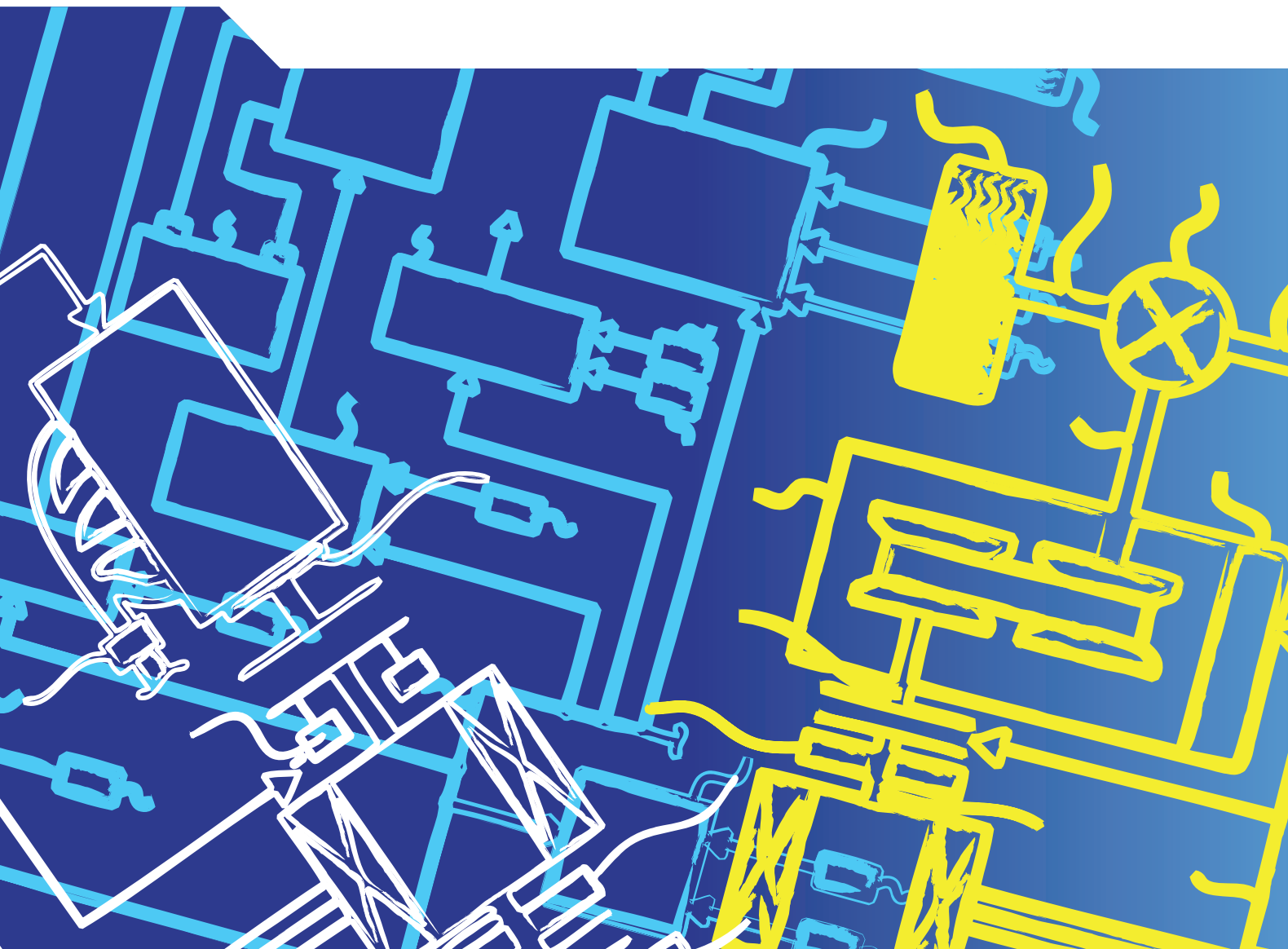




OECD Studies on Environmental Innovation

Energy and Climate Policy

BENDING THE TECHNOLOGICAL TRAJECTORY



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Please cite this publication as:

OECD (2012), *Energy and Climate Policy: Bending the Technological Trajectory*, OECD Studies on Environmental Innovation, OECD Publishing
<http://dx.doi.org/10.1787/9789264174573-en>

ISBN 978-92-64-17456-6 (print)

ISBN 978-92-64-17457-3 (PDF)

Series: OECD Studies on Environmental Innovation

ISSN 2074-3491 (print)

ISSN 2074-3483 (online)

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Foreword

Innovation is of key importance for climate change mitigation because it has the potential to lower the cost of achieving policy objectives. Whether this potential materialises will depend much on public policy. On the one hand, the economic costs of mitigation are likely to be very high, but will be critically influenced by the rate of innovation. In addition, the long-run nature of the climate challenge means that there is great variation in possible trajectories resulting from alternative innovation pathways. Public policy has a key role to play in both the rate and direction of innovation.

However, empirical evidence on the role that public policy can play in accelerating the development and diffusion of climate change mitigation technologies is limited. This book is a contribution to fill that gap: it provides new data on trends and patterns of invention in climate mitigation technologies; it assesses the determinants of invention, adoption and diffusion of innovations in climate mitigation technologies; and, provides guidance on the design of innovation policies to meet climate change mitigation objectives. The book covers all the main mitigation technologies, including renewable energy, improved combusting efficiency in the electricity sector, carbon capture and storage, as well as those with potential mitigation benefits such as fuel cells, hydrogen and energy storage.

The book has been prepared by Nick Johnstone and Ivan Haščič (OECD Environment Directorate) under the guidance of delegates to the OECD's Working Party on Climate, Investment and Development. In addition to the chapter authors, a number of other researchers have made substantive contributions to individual chapters, including Fleur Watson and Jérôme Silva (OECD Secretariat), Victor Veeffkind (European Patent Office) and Javier Hurtado-Albir (European Patent Office). Last, but not least, the contribution of Barbara Aiello and Šárka Svobodová (OECD Secretariat) in the preparation of the final manuscript is gratefully acknowledged.

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Acronyms

AFS	Average patent family size
AMI	Advanced metering infrastructure
BRICS	Brazil, Russia, India, China and South Africa
CCMT	Climate change mitigation technologies
CCS	Carbon capture and storage
CH₄	Methane
CHP	Combined heat and power
CO₂	Carbon dioxide
CP	Claimed priority
DUPL	Duplicate patent application
ECLA	European Classification System
EPO	European Patent Office
FACTS	Flexible AC transmission systems
HFC	Hydrofluorocarbons
IA	Implementing Agreements
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
IPC	International Patent Classification
N₂O	Nitrous oxide
OECD	Organisation for Economic Co-operation and Development
PATSTAT	<i>EPO World Patent Statistics Database</i>
PFC	Perfluorocarbons
PV	Photovoltaic
R&D	Research and Development
RD&D	Research, Development and Demonstration
SF₆	Sulphur Hexafluoride
SING	Singular (or singleton) priority
WIPO	World Intellectual Property Organization

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
 - CO₂ capture and storage (CCS)
 - Capture or disposal of greenhouse gases other than carbon dioxide (N₂O, CH₄, PFC, HFC, SF₆)
- *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 CO₂ 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 CO₂ 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.

Chapter 1

Recent trends in innovation in climate change mitigation technologies

by

Ivan Haščič, Fleur Watson, Nick Johnstone and Chris Kaminker*

In this chapter we present data on trends in innovation in climate mitigation technologies. The data have been generated using newly developed search strategies to extract data from a worldwide database of patent documents (PATSTAT). In comparison with previous reports, this chapter draws upon the more detailed European Classification System (ECLA) and, most significantly, draws upon the expertise of patent examiners at the European Patent Office (EPO) in the development of search strategies. We present data on invention, technology transfer and research co-operation for a broad cross-section of countries over the last three decades. We also review some of the relevant empirical evidence on the determinants of innovation in these fields.

* The authors wish to acknowledge the inputs of Victor Veefkind and colleagues at the European Patent Office for the development of the search strategy upon which the patent data used in this report is based.

1. Introduction

Technological innovation can lower the cost of achieving environmental objectives. As such, understanding the linkages between environmental policy and technological innovation in achieving environmental objectives is important. This is particularly true in the area of climate change, where the economic costs of slowing the rate of change are affected to a great extent by the rate of innovation.¹ While the role that public policy can play in accelerating the development and diffusion of climate change mitigation technologies is important, empirical evidence in this area remains scant.

This publication brings together recent work undertaken at the OECD Environment Directorate with respect to innovation in climate change mitigation technologies (CCMTs). This chapter presents data on innovation across OECD economies over the last three decades. Related work on the international transfer of CCMTs is also presented, as well as evidence on the extent of international research co-operation.²

Empirical analysis of the effects of policy on technical innovation requires a quantitative measure of innovation. While there is no ideal measure, patent data have been widely used as a proxy measure to assess the effects of policy and other factors on technological innovation in general. Given the means by which patent claims are classified, they are particularly useful when analysing innovation in specific technological fields. As such, in this report we use patent data to assess the nature, extent, and causes of innovation in the “environmental” context, with a focus on selected climate change mitigation technologies (CCMTs).³

Dechezleprêtre et al. (2011) report on trends in a wide range of CCMTs. They use the EPO/OECD World Patent Statistics Database (PATSTAT) to extract data based on the International Patent Classification (IPC) system. The use of a relational database such as PATSTAT allows for greater commensurability of data across fields, time and economies.⁴ In this chapter, we present data using refined search strategies, using the more detailed European Classification System (ECLA), and drawing upon the expertise of patent examiners at the European Patent Office (EPO).

This chapter is structured as follows. Section 2 discusses the construction of the data. Section 3 presents data on the evidence of inventive activity through patent counts. Section 4 presents evidence on the transfer of such technologies and the extent of international co-operation in CCMT innovation research. Section 4 reviews the empirical literature on the factors that drive innovation in these areas. There is a brief concluding section which ties the findings together.

2. Construction of patent indicators

The search strategies developed in collaboration with the European Patent Office cover a wide range of climate change mitigation technologies including renewable energy, combustion technologies for electricity generation, carbon capture and storage, advanced energy storage, hydrogen technologies, fuel cells, building and lighting efficiency, and

alternative fuel vehicles. This provides a robust and broad set of data on patented innovations in the area of climate change mitigation.

In this chapter, we focus on trends in renewable energy technologies and important mitigation technologies related to combustion of fossil fuels in electricity supply (i.e. integrated gasification combined cycle, carbon capture and storage). A previous report has examined the case of alternative fuel vehicles (OECD, 2011), and subsequent chapters report on data in many of the other fields (e.g. fuel cells, advanced energy storage).⁵

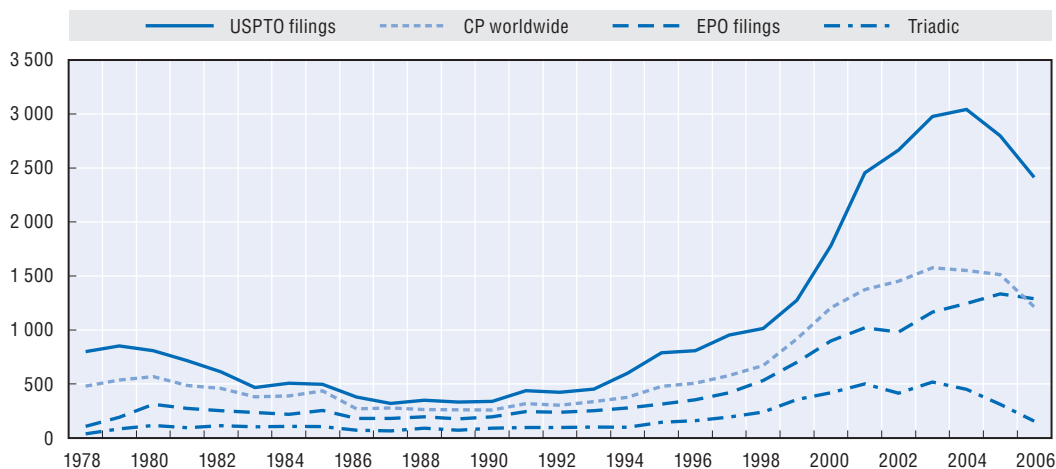
However, it must be noted that all measures of innovation are imperfect. For instance, R&D data are unsatisfactory insofar as it measures an input to innovation, rather than an output. Data on scientific personnel suffers from a similar shortcoming. In recent years, bibliometric data has been used, but it can be difficult to develop efficient search strategies, and the link between publication and value is likely to be imperfect at best (see OECD 2011 for a discussion).⁶

As an alternative, patent data have often been used as a measure of technological innovation because they focus on outputs of the inventive process (Griliches, 1990, OECD 2009a). Patent data provide a wealth of information on the nature of the invention and the applicant, the data are readily available (if not always in a convenient format), discrete (and thus easily subject to the development of indicators). Significantly, there are very few examples of economically significant inventions that have not been patented (Dernis and Guellec, 2001). Most importantly, the application-based nature of the patent classification systems allows for a richer characterisation of relevant technologies.

This report has been prepared using data extracted from PATSTAT⁷ based on EPO's identification of patent applications that are relevant to CCMTs. There is no ideal way of measuring patenting activity across economies, patent offices, and over time. However, some approaches to such international comparisons are more suitable than others. For example, the concept of a triadic patent family (TPF) has been developed by constraining the interest only to a small subset of high-value patents. However, in the context of the CCMTs the TPF is not a suitable approach because the constraint it imposes is overly restrictive (this would of course hold for other rather narrow technological fields as well). Indeed, the TPF counts for many CCMT fields are very low, limiting the variation in the data and thus rendering any useful international comparisons impossible (see Figure 1.1). This problem is, of course, even greater for the individual CCMT sub-categories.

Figure 1.1. Alternative indicators of CCMT patenting activity

Based on counts of USPTO and EPO filings, CPs worldwide, and triadic counts



In this chapter, we apply the concept of “claimed priorities” (i.e. patent applications that have been claimed as priority elsewhere in the world) to measure patenting activity because, other things being equal, these are inventions of higher value. Previous research has shown that the number of additional patent applications (other than the priority application) is a good indicator of patent value (Guellec and van Pottelsberghe de la Potterie, 2000; Harhoff et al., 2003).⁸

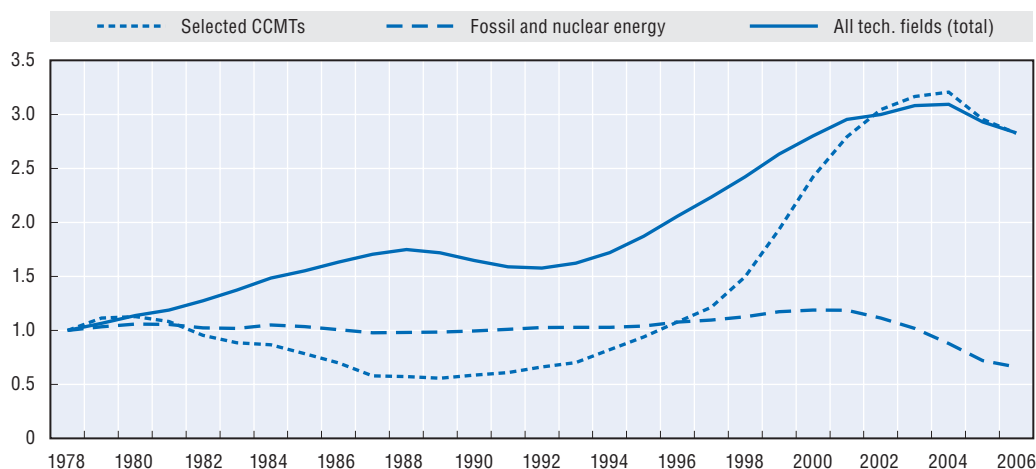
For the purpose of international comparisons, this statistic may be preferable for several reasons: i) considering only priority applications (and not their duplicates) avoids double-counting – which would occur if data from multiple patent offices were pooled. The data are thus better suited for cross-country analysis; ii) considering only “claimed priorities” provides a quality threshold as priority applications which have never been claimed (singulars) are excluded. This helps contain any concerns over strategic patenting; and finally, iii) the data are truly world-wide in their coverage, because the entire stock of patent priorities is considered.

We identify the relevant patent applications using data on patent families (priorities and equivalents).⁹ We construct frequency counts of claimed priorities (CP) deposited at any office world-wide, classified by *technological field* (based on identification developed by the EPO), *priority date*¹⁰ (based on the first application filing date world-wide), *application authority*,¹¹ and *inventor country* (country of residence of the inventors,¹² generated as fractional counts¹³). CPs account for a relatively small proportion of the stock of CCMT patent applications, with protection for over 60% of all CCMT inventions only being sought at a single office (SING). However, there is significant variation across offices.

3. Evidence of CCMT inventive activity

The rate of increase in CCMT claimed priorities has been remarkably rapid in the last decade – sometimes in excess of 20% per annum (see Figure 1.2). However, it is well-known that there has been a general increase in inventive activity (and the propensity to patent) across all technology fields. As such in order to gain a better indication of the rate of increase the Figure also shows claimed priorities for patents which relate to patenting in conventional (fossil-fuel and nuclear) energy fields and for patenting overall.¹⁴ As can be

Figure 1.2. **Growth rate of CCMT patenting**
Count of CPs worldwide, 3-year moving average, normalised to 1978=100

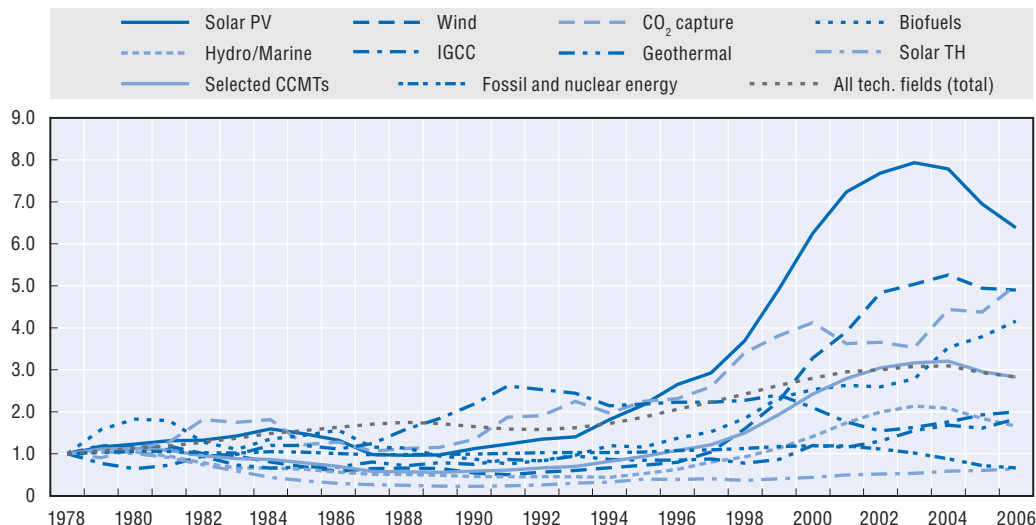


seen, CCMT innovation is far outstripping the rate of increase in patenting in general. Fossil fuel efficiency patents have been stagnant.

Figure 1.3 disaggregates the data by the classifications. Wind power, solar photovoltaic (but not thermal) and CO₂ capture have been exhibiting particularly rapid growth in recent years. Somewhat surprisingly, Integrated Gasification Combined-Cycle (IGCC) patent activity is growing more slowly than the rate of patenting in general. However, this is probably attributable to the general stagnancy of fossil fuel patenting in general.

Figure 1.3. Growth rate of CCMT patenting by technology

Count of CPs worldwide, 3-year moving average, normalised to 1978 = 100



The aggregate data presented thus far gives a good indication of trends in the invention of CCMT technologies. However, within individual fields there can be significant variation, with different technology types being much more mature than others. This can be seen clearly in Figure 1.4 below where data on solar thermal and solar PV technologies are compared. Solar thermal (a much more mature technology) reached its peak in the late 70s, while solar PV is still growing.

Figure 1.4. Inventive activity in solar thermal versus solar PV

CPs worldwide, 3-year moving average

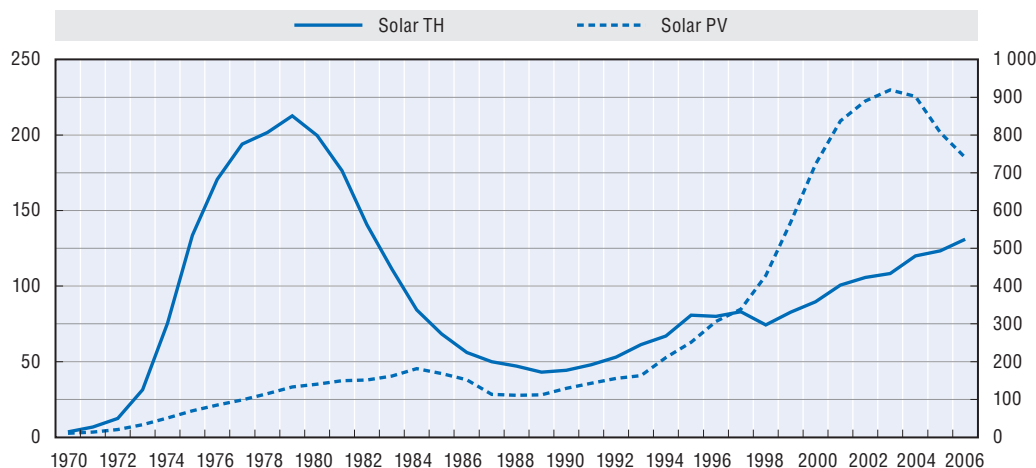
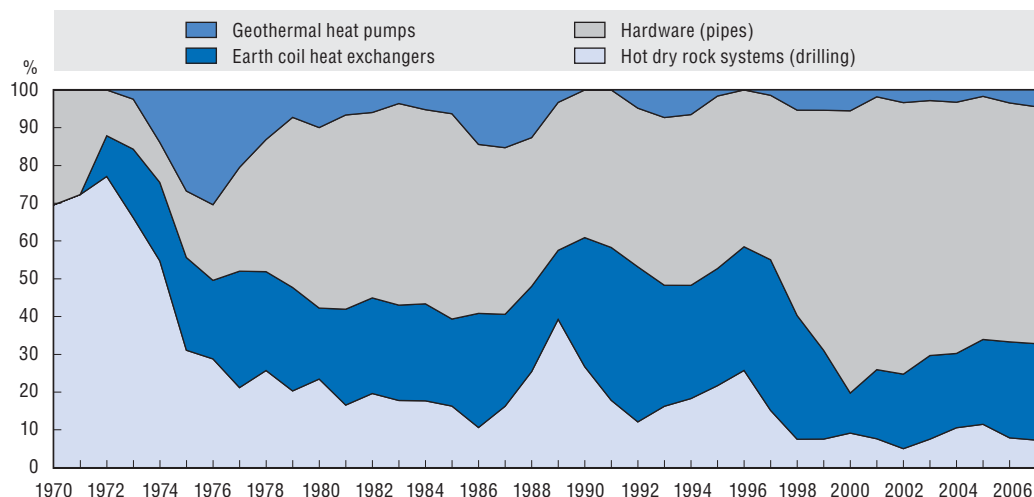
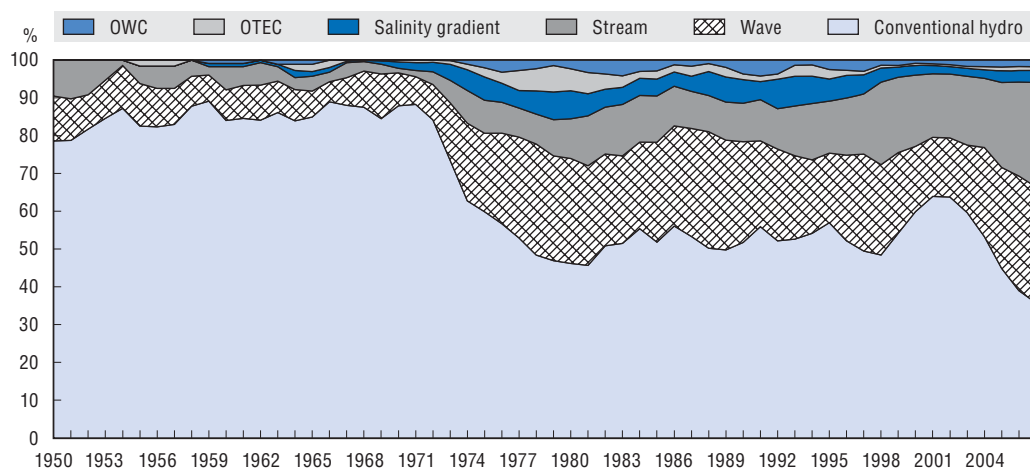


Figure 1.5. **Inventive activity in geothermal technologies (1970-2007)**

% share of all geothermal, 3-year moving average

Figure 1.6. **Inventive activity in hydro/marine technologies (1950-2007)**

% share of all hydro/marine, 3-year moving average



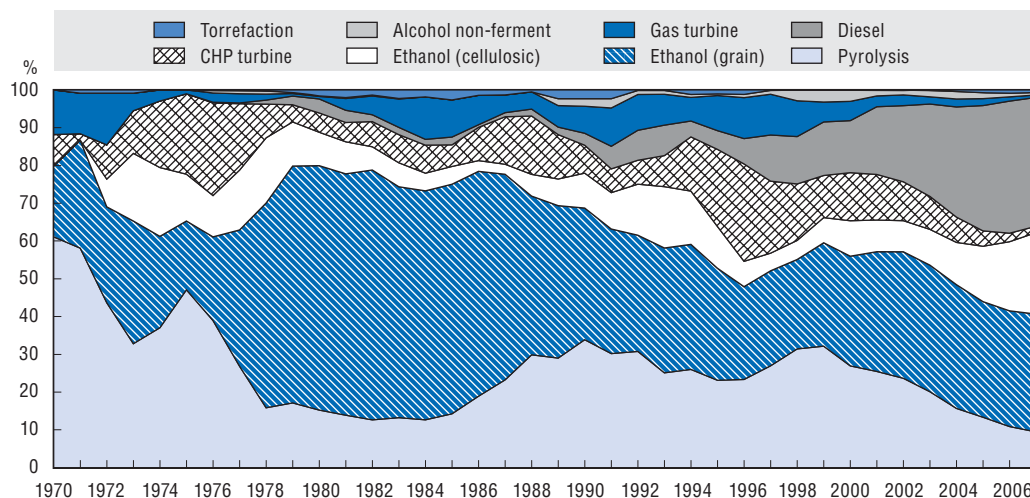
Note: OTEC = Ocean thermal energy conversion; OWC = Oscillating water column; "Stream" is mainly "river and tidal".

In the case of solar thermal technologies the most evident trend is the fall in the proportion of patents which relate to heat exchange systems, with mechanical technologies (mounting and tracking) showing growth. Conversely, in the case of geothermal technologies, hydro/marine, biofuels, and CO₂ capture technologies there are clear trends:

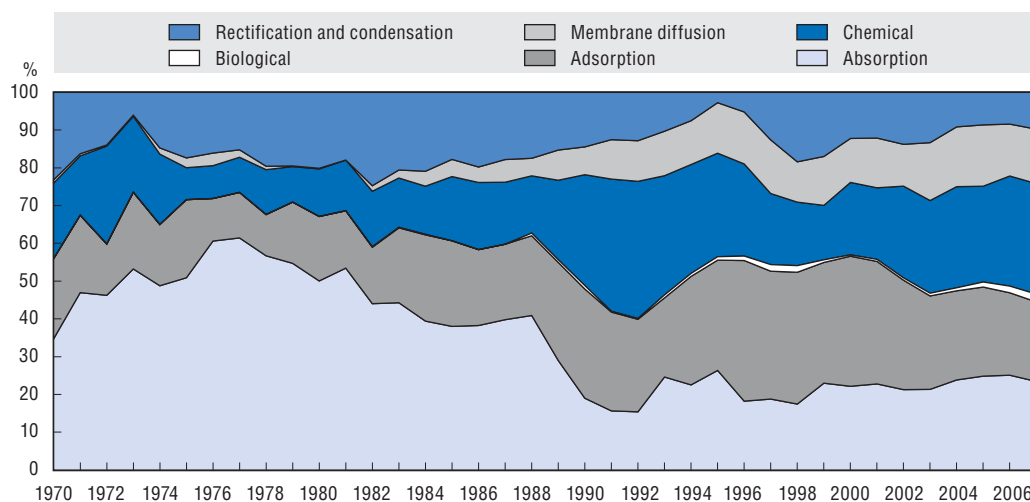
- in the case of geothermal it is material technologies related to pipes which have grown, while drilling technologies have fallen;
- in hydro, conventional hydro technologies have become less important, while stream and wave technologies have grown;
- in biofuels it is diesel technology patenting which has grown most quickly; and,
- in CO₂ capture, absorption and condensation have fallen, while absorption technologies and chemical capture have risen.

Figure 1.7. **Inventive activity in biofuel technologies (1970-2007)**

% share of all biofuel, 3-year moving average



Note: CHP turbines = combined heat and power plant turbines for bio-feed; Gas turbines = gas turbines for bio-feed; Alcohol non-ferment = bio-alcohols produced by other means than fermentation.

Figure 1.8. **Inventive activity in CO₂ capture (1970-2007)**% share of all CO₂ capture, 3-year moving average

Aggregating all technology fields, the relative importance of different economies is depicted in Figure 1.9. Japan, the United States and Germany lead, followed by Korea (which has had exceptionally high growth rates in recent years), and then Great Britain and France. This rank order is more or less true across all technology fields (see *OECD Patent Statistics Manual*). However, it is important to bear in mind that there is likely to be a bias toward the inclusion of documents filed at the EPO (since we use ECLA codes in the searches) and from intellectual property offices in which titles and abstracts are in English (since keyword searches are used). The first point can be seen by comparing the count of claimed priorities (Figure 1.9) with counts of all applications deposited at the EPO (Figure 1.10). There is a strong correlation between the trends for individual inventor country time-series.

Figure 1.9. **Trends in “claimed priorities” for CCMT inventive activity**
Count of CPs worldwide, 3-year moving average, by inventor country

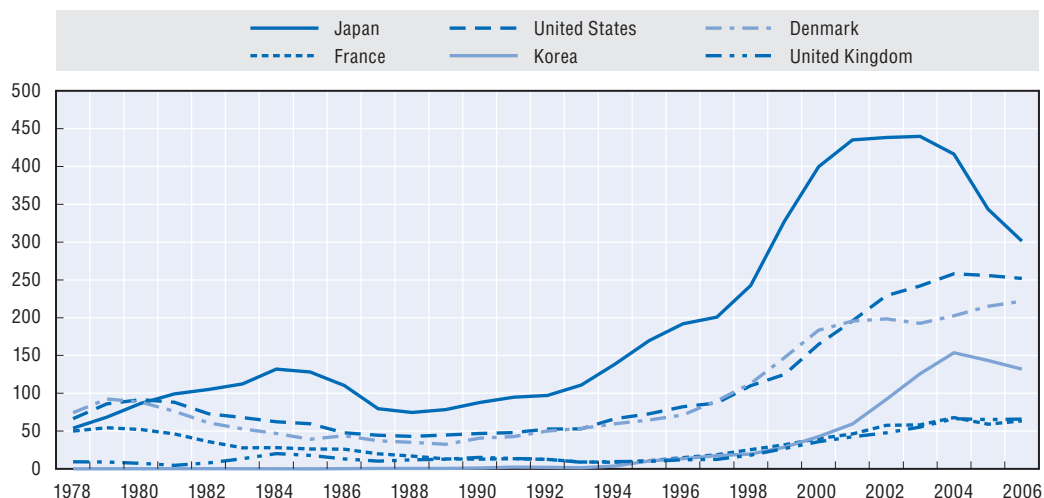
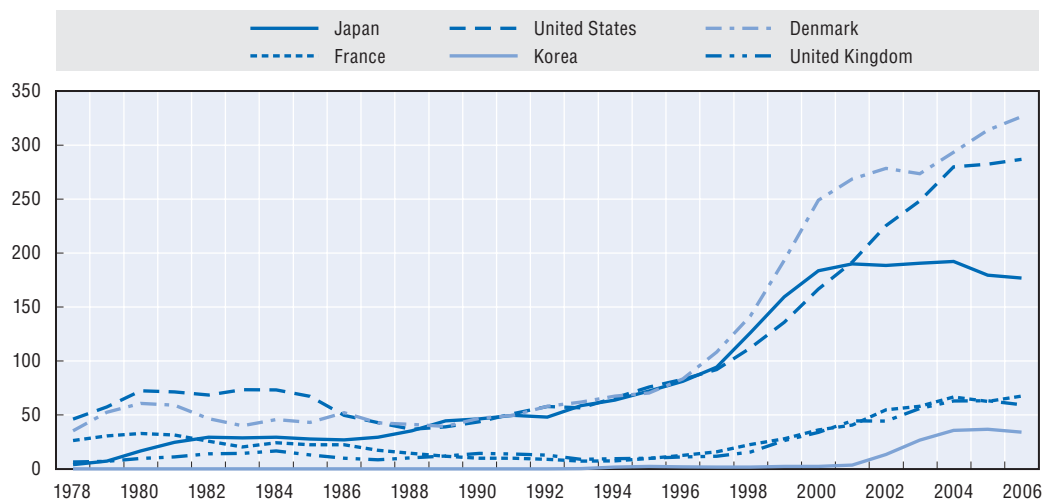


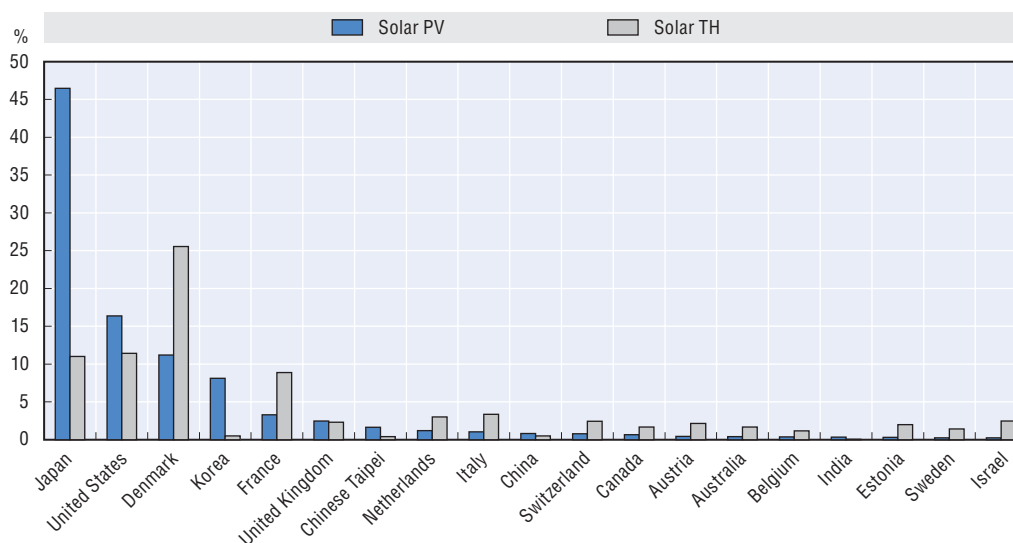
Figure 1.10. **Trends in EPO patents for CCMT inventive activity**
Count of all applications deposited at the EPO, 3-year moving average, by inventor country



Different economies have specialised in the two types of solar energy. While Japan and the US are dominant in solar PV, Germany and France have played a leading role in solar thermal. Most of the smaller economies have also been more active in solar thermal (e.g. Israel, Spain, and Netherlands). Interestingly, China, India, Chinese Taipei (CT), and Korea are amongst the relatively few economies in which solar PV inventions exceed solar thermal.

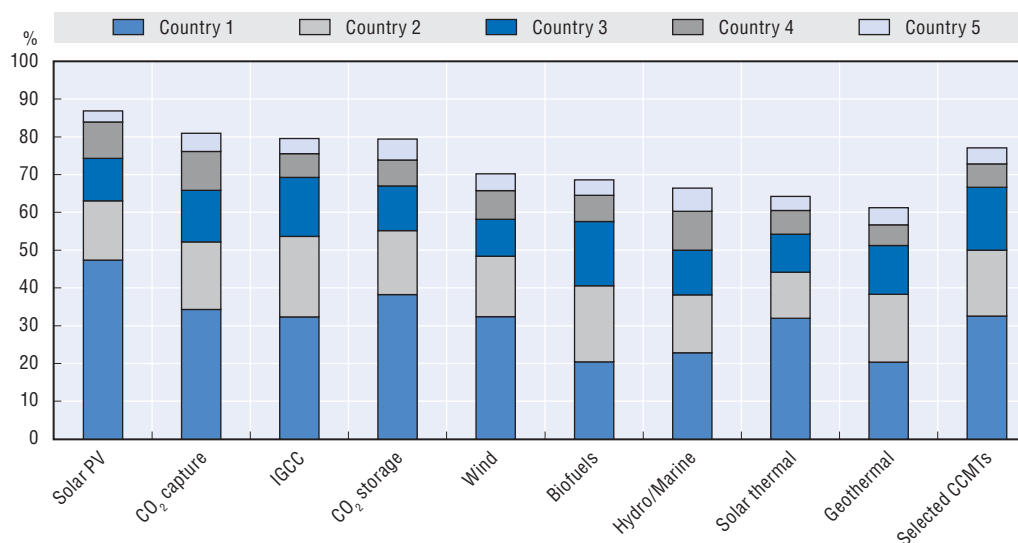
Figure 1.12 shows the proportion of claimed priority applications that the top five economies comprise. Overall, nearly 80% of all CCMT CP applications come from Japan, the US, Germany, Korea and France. Approximately one-third comes from Japan. The overall figures are heavily dominated by solar PV, the CCMT category with the largest number of

Figure 1.11. **Inventor countries for solar thermal and solar PV¹**
 % share of inventions (CPs worldwide), 1978-2007



1. The identifiers used in this table are without prejudice to the status of or sovereignty over any territory, and to the name of any territory, city or area.

Figure 1.12. **Proportion of patenting (CP) by the top five ranking inventor countries for each CCMT field, 1988-2007**



Note: Patent applications with missing inventor countries have been removed when calculating the above proportions.

applications. For solar PV, 87% of CPs are invented by five economies (JP, US, DE, KR and FR), with Japan inventing nearly half of all PV CPs. Geothermal is the least concentrated technology field, with just over 60% of CP patent applications invented by the top five economies, and 20% by the top inventor country (a similar percentage to biofuels).

Table 1.1 shows the rank of inventor countries. In the 1988-2007 period, Japanese-invented patents had the highest number of claimed priorities for all CCMT fields combined, followed by the US, Germany, Korea and France. Japan ranked in the top three for all CCMT fields investigated, while the US ranked in the top 2 and Germany in the top 4

Table 1.1. **Rank of top inventor countries 1988-2007 (counting CP), by CCMT class**¹

	Selected CCMTs	Solar PV	Wind	Hydro/Marine	Solar TH	Biofuels	CO ₂ capture	Geothermal	IGCC	CO ₂ storage
JP	1	1	3	3	3	3	2	3	2	3
US	2	2	2	1	2	1	1	1	1	1
DE	3	3	1	2	1	2	3	2	3	4
KR	4	4								
FR	5	5		5	4	4	4			2
GB	6			4		5	5		4	
IT	7				5					
CA	9							5		5
DK	12		4							
ES	13		5							
FI	19								5	
IL	20							4		

1. Note that throughout this volume we apply the ISO two-letter country codes since these are the standard designations for patent data.

for all categories. Korea was ranked fourth overall, but appeared in the top five for PV only, the largest category where Korea was ranked fourth. France and Germany were also notable inventors. Some smaller economies also figure in particular fields: Denmark in wind, Finland in IGCC, and Israel in geothermal.

These ranks have changed over the years. For instance, German's dominance of wind power innovation has grown, while the relative importance of its role in the area of CO₂ capture and IGCC (particularly) has decreased over time. Specialisation in individual technology field within CCMT in general is documented in Table 1.2. Figures in red indicate that the degree of specialisation is amongst the five highest for the field. In some cases this may result in a relatively high percentage overall (i.e. solar PV), but in other cases percentage is relatively low since the overall level of activity in these areas (i.e. carbon capture, storage and IGCC) is very limited.

It is important to note that a high degree of specialisation at the country level does not necessarily translate into a high degree of market concentration. Concentration data are generated on the basis of "assignee" (patent owner) data that is held in PATSTAT. Statistics reported are based on applicant names from PATSTAT that have been partially cleaned (name matching). The data have not been adjusted for changes in company structure (mergers and acquisitions, etc.).

Figure 1.12 shows the one-firm, five-firm, and ten-firm concentration ratios for the different technology fields. CO₂ storage (for which there are relatively few CPs) has the highest concentration with over 36% of inventions attributable to ten firms. Conversely, for solar thermal the relevant figure is 5%. The figure also includes the concentration ratio for CCMTs overall, with 10 firms accounting for almost 10% of all CPs. This is closely comparable with concentration observed in conventional (fossil and nuclear) energy technology fields.

Table 1.3 provides the names of the most important assignees in CCS and IGCC technologies. Concentration has decreased in all areas in the last few years. However, carbon storage (in particular) continues to be dominated by a very small number of firms. Across the three areas there is a split between petroleum firms (e.g. Shell, Exxon), general engineering firms (e.g. Siemens, Schlumberger, General Electric), chemical firms

Table 1.2. **Specialisation of inventor countries in CCMT fields (1988-2007)**¹
 % share of patenting in a CCMT field on CCMTs overall

	Solar PV	Solar TH	Wind	Geothermal	Hydro/Marine	Biofuels	CO ₂ capture	CO ₂ storage	IGCC	Selected CCMTs
JP	84	3	4	1	4	2	2	0	1	100
US	52	7	13	2	15	5	8	1	2	100
DE	39	19	27	2	11	6	3	0	1	100
KR	91	1	4	0	3	1	1	0	0	100
FR	40	15	14	2	17	7	10	1	1	100
GB	38	8	15	2	31	5	5	0	2	100
IT	32	19	15	3	28	10	3	0	0	100
NL	41	21	24	4	9	6	6	0	1	100
CA	22	17	21	5	25	10	7	1	1	100
CT	82	6	4	1	7	2	0	0	0	100
CH	42	19	9	4	22	7	2	1	3	100
DK	3	3	86	1	10	2	1	0	0	100
ES	17	24	52	1	15	3	1	1	0	100
CN	56	9	14	4	10	8	3	0	1	100
AT	29	25	14	8	27	8	1	0	1	100
SE	19	15	28	6	29	5	1	0	5	100
NO	11	10	23	6	45	0	17	2	2	100
AU	36	38	9	1	19	6	3	0	2	100
FI	13	10	22	4	12	31	5	0	8	100
IL	24	47	11	17	20	4	2	0	4	100
BE	39	15	24	1	9	14	4	0	2	100
IN	62	2	7	0	2	13	13	1	1	100
RU	33	25	21	0	19	6	7	0	1	100
GR	33	42	21	0	34	0	0	0	4	100
BR	1	0	18	0	59	21	0	0	0	100
PT	14	36	9	5	31	5	0	5	0	100
IE	26	5	11	0	46	17	0	0	0	100
HU	8	60	6	25	19	6	0	0	0	100
SG	86	7	7	7	14	0	0	0	0	100
UA	7	13	29	0	7	36	7	0	7	100
NZ	26	35	8	8	23	8	12	0	0	100
HK	36	30	21	0	24	0	10	0	0	100
TR	28	31	15	0	31	0	5	0	0	100
TH	58	53	42	0	0	0	0	0	0	100
CZ	18	24	12	12	35	24	0	0	0	100
PL	2	38	30	0	45	0	0	0	0	100
MX	19	19	0	0	56	6	19	0	0	100

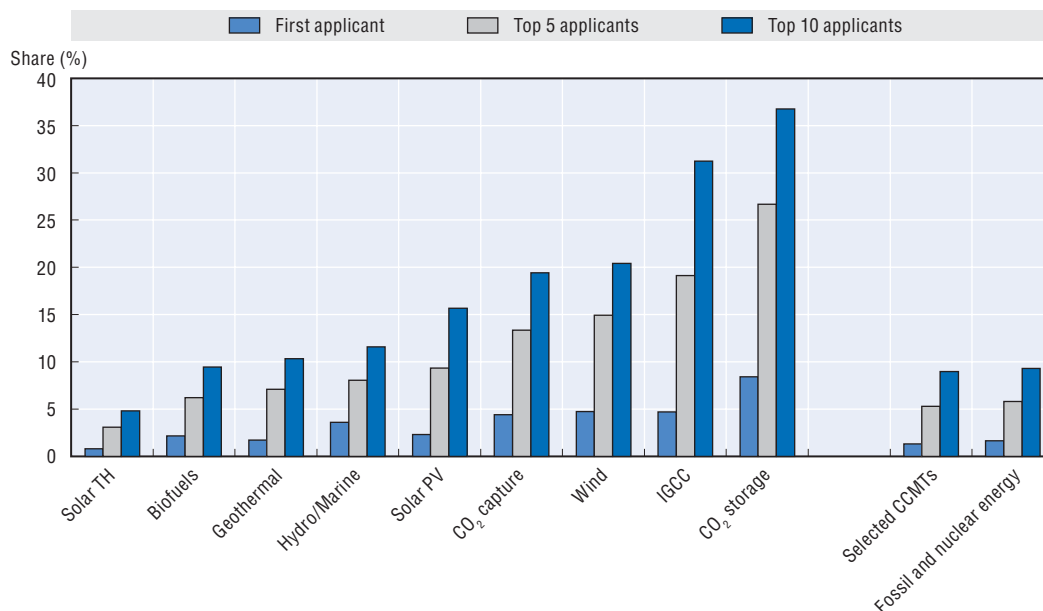
Note: The top five economies in each field are shown in bold.

1. The identifiers used in this table are without prejudice to the status of or sovereignty over any territory, and to the name of any territory, city or area.

(e.g. AirLiquide, Praxair), and even mineral companies (BHP). Some firms (e.g. Mitsubishi) are important in all areas, and have been for some time, while others have emerged recently. Many of the firms are the same as those found in Lee et al. (2009), but there are some differences.

Figure 1.13. **Market concentration (1998-2007)**

% market share by the first 1, 5 and 10 applicants



Note: Statistics are based on data on applicant names as they appear in PATSTAT; the data have not been cleaned or harmonized.

Table 1.3. **Major applicants in CCS & IGCC technologies (1988-2007)**

Number of filings and % share

CO ₂ capture					
	n	%	1998-2007	n	%
BOC GROUP	157	9.7	PRAXAIR	206	6.3
MITSUBISHI	138	8.6	AIR LIQUID	162	5.0
AIR PRODUCTS AND CHEMICALS	93	5.8	AIR PRODUCTS AND CHEMICALS	141	4.3
KANSAI	78	4.8	BOC GROUP	113	3.5
AIR LIQUID	58	3.6	SHELL	100	3.1
PRAXAIR	53	3.3	MITSUBISHI	96	3.0
UNION CARBIDE	45	2.8	EXXON	81	2.5
UOP	34	2.1	CECA	70	2.2
LINDE	32	2.0	GENERAL ELECTRIC	59	1.8
UNITED TECHNOLOGIES CORP.	28	1.7	INSTITUT FRANÇAIS DU PÉTROLE	57	1.8
		44			33
CO ₂ storage					
	n		1998-2007	n	
MITSUBISHI	18	38	SHELL	98	21
AGRICULTURAL GAS CO	9	19	INSTITUT FRANCAIS DU PETROLE	43	9.3
NKK CORP	5	10	TERRALOG	23	5.0
SEEC INC	4.5	9.4	EXXON	20	4.2
ELECTRIC POWER RESEARCH INST	2.5	5.2	SCHLUMBERGER	18	3.9
BAL AB	2	4.2	CDX GAS	17	3.7
UNION OIL CO. OF CALIFORNIA	2	4.2	AIR PRODUCTS AND CHEMICALS	15	3.2
DANIEL STEWART ROBERTSON	1	2.1	DIAMOND QC TECHNOLOGIES	14	3.0
HEINZ SEBASTIAN, LEIPZIG DE	1	2.1	DROPSONE	11	2.4
NAUCHNO-TEKHNIKESKIJ TSENTR PODZEMGAZPROM	1	2.1	BHP BILLITON INNOVATION	8.5	1.8
		96			57

Table 1.3. **Major applicants in CCS & IGCC technologies (1988-2007)** (cont.)

Number of filings and % share

IGCC					
1988-1997	n		1998-2007	n	
MITSUBISHI	90	9.3	MITSUBISHI	57	7.8
AIR PRODUCTS AND CHEMICALS	82	8.5	SIEMENS	56	7.7
EBARA	80	8.3	GENERAL ELECTRIC	54	7.4
HITACHI	52	5.4	TEXACO	46	6.2
FOSTER WHEELER	47	4.9	HITACHI	39	5.3
TEXACO	42	4.4	TOSHIBA	27	3.7
IMATRA VOIMA	32	3.3	ISHIKAWAJIMA HARIMA	22	3.0
ISHIKAWAJIMA HARIMA	32	3.3	NORSK HYDRO	21	2.9
SIEMENS	32	3.3	ALSTOM	19	2.7
AHLSTROM	25	2.6	ORMAT	19	2.6
		53			49

Note: Data on applicant names have been partially cleaned (name matching).

4. Technology transfer, knowledge spillovers and research co-operation

The international diffusion of mitigation technologies and knowledge is key to addressing trans-frontier and global environmental problems. In the case of a global public “bad” (such as global warming), all economies benefit from increased greenhouse gas mitigation arising out of the wide international diffusion of climate change mitigation technologies and knowledge (see Haščič and Johnstone 2011 for a discussion). Indeed, in the debate surrounding the recent climate talks it was apparent that achieving an effective global response to the climate change problem would necessitate significant involvement of non-OECD developing economies in mitigation efforts.

The potential to use patent data as the base from which to develop a proxy measure of technology transfer arises from the fact that protection for the invention may be sought in a number of offices.¹⁵ While the vast majority of inventions are only patented at one office (often that of the inventor, particularly for large economies), some are patented in several countries (i.e. the “international patent family size” is greater than one). Such “duplicate” applications can then be used to develop indicators of technology transfer. Of course, patents only give the applicant protection from potential imitators. It does not reflect actual transfer of technologies. If applying for protection did not cost anything, inventors might patent widely and indiscriminately.

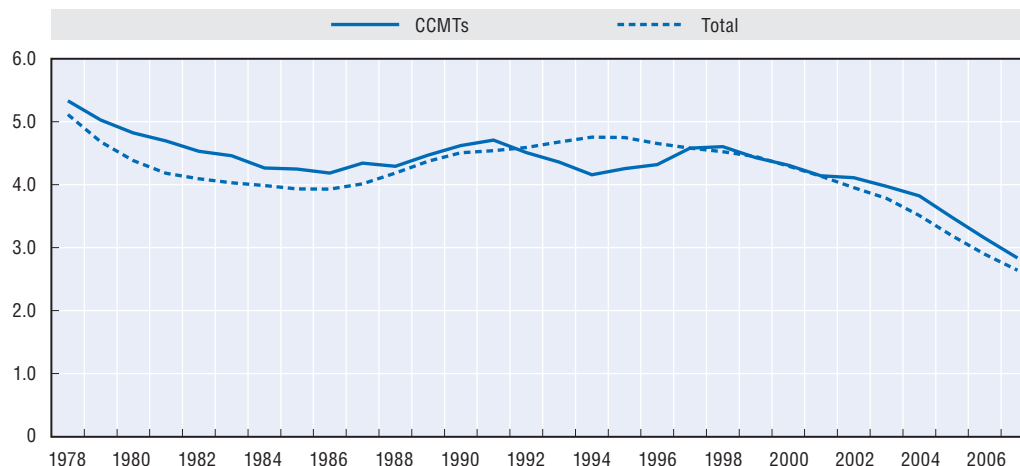
However, patenting is costly – both in terms of the costs of preparation of the application and in terms of the administrative costs and fees associated with the approval procedure. (See Helfgott 1993 for some comparative data. Van Pottelsberghe de la Potterie and Francois [2006] also provide more recent data for European Patent Office applications.) If enforcement is weak, the publication of the patent in a local language can also increase vulnerability to imitation (see Eaton and Kortum 1996 and 1999). As such, inventors are unlikely to apply for patent protection at a second office unless they are relatively certain of the potential market for the technology that the patent covers.

As a consequence, one measure of the extent of “transfer” is “family” size, which indicates the number of offices in which protection for a particular invention has been sought. Using the data extracted for this report, In Figure 1.13 the change in family size for CCMT technologies is presented, along with that for patents in general. The two correlate very highly.

In terms of specific technology fields, however, there is variation. For instance, in the case of CO₂ storage family size has been increasing rapidly. On the other other hand, IGCC family size has fallen in recent years (see Figure 1.14).

Patent documentation also allows us to look at bilateral transfers between pairs of countries.¹⁶ Table 1.4 presents data on the main source and recipient economies for CCMT technology transfers during the period of 1988-2007. As can be seen the most important bilateral relationships are between OECD economies.

Figure 1.14. **Trends in average patent family size**
Conditional AFS = (DUPL + CP)/CP worldwide, 3-year moving average



Note: The statistic for average family size shown here is calculated as the mean number of simple patent family members, given that the family size > 1; hence, “conditional AFS”. This is because the decision to “file abroad” (the first foreign filing) is conceptually different from the decision in how many countries to file (additional foreign filings).

Table 1.4. **Major bilateral transfer relations in CCMT (1988-2007)**¹
Count of duplicate patent applications between pairs of priority and duplicate offices

	US	EP	JP	DE	AU	CN	CA	KR	AT	ES	GB	CT	BR	NO	FR	DK	MX
US		2188	1798	1146	1312	1136	946	569	165	162	142	344	235	91	48	90	163
JP	4633	1533		1161	561	1338	213	883	65	59	72	536	36	42	65	28	14
DE	1252	2501	751		610	471	344	186	406	310	35	49	192	136	62	160	75
GB	463	485	263	260	334	142	149	60	78	65	742	20	39	43	7	32	19
FR	393	521	255	314	188	116	175	27	94	100	13	10	37	35	414	26	21
KR	1008	140	484	95	37	348	9	168	2	3	22	41	2	4	8	1	2
EP	327		157	243	129	146	73	47	137	75	6	5	17	18	2	66	8
SE	84	106	47	82	103	28	42	10	31	24		6	13	23	1	16	3
NL	77	167	53	110	121	28	33	7	37	34	4	2	15	13	1	25	6
AU	105	86	52	25	346	46	39	9	10	10	3	2	15	5		2	11
NO	74	98	41	53	104	41	53	14	30	20	7		11	179		14	1
IT	88	207	32	78	46	32	28	6	27	23	1	6	13	9	1	8	2
DK	80	114	27	74	93	65	52		35	23	1		6	16		107	6
ES	60	115	18	47	47	37	16	1	24	179	2		11	4	2	8	10
AT	38	102	24	54	38	21	28	11	91	19			14	12	1	5	8
FI	46	71	29	49	51	16	31	4	20	12	1		7	10	1	9	1
CA	97	45	24	30	53	17	104	5	9	7	5		8	6	2	2	7
CN	60	35	11	8	46	158	8	5	2	1			2		2	1	1
IL	48	32	13	23	47	10	7	3	9	9	3		9	2		4	4

1. The identifiers used in this table are without prejudice to the status of or sovereignty over any territory, and to the name of any territory, city or area.

Given the relative importance of developed economies in CCMT innovation, there are particular benefits from encouraging flows of climate change mitigation inventions originating in Annex 1 economies to non-Annex 1 economies. Indeed, the Clean Development Mechanism within the Kyoto Protocol has sought to encourage diffusion of technologies (amongst other aims) to non-Annex 1 economies in an effort to accelerate efforts to mitigate climate change. Tables 1.5-1.6 below provide data on the extent of flows from Annex 1 to non-Annex 1 economies with respect solar PV and solar thermal technologies. In addition to China, Korea and Chinese Taipei, other economies listed include Israel, Brazil, Mexico, South Africa and Morocco.

Figure 1.15. **Average patent family size in selected CCMTs**

Conditional AFS = (DUPL + CP)/CP, worldwide

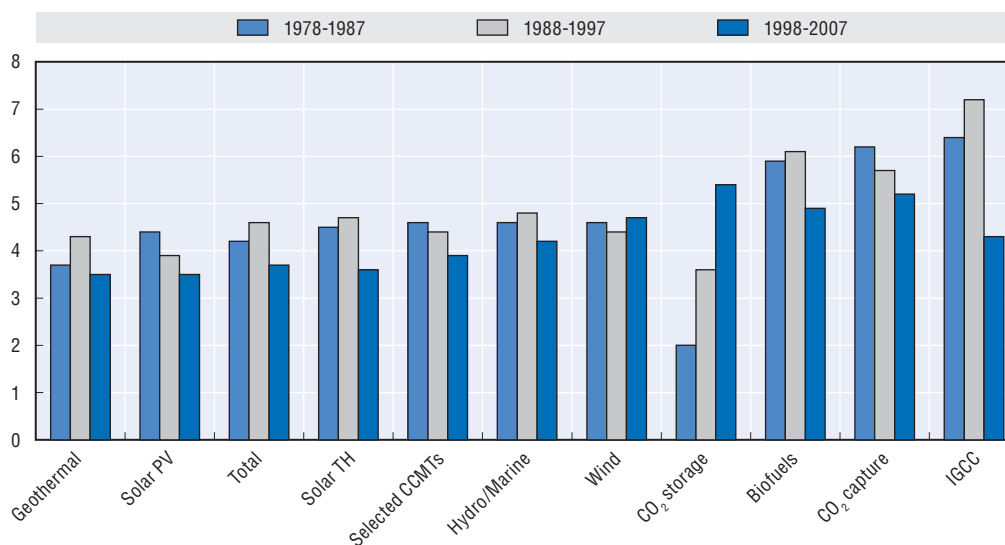


Table 1.5. **Transfer of solar PV to non-Annex I economies (1988-2007)**

Count of duplicate patent applications between pairs of priority and duplicate offices

	CN	KR	CT	BR	SG	MX	IL	HK	ZA	AR	ID	IN	MA
JP	1067	788	503	7	13	3	1	9	1		3	1	
US	663	409	318	47	74	46	46	20	11	15	1	2	
DE	185	104	46	19	3	14	10	11	9			1	
GB	57	41	17	6		4	4	6	8			2	
FR	35	10	3	8	1	7	5		7				2
AU	18	5	1	3		3	3		5		3		1
NL	10	3	2	4	1	2	1	1	1				
SE	6	3	3					1					
IT	5	1	2				1	2					
NO	9			2				4					
ES	5					3							
AT	7	3								1			
CH	4	1	1										

Note: While CT and HK were not parties to the UNFCCC Convention, they are included in the table due to the important volume of transfer. The identifiers used in this table are without prejudice to the status of or sovereignty over any territory, and to the name of any territory, city or area.

Table 1.6. Transfer of solar TH to non-Annex I Economies (1988-2007)

Count of duplicate patent applications between pairs of priority and duplicate offices

	CN	IL	BR	MX	KR	ZA	HK	MA	AR	EG	DZ	CT	ID	SG	IN
DE	46	28	16	11	8	11	2	4	1	3	1			1	3
US	58	33	23	25	18	7	8	1	4	1		3	1	1	
JP	49	1	3	5	16		1					2	1	1	
FR	8	7	6	7	1	4		2			1				
AU	19	2	7	4	3	8	1	1		1	1		1		1
GB	9	1	1	3		4									
NL	7	3	4	4	2	1	2	2							
AT	4	2	3	2	2	1	1	1			1			1	
ES	9	3	4	2		1		1	1						
IT	4	2	1	1	2	1	2		2						
SE	6				1										
NO	2														
CA	3	1	1	3	1	1	1	1							
HU	3	1	5	1	1	1							1		
CH	3			1											
GR	3					1									

Note: While CT and HK were not parties to the UNFCCC Convention, they are included in the table due to the important volume of transfer. The identifiers used in this table are without prejudice to the status of or sovereignty over any territory, and to the name of any territory, city or area.

The largest flows of solar PV, wind power, biofuels and CO₂ capture are represented graphically in Figure 1.15. In this case, European inventors are shown as one economy.¹⁷ The sizes of arrows are comparable within and between the figures; with the exception of solar PV where the flows are approximately three orders of magnitude greater than in the remaining three cases.

China dominates as the most important recipient country, with Korea, Brazil and South Africa also important in all areas. However, in some specific areas other economies emerge as important recipients – e.g. Morocco for wind power and Indonesia for carbon capture. The relative importance of the source economies is also very different in the different fields. While the US dominates PV, Europe is most important for wind power and biofuels. While Japan is a dominant innovator in all fields, there is less evidence of transfer.

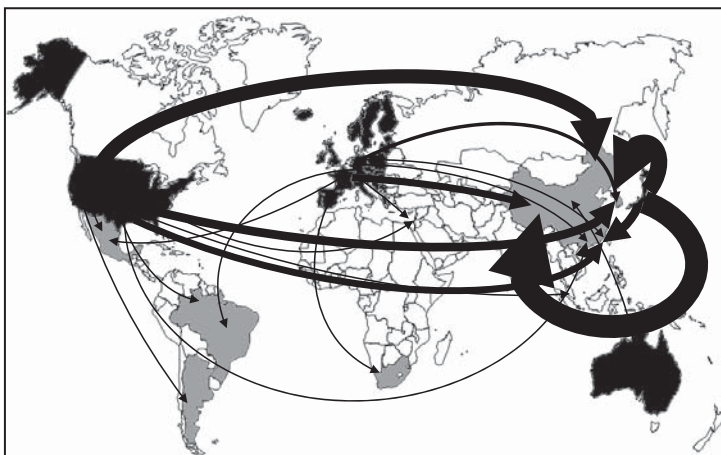
As noted above, climate change is a global problem, requiring international co-operation – both at the level of policy and at the level of innovation itself. Moreover, some of the most important channels of “transfer” are not embedded in technologies, but in knowledge itself. At the crudest level it is interesting to examine the propensity for inventors to patent abroad. Distinguishing by field of technology, the figure below presents this data for the last thirty years. There has been a general increase, since the fall in recent years is certainly due to the lags associated with duplicate applications.

However, it is more illuminating to examine the extent of direct research collaboration. To this end, Table 1.7 shows the rank of economies in different fields in terms of the likelihood of the technologies having been invented by researchers from more than one country. While Japan is the dominant inventor in many fields, co-operation is much less evident. Conversely, the US is the biggest “co-inventor” in all but two fields. Table 1.8 shows the bilateral relations for all CCMT fields.

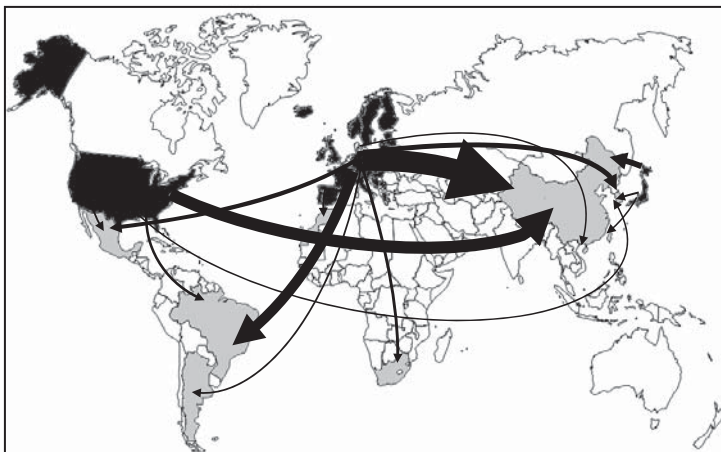
Overall, 4.3% of all the selected CCMT inventions involve inventors from more than one country. In terms of individual CCMT fields, the rate of co-invention is highest for CO₂ storage (15.2%) and lowest for hydro/marine, geothermal and solar thermal (2.6-2.1%) (Figure 1.18).

Figure 1.16. **Transfer of selected CCMT technologies from Annex I to non-Annex I economies (1988-2007)**¹

A. Solar PV



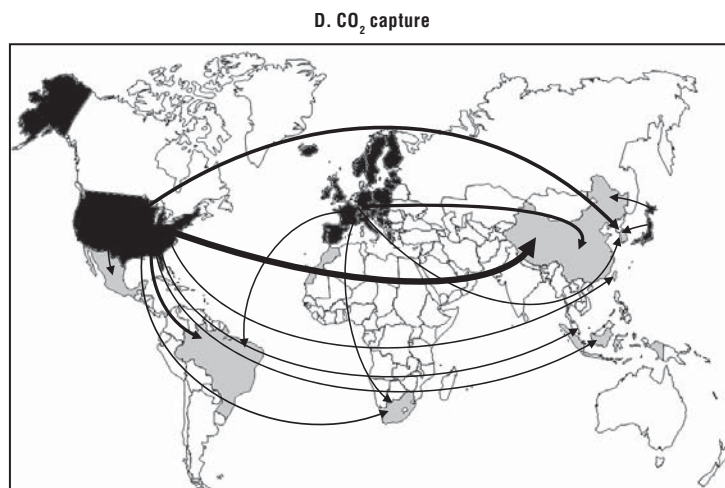
B. Wind power



C. Biofuels



Figure 1.16. **Transfer of selected CCMT technologies from Annex I to non-Annex I economies (1988-2007)¹** (cont.)



1. This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries.

Figure 1.17. **Propensity to patent abroad**

% share of CP/(CP + SING)

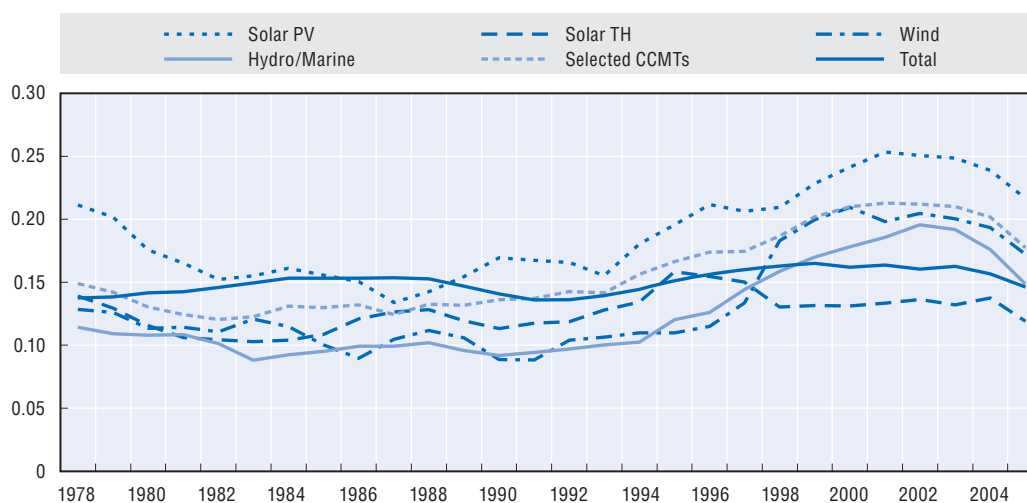


Table 1.7. **International research collaboration in CCMT (co-invention)**

Top five co-inventor countries, measured as number of inventions that involve co-invention, 1978-2007

	1	2	3	4	5
Solar PV	US	DE	JP	GB	CN
Solar TH	DE	US	CH	ES	FR
Wind	US	DE	DK	GB	NL
Geothermal	GB	US	AT	CN	NO
Hydro/Marine	US	DE	CA	GB	CH
Biofuels	US	DK	DE	NL	GB
CO ₂ capture	US	GB	DE	CA	NL
CO ₂ storage	US	NL	CA	GB	FR
IGCC	US	GB	NL	DE	FI
Selected CCMTs	US	DE	GB	JP	NL

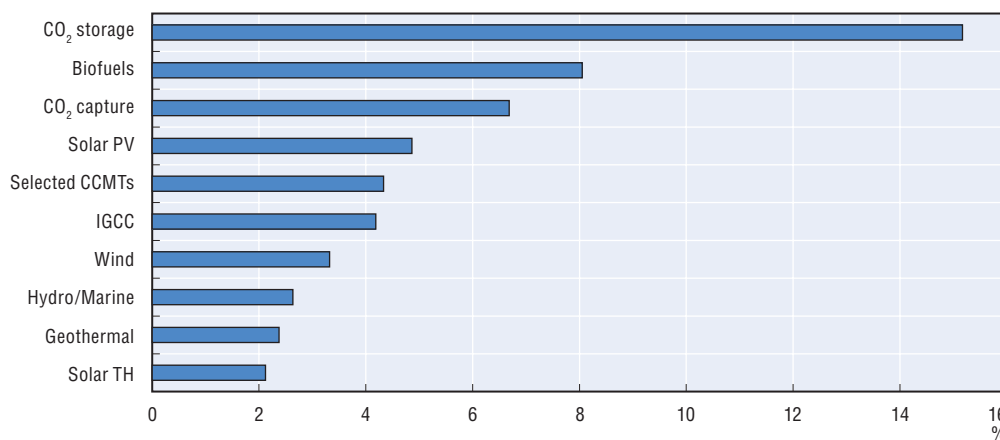
Table 1.8. International research collaboration in CCMT technologies¹
 Number of inventions (priorities) that involve co-invention between a pair of countries, 1978-2007

21	DE	GB	CN	CA	CH	JP	BE	FR	AT	IN	NL	DK	RU	AU	IT	KR	CT	ES	SE	Other
US	309	181	132	143	43	175	40	62	33	98	107	53	44	27	35	54	52	27	9	186
DE			23	11	102		20		51					17						
NL	47	48	1	2	3	5	32	7	1	1		3		5	5			14		
GB	58		22	13	7		4	17	4			29		6				10		
JP	46	38	31	6	13		1	4		3		11		6	1					
FR	44		3	17	26		24		6			1		1				3		
IT	26	13	1	4	14		4	11	4	2		1						1		
KR	22	6	9	6		21		7		5						2				
DK	35		18		4		7							2						
CT	6	3	44			5	3			2							2			
IN	13	16	11	7	1		2	6	1					1						
SE	13	2	1	5	12		1	6	2	1	1	3	1			8				
RU	12	15	2	2	2	1		1		2	2	1		2	1	6				
ES	16			1	5		6		2			11								
CH				4			6		11						12					
CN				7	4		4		4						5					
CA							8		1					1						
Other	90	82	27	40	14	26	21	26	12	23	13	2	55	11	20	10	13	2	21	74

1. The identifiers used in this table are without prejudice to the status of or sovereignty over any territory, and to the name of any territory, city or area.

Figure 1.18. CCMT fields by rate of co-invention

% share of inventions that involve co-invention, 1978-2007



Note: The proportions are relative to the stock of inventions with known inventor countries. Inventions with missing information on country of the inventor(s) are not considered here.

Focusing on solar PV, solar thermal, wind, and biofuels, the maps below show the important co-invention relationships graphically. In all areas, the US and Europe have a high degree of co-operation. Other interesting bilateral relationships include Belarus and Russia (solar PV and thermal), South Africa-Europe (biofuels and wind), India-US (solar PV, wind), China-US (solar PV). It is interesting to note that there is relatively little co-operation with China in terms of wind power, despite its importance in the field.

Figure 1.19. **International research collaboration in selected CCMT technologies (1988-2007)¹**

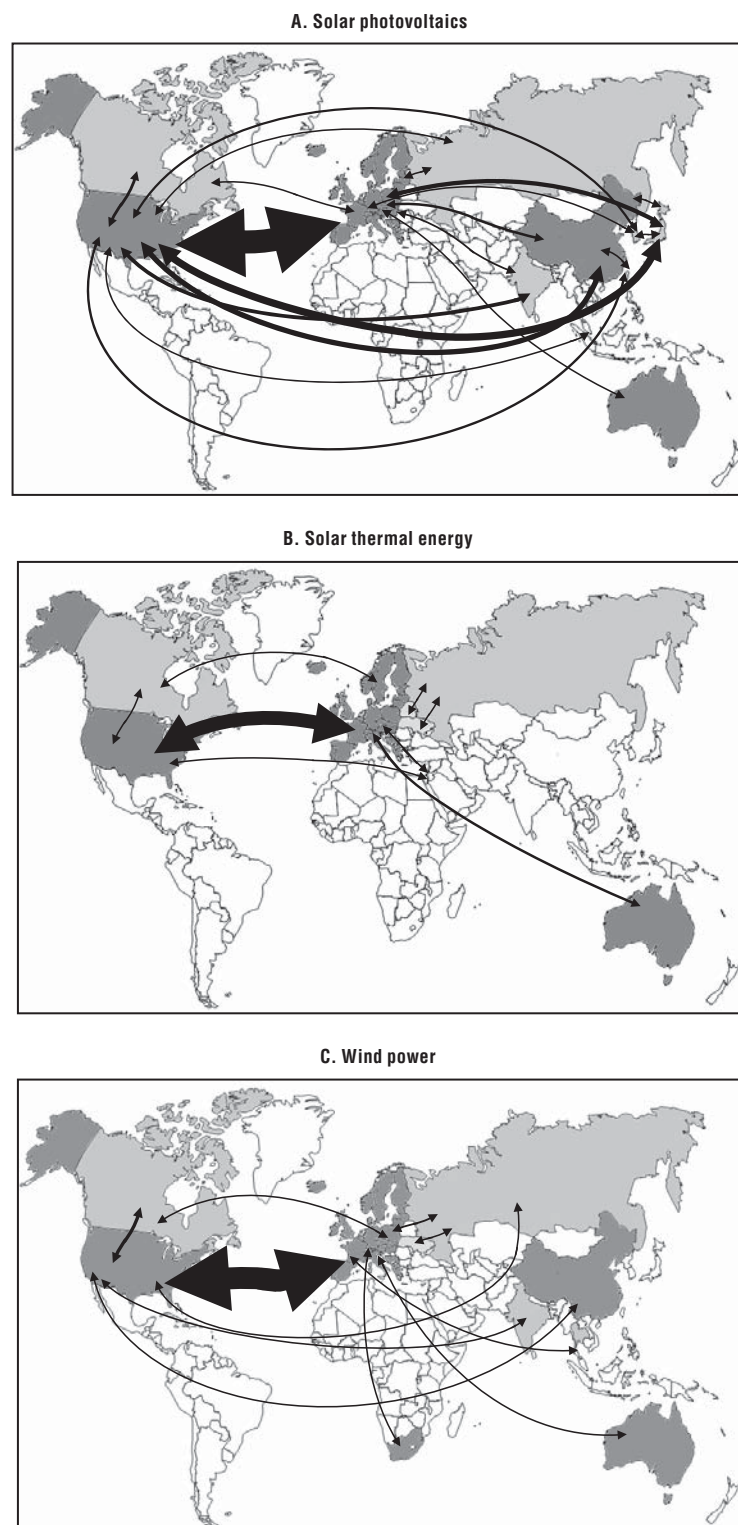


Figure 1.19. **International research collaboration in selected CCMT technologies (1988-2007)¹ (cont.)**

D. Biofuels



1. This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries.

5. Lessons from studies on renewable energy and energy efficiency

What is driving these trends? There is now a reasonable body of empirical evidence that relates to policy drivers of innovation in renewable energy. Johnstone *et al.* (2010a) examine the effect of environmental policies on technological innovation for six renewable-energy sources (wind, solar, geothermal, ocean/tide, biomass and waste). The analysis is conducted using patent data on a panel of 25 countries over the period 1978-2003. The unique contribution of this paper is the construction of quantitative variables for feed-in tariffs and renewable energy quotas. Dummy variables are included for other policy measures (e.g., investment subsidies, voluntary measures) for which data are not available in a commensurable format. They find that the different types of policy instruments are effective for different renewable-energy sources. In particular, they find that broad-based policies, such as tradable energy certificates, are more likely to induce innovation in technologies that are close to competitive with fossil fuels, such as wind power. More targeted subsidies, such as feed-in tariffs, are needed to induce innovation in more costly energy technologies, such as solar power.

In a similar vein, Braun *et al.* (2010) undertook a study of patented wind- and solar-power inventions in 21 OECD economies over the period 1978-2004. They include dummy variables that reflect whether or not a government has introduced a feed-in tariff, quota obligations, or tradable certificates. These policy variables are never significant, although public R&D is significant and positive in all of the solar-power models and some of the wind-power models.

Since renewable energy sources and fossil fuels are competing inputs in the generation of electricity, it is important to examine the effects of policy on substitution of innovation efforts in the two areas. Lanzi and Wing (2011) find that an increase in relative fossil-fuel prices results in a decrease in innovation in the fossil-fuel sector only above a certain level. Below this threshold, innovation increases for both fossil-fuel and renewable-energy sources, with a greater increase in the latter. This shows that increasing prices of

fossil-fuel energy may actually lead to an increase in innovation in both energy sectors up to a certain point, beyond which the substitution effect dominates.

Noailly and Smeets (2011) also assess the factors that induce firms to shift innovative activities away from fossil-fuel technologies towards renewable-energy innovations. Drawing upon firm-level data on patents filed by 9 000 European firms from 1978 until 2006, they find evidence that in the face of higher fossil-fuel prices, firms with a historical record of having patented inventions in both technology types tend to substitute renewable innovation for innovation in fossil-fuel combustion. However, firms that have only been active in the development of fossil-fuel technologies respond to an increase in fossil-fuel prices through increased patenting within the field, and not in substitute fields.

The role of international knowledge spillovers has also been assessed in the area of renewable energy. In a study of wind and solar power, Braun *et al.* (2010) find that, while previous domestic innovation in the field has an effect on actual rates of innovation, foreign knowledge stocks do not have an effect on domestic innovation capacity. While the technology fields assessed are different from those examined in Verdolini and Galeotti (2011), part of the difference in results might be attributable to the citation-weighted nature of the knowledge-stock variables in the latter study (they account for geographical dispersion of knowledge).

Renewable energy policies are often designed to promote technology diffusion. These can have either positive or negative indirect impacts on technology development. For example, in a study of wind power in four European countries, Söderholm and Klaassen (2007) find that while feed-in tariffs play an important role for diffusion, high rates of feed-in tariffs have a negative effect on technology development because they provide fewer incentives for cost-reducing innovations.

Also looking at adoption, Popp *et al.* (2011) extend the analysis presented in Johnstone *et al.* (2011a) in order to assess the downstream impacts on penetration of renewable energy in the electricity grid. They find a positive and significant impact of knowledge stocks on the penetration of renewable energy in the electricity supply sector, although the effect is generally small. For instance a 10% increase in wind-power knowledge stocks results in only a 3% increase in wind-power investment. The one area where knowledge stocks have a large impact is biomass, where a 10% increase in the knowledge stock results in a 37% increase in penetration.

Many studies have examined the role of energy prices in inducing innovation in energy efficiency. A seminal paper by Popp (2002) on the effect of energy prices in the US finds that energy prices have a significant and positive effect on patents in energy-saving technologies (e.g., heat pumps, coal liquefaction and gasification, fuel cells, continuous casting), with a mean lag of approximately 4 years.

Martin *et al.* (2009) estimate the impact of an energy tax using data on a panel of UK manufacturing plants, by comparing outcomes between plants subject to the tax (the Climate Change Levy) and plants that were granted an 80% discount on the levy subject to plants' participation in a voluntary agreement (the Climate Change Agreement). They do not find any statistically significant impact of the tax on employment, gross output or total factor productivity. However, they do find evidence that participation in the voluntary initiatives increased both energy intensity and energy expenditures, mainly on electricity, translating into an increase of CO₂ emissions. As such, they conclude that "had the CCL

been implemented at full rate for all businesses, further cuts in energy use of substantial magnitude could have been achieved without jeopardizing economic performance”.

Of course, in many cases policies are used in combination. Newell *et al.* (1999) examine the effects of energy prices and performance standards on innovation in energy-using home appliances (air conditioners, gas water heaters). While both have an impact on the efficiency of models supplied, the segments of the market through which these efficiency gains are realised are different. While standards result in less-efficient models being removed from the market, energy prices have an additional impact on the relative efficiency of new models being commercialised. Newell *et al.* (1999) also find that the energy labelling of appliances has a significant (and positive) effect on the efficiency of models offered for sale. More significantly, responsiveness to the price signal is heightened following the introduction of the labelling scheme.

A recent paper by Noailly (2010) focuses on the effects of regulatory standards and energy taxes in Europe on patents related to building-energy efficiency (insulation, lighting and boilers). She finds that a 10% increase in the insulation standard (measured as mandated U-values, or maximum heat transmission) results in a 3% increase in patents. Conversely, taxes (as reflected in energy prices) do not have an impact on patents.

The use of subsidies in support of “environmental” R&D is common, whether in the form of grants or tax credits. There is some positive evidence of their impacts in the area of energy efficiency (Jaffe *et al.*, 2005). However, there is some concern that public R&D may crowd out private efforts. In a study of energy-related R&D investments in the US, Popp and Newell (2009) find little evidence that there is crowding out across sectors. Investment in energy R&D does not reduce R&D in other fields, at least insofar as it is measured in terms of sectoral reallocation. However, there may be some “within-sector” crowding out, since increased energy R&D does not result in equivalent increases in overall R&D. Using firm-level patent data they find some evidence that the latter effect mainly arises from a shift of research efforts from “dirty” technologies (i.e., fossil-based energy) toward “clean” technologies (i.e., renewable energy), and not a more general fall in R&D expenditures.

In his study of energy technologies, Popp (2002) finds weak evidence for “crowding out” caused by US-government energy R&D expenditures as reflected in private patents. However, it appears that the role of government R&D may have changed through time. More specifically, he finds that government energy R&D was a substitute for private research efforts in the 1970s, but became a complement thereafter. This result is consistent with Jaffe and Lerner (2001), who assess the effectiveness of federal research laboratories owned by the US Department of Energy, using patent citation data. They find that rates of patenting and citations increased once the government focussed its research efforts on basic rather than applied research, and efforts were made to transfer technologies to the private sector. The benefit of focussing on basic research is confirmed in a later study by Popp (2006a), which examines citations for 11 energy-related technology fields. He finds that citation rates in the energy field are higher for patents arising out of government R&D than for other energy patents.

A body of literature has looked at the role of foreign policy conditions and knowledge stocks on domestic efforts in environmental innovation. In a recent contribution, Verdolini and Galeotti (2011) draw upon citation data from a sample of 38 countries to assess how knowledge related to energy technologies flows across borders. They show that both geographical proximity and similar technological specialisation increase the flow of

knowledge between pairs of countries. They also find that energy prices and domestic and foreign knowledge stocks increase the probability of applying for a patent in energy-efficient technologies. Indeed, for economies that are relatively less innovative, foreign knowledge stocks play a relatively more important role than domestic knowledge stocks. Taking the latter two results together, this indicates that domestic policy measures will induce innovation at home and abroad.

The issue of adoption has been addressed in a small number of papers. A particularly valuable study is that of Hassett and Metcalf (1995), which focuses on the adoption of energy conservation measures (e.g., more efficient boilers and insulation measures) for households. Exploiting variation in tax credits provided at the state level in the US, they find that a 10 percentage-point change in the tax price for energy investment would lead to a 24% increase in the probability of making such investments. In an earlier paper, Jaffe and Stavins (1995) assess the effects of energy taxes, energy-efficiency subsidies and technology standards on investments in the thermal efficiency of homes. They find that a given percentage increase in adoption subsidies would have a greater effect on investment in thermal efficiency than an equivalent increase in tax rates. The effect of standards is not significant, which may be attributable to the relatively lax nature of the standards applied.

However, “secondary” market failures can affect the responsiveness of some potential “adopters”. The classic case is the landlord-tenant relationship, in which neither party will have an incentive to adopt energy-efficient technologies that are relatively long-lived and non-recoverable. In such cases, the effect of mandated appliance or thermal standards may be more pronounced than that of energy taxes. Indeed, this is the argument put forward by Noailly (2010) to explain the significance of standards and insignificance of taxes in her study.

In two other studies, drawing upon data from over 10,000 households in 10 OECD countries, it is found that home-ownership status has a significant and large effect on incentives to invest in both water-efficiency devices (Millock *et al.* 2012) and energy-efficient appliances (Ščasný and Urban 2010). This is true even when the initial investment costs are rather small. For instance, it is interesting that the marginal effect of ownership status (owner-occupier rather than tenant) the probability of having invested in water restrictor taps is approximately 0.06 to 0.10.

6. Conclusions

This paper has provided evidence on the generation and diffusion of selected climate change mitigation technologies (CCMTs) and their respective links to key policies. The evidence presented indicates that the rate of innovation has accelerated in many CCMTs. This is particularly true of those technologies that were closest to being competitive – i.e. wind power, some solar power, biofuels, geothermal and hydro. Patent activity for other technologies (i.e. CCS) showed falls, even in comparison with the rate of patenting in general and for other energy technologies.

With respect to technology diffusion and transfer, there is evidence of significant CCMT equipment and knowledge flows across economies. While much of the technology transfer and international research co-operation is amongst Annex 1 countries, there are non-Annex 1 countries that have become significant trade and research partners. The international diffusion of environmental and CCMTs and knowledge is key to addressing global environmental problems such as climate change.

The final section of this chapter reviewed some of the key empirical evidence on the determinants of innovation in selected energy and climate mitigation technologies. However, it is clear that the evidence remains scant. As a consequence, further work discussed in the subsequent chapters of this volume report on empirical assessments of the role of market factors, national policies and international mechanisms on the invention, adoption and international diffusion of climate change mitigation technologies and knowledge.

Notes

1. See OECD (2009d), *The Economics of Climate Change Mitigation* (Paris, OECD).
2. Later chapters will present the results of empirical work undertaken on the determinants and consequences of innovation in this area.
3. See OECD (2011), *The Invention and Transfer of Environmental Technologies* (Paris, OECD) for a lengthy discussion.
4. For instance, documents which are members of a single patent family can be identified. However, some relevant documents captured through more “*ad hoc*” search strategies may be missed.
5. The complete hierarchy of the CCMT fields is provided in Appendix 1.A1. Data on all of the CCMT fields can be obtained from OECD.Stat.
6. For a discussion of the relative merits of different measures see OECD (2008) and Johnstone and Haščić (2009b).
7. Specifically, the April 2009 version of PATSTAT.
8. The results in Guellec and van Pottelsberghe (2000) suggest that patent value increases up to family size of 4 (or 5), and decreases thereafter. However, few patent applications have family size greater than five.
9. Using data on patent family, the following types of documents are distinguished: Singular is patent applied for at a single office, with no subsequent filings elsewhere (i.e. patent family size = 1); Claimed priority (CP) is patent for which an application is filed at an additional office to that of the “priority office”; these are inventions that have been applied for protection in multiple countries (patent family size > 1); Finally, duplicate is the additional application.
10. “Priority date” indicates the earliest application date worldwide (within a given patent family).
11. For a list of application authorities (patent offices) included, and their abbreviations used, see [http://documents.epo.org/projects/babylon/eponet.nsf/0/2464E1CD907399E0C12572D50031B5DD/\\$File/global_patent_data_coverage_0708.pdf](http://documents.epo.org/projects/babylon/eponet.nsf/0/2464E1CD907399E0C12572D50031B5DD/$File/global_patent_data_coverage_0708.pdf). See also www.wipo.int/standards/en/pdf/03-03-01.pdf.
12. For a list of two-digit abbreviations of country names, developed by the International Organisation for Standardisation, see www.iso.org/iso/country_codes.htm; The relevant WIPO document is available at www.wipo.int/standards/en/pdf/03-03-01.pdf.
13. Generating the counts as “fractional” means that if inventors from two (or three, or more) different countries are involved, only a fraction of 0.5 (0.33, etc.) will be counted for a given patent application.
14. Note that “TOTAL” refers to the entire stock of corresponding patent applications contained in PATSTAT. It is commonly used as a “normalisation” factor to account for differences in propensity to patent across countries and over time. This is fully appropriate when the “environmental” patents are identified using IPC classes, since most patent documents in PATSTAT do have an IPC class attributed. In cases when (English) keywords are used to complement the IPC search strategy, a corresponding “PATSTAT TOTAL” can be constructed by selecting only applications with (English) abstracts to mitigate the potential language bias. However, the EPO’s CCMT search strategy is rather complex, including not only IPC classes and keywords but also symbols from ECLA and other alternative classification systems which are not included in the current edition of PATSTAT. Consequently, we are unable to construct a corresponding “PATSTAT TOTAL” and the current approach has some shortcomings. These include the potential ECLA bias (the population of patent applications attributed an ECLA code is unknown) and language bias (due to searches in selected languages).

15. See www.oecd.org/environment/innovation/indicator for a discussion of the reliability of the use of duplicate patent applications as a measure of technology transfer.
16. See OECD (2011).
17. This includes countries of the European Economic Area (i.e. EU27 + Norway, Iceland, Switzerland, Liechtenstein).

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ANNEX 1.A1

List of CCMT fields available in OECD.stat

SEARCHES: ECLA CLASSES	
ENERGY GENERATION FROM RENEWABLE AND NON-FOSSIL SOURCES	ECLA class
RENEWABLE ENERGY GENERATION	
Wind energy	Y02E10/7
Wind turbines with rotation axis in wind direction	Y02E10/72
Blades or rotors	Y02E10/72B
Components or gearbox	Y02E10/72D
Control of turbines	Y02E10/72F
Generator or configuration	Y02E10/72H
Nacelles	Y02E10/72J
Offshore towers	Y02E10/72L
Onshore towers	Y02E10/72N
Wind turbines with rotation axis perpendicular to the wind direction	Y02E10/74
Power conversion electric or electronic aspects	Y02E10/76
For grid-connected applications	Y02E10/76B
Concerning power management inside the plant, e.g. battery charging/discharging, economical operation, hybridisation with other energy sources	Y02E10/76D
Solar thermal energy	Y02E10/4
Tower concentrators	Y02E10/41
Dish collectors	Y02E10/42
Fresnel lenses	Y02E10/43
Heat exchange systems	Y02E10/44
Trough concentrators	Y02E10/45
Solar thermal plants for electricity generation, e.g. Rankine, Stirling solar thermal generators	Y02E10/46
Mountings or tracking	Y02E10/47
Mechanical power, e.g. thermal updraft	Y02E10/48
Solar photovoltaic (PV) energy	Y02E10/5
PV systems with concentrators	Y02E10/52
Material technologies (not used; see subgroups)	Y02E10/54
CuInSe ₂ material PV cells	Y02E10/54B
Dye sensitized solar cells	Y02E10/54D
Solar cells from Group II-VI materials	Y02E10/54F
Solar cells from Group III-V materials	Y02E10/54H
Microcrystalline silicon PV cells	Y02E10/54J
Polycrystalline silicon PV cells	Y02E10/54L
Amorphous silicon PV cells	Y02E10/54N
Power conversion electric or electronic aspects	Y02E10/56
For grid-connected applications	Y02E10/56B
Concerning power management inside the plant, e.g. battery charging/discharging, economical operation, hybridisation with other energy sources	Y02E10/56D
Maximum power point tracking [MPPT] systems	Y02E10/58

SEARCHES: ECLA CLASSES	
Solar thermal-PV hybrids	Y02E10/6
Thermal-PV hybrids	Y02E10/60
Geothermal energy	Y02E10/1
Earth coil heat exchangers	Y02E10/12
Compact tube assemblies, e.g. geothermal probes	Y02E10/12B
Systems injecting medium directly into ground, e.g. hot dry rock system, underground water	Y02E10/14
Systems injecting medium into a closed well	Y02E10/16
Systems exchanging heat with fluids in pipes, e.g. fresh water or waste water	Y02E10/18
Marine energy	Y02E10/3
Oscillating water column [OWC]	Y02E10/32
Ocean thermal energy conversion [OTEC]	Y02E10/34
Salinity gradient	Y02E10/36
Wave energy or tidal swell, e.g. Pelamis-type	Y02E10/38
<i>Note: For tidal energy see below</i>	
Hydro energy – tidal, stream or damless	
Tidal stream or damless hydropower, e.g. sea flood and ebb, river, stream	Y02E10/28
Hydro energy – conventional	
Conventional, e.g. with dams, turbines and waterwheels	Y02E10/22
Turbines or waterwheels, e.g. details of the rotor	Y02E10/22B
Other parts or details	Y02E10/22D
	(Y02E10/20) and not (Y02E10/28)
ENERGY GENERATION FROM FUELS OF NON-FOSSIL ORIGIN	
Biofuels	Y02E50/1
CHP turbines for biofeed	Y02E50/11
Gas turbines for biofeed	Y02E50/12
Bio-diesel	Y02E50/13
Bio-pyrolysis	Y02E50/14
Torrefaction of biomass	Y02E50/15
Cellulosic bio-ethanol	Y02E50/16
Grain bio-ethanol	Y02E50/17
Bio-alcohols produced by other means than fermentation	Y02E50/18
Fuel from waste	Y02E50/3
Synthesis of alcohols or diesel from waste including a pyrolysis and/or gasification step	Y02E50/32
Methane (not used, see subgroups)	Y02E50/34
Production by fermentation of organic by-products, e.g. sludge	Y02E50/34B
From landfill gas	Y02E50/34D
COMBUSTION TECHNOLOGIES WITH MITIGATION POTENTIAL (E.G. USING FOSSIL FUELS, BIOMASS, WASTE, ETC.)	
TECHNOLOGIES FOR IMPROVED OUTPUT EFFICIENCY (COMBINED COMBUSTION)	Y02E20/1
Heat utilisation in combustion or incineration of waste	
Heat utilisation in combustion or incineration of waste	Y02E20/12
Combined heat and power	
Combined heat and power generation [CHP]	Y02E20/14
Combined cycles	
Combined cycle power plant [CCPP], or combined cycle gas turbine [CCGT]	Y02E20/16
Integrated gasification combined cycle [IGCC]	Y02E20/18
Combined with carbon capture and storage [CCS]	Y02E20/18B
TECHNOLOGIES FOR IMPROVED INPUT EFFICIENCY (EFFICIENT COMBUSTION OR HEAT USAGE)	Y02E20/3
Direct CO ₂ mitigation	Y02E20/32
Use of synair, i.e. a mixture of recycled CO ₂ and pure O ₂	Y02E20/32B
Use of reactants before or during combustion	Y02E20/32D
Segregation from fumes, including use of reactants downstream from combustion or deep cooling	Y02E20/32F
Controls of combustion specifically inferring on CO ₂ emissions	Y02E20/32H
Indirect CO ₂ mitigation, i.e. by acting on non CO ₂ directly related matters of the process, e.g. more efficient use of fuels	Y02E20/34

SEARCHES: ECLA CLASSES	
Cold flame	Y02E20/34B
Oxyfuel combustion	Y02E20/34D
Unmixed combustion	Y02E20/34F
Air pre-heating	Y02E20/34H
Heat recovery other than air pre-heating	Y02E20/36
At fumes level	Y02E20/36B
At burner level	Y02E20/36D
TECHNOLOGIES SPECIFIC TO CLIMATE CHANGE MITIGATION	
CAPTURE, STORAGE, SEQUESTRATION OR DISPOSAL OF GREENHOUSE GASES	
CO₂ capture or storage (CCS)	Y02C10
Capture by biological separation	Y02C10/02
Capture by chemical separation	Y02C10/04
Capture by absorption	Y02C10/06
Capture by adsorption	Y02C10/08
Capture by membranes or diffusion	Y02C10/10
Capture by rectification and condensation	Y02C10/12
Subterranean or submarine CO ₂ storage	Y02C10/14
Capture or disposal of greenhouse gases other than CO₂	Y02C20
Of nitrous oxide (N ₂ O) [N1006]	Y02C20/10
Of methane [N1006]	Y02C20/20
Of perfluorocarbons [PFC], hydrofluorocarbons [HFC] or sulfur hexafluoride [SF ₆] [N1006]	Y02C20/30
TECHNOLOGIES WITH POTENTIAL OR INDIRECT CONTRIBUTION TO EMISSIONS MITIGATION	
ENERGY STORAGE	Y02E60/1
Battery technology	Y02E60/12
Lithium-ion batteries	Y02E60/12B
Alkaline secondary batteries, e.g. NiCd or NiMH	Y02E60/12D
Lead-acid batteries	Y02E60/12F
Hybrid cells	Y02E60/12H
Ultracapacitors, supercapacitors, double-layer capacitors	Y02E60/13
Thermal storage (empty, covered by subgroups)	Y02E60/14
Sensible heat storage	Y02E60/14B
Latent heat storage	Y02E60/14D
Cold storage	Y02E60/14F
Pressurised fluid storage	Y02E60/15
Mechanical energy storage, e.g. flywheels	Y02E60/16
Pumped storage	Y02E60/17
HYDROGEN TECHNOLOGY	Y02E60/3
Hydrogen storage	Y02E60/32
Storage of liquefied, solidified, or compressed hydrogen in containers	Y02E60/32B
Storage in caverns	Y02E60/32D
Reversible uptake of hydrogen by an appropriate medium	Y02E60/32F
The medium being carbon	Y02E60/32F2
The medium being a metal or rare earth metal, an intermetallic compound or a metal alloy	Y02E60/32F4
The medium being an organic compound or a solution thereof	Y02E60/32F6
Hydrogen distribution	Y02E60/34
Hydrogen production from non-carbon containing sources	Y02E60/36
By chemical reaction with metal hydrides, e.g. hydrolysis of metal borohydrides	Y02E60/36B
By decomposition of inorganic compounds, e.g. splitting of water other than electrolysis, ammonia borane, ammonia	Y02E60/36D
By electrolysis of water	Y02E60/36F
By photo-electrolysis	Y02E60/36F2
FUEL CELLS	Y02E60/5
characterised by type or design	Y02E60/52
Proton Exchange Membrane Fuel Cells [PEMFC]	Y02E60/52B
Direct Alcohol Fuel Cells [DAFC]	Y02E60/52B2

SEARCHES: ECLA CLASSES	
Direct Methanol Fuel Cells [DMFC]	Y02E60/52B2B
Solid Oxide Fuel Cells [SOFC]	Y02E60/52D
Molten Carbobate Fuel Cells [MCFC]	Y02E60/52F
Bio Fuel Cells	Y02E60/52H
Regenerative or indirect fuel cells, e.g. redox flow type batteries	Y02E60/52J
Specially adapted for a certain application	Y02E60/54
Stationary systems, e.g. emergency power sources	Y02E60/54B
Transport applications, e.g. automobile, bus, ship	Y02E60/54D
Portable applications, e.g. mobile phone, laptop	Y02E60/54F
Integrally combined with other energy production systems	Y02E60/56
Cogeneration of electricity with other electric generators	Y02E60/56B
Cogeneration of heat, e.g. hot water, steam	Y02E60/56D
Cogeneration of mechanical energy, e.g. integral combination of fuel cells and electric motors	Y02E60/56F
Production of chemical products inside the fuel cell; incomplete combustion	Y02E60/56H
SEARCHES USING IPC CLASSES	
EMISSIONS ABATEMENT AND FUEL EFFICIENCY IN TRANSPORTATION	IPC Class
VEHICLE TECHNOLOGIES SPECIFIC TO PROPULSION USING ELECTRIC MOTOR (e.g. electric vehicle, hybrid vehicle)	
Arrangement or mounting of electrical propulsion units	B60K1
Dynamic electric regenerative braking for vehicles	B60L7/10-20
Electric propulsion with power supplied within the vehicle	B60L11
Methods, circuits, or devices for controlling the traction- motor speed of electrically-propelled vehicles	B60L15
Electric circuits for supply of electrical power to vehicle subsystems characterized by the use of electrical cells or batteries	B60R16/033
Arrangement of batteries in vehicles	B60R16/04
TECHNOLOGIES SPECIFIC TO PROPULSION USING ELECTRIC MOTOR (e.g. electric vehicle, hybrid vehicle)	
Arrangement or mounting of electrical propulsion units	B60K1
Dynamic electric regenerative braking for vehicles	B60L7/10-20
Electric propulsion with power supplied within the vehicle	B60L11
Methods, circuits, or devices for controlling the traction- motor speed of electrically-propelled vehicles	B60L15
Electric circuits for supply of electrical power to vehicle subsystems characterized by the use of electrical cells or batteries	B60R16/033
Arrangement of batteries in vehicles	B60R16/04
ENERGY EFFICIENCY IN BUILDINGS AND LIGHTING	
INSULATION (incl. thermal insulation, double-glazing)	
Insulation or other protection; Elements or use of specified material for that purpose	E04B1/62
Heat, sound or noise insulation, absorption, or reflection; Other building methods affording favorable thermal or acoustical conditions, e.g. accumulating of heat within walls	E04B1/74-78
Insulating elements for both heat and sound	E04B1/88
Units comprising two or more parallel glass or like panes in spaced relationship, the panes being permanently secured together	E06B3/66-677
Wing frames not characterized by the manner of movement, specially adapted for double glazing	E06B3/24
G.2. HEATING (incl. water and space heating; air-conditioning)	
Hot-water central heating systems – in combination with systems for domestic hot-water supply	F24D3/08
Hot-water central heating systems – using heat pumps	F24D3/18
Hot-air central heating systems – using heat pumps	F24D5/12
Central heating systems using heat accumulated in storage masses – using heat pumps	F24D11/02
Other domestic- or space-heating systems – using heat pumps	F24D15/04
Domestic hot-water supply systems – using heat pumps	F24D17/02
Use of energy recovery systems in air conditioning, ventilation or screening	F24F12
Combined heating and refrigeration systems, e.g. operating alternately or simultaneously	F25B29
Heat pumps	F25B30
LIGHTING (incl. CFL, LED)	
Gas- or vapor-discharge lamps (Compact Fluorescent Lamp)	H01J61
Electroluminescent light sources (LED)	H05B33

Note: The classification of CCMT fields with Y02 codes as well as their tagging inside PATSTAT was provided by the European Patent Office (EPO). For further details see www.oecd.org/environment/innovation/indicator.

ANNEX 1.A2

*Supplementary data*Table 1.A2.1. **Patenting activity in selected CCMT fields (1988-2007)**

	Solar PV	Solar TH	Wind	Geothermal	Hydro/ Marine	Biofuels	CO ₂ capture	CO ₂ storage	IGCC	Selected CCMTs	F&N energy	All sectors (TOTAL)
JP	3 941	142	196	32	199	112	104	6	37	4 672	5 751	691 751
US	1 303	172	320	50	387	135	199	19	56	2 508	5 543	423 187
DE	931	450	649	44	259	133	79	4	27	2 391	5 840	334 119
KR	802	13	32	1	26	11	10			885	584	107 001
FR	242	88	84	10	104	45	60	9	4	607	2 795	126 924
GB	212	47	87	9	174	27	28	3	11	560	1 039	84 062
IT	87	53	41	8	75	27	9		1	272	849	46 492
NL	96	51	56	9	22	13	14	1	3	236	539	29 009
CA	51	39	49	11	59	22	17	3	2	233	549	35 528
CT	160	11	9	2	14	4				195	122	20 850
CH	75	35	16	7	39	12	4	1	5	179	600	27 081
DK	5	5	152	2	17	4	1			177	175	7 929
ES	29	42	90	1	25	6	2	1		174	176	10 738
CN	80	13	20	6	14	11	4		1	143	108	18 892
AT	39	35	20	11	37	11	1		2	137	416	19 144
SE	23	18	34	7	35	6	1		7	122	719	27 986
NO	13	12	28	7	54	0.2	20	3	2	119	165	6 362
AU	41	43	11	1	22	7	3		3	112	132	10 150
FI	11	8	18	3	10	25	4		7	82	399	20 178
IL	19	38	9	14	16	3	2		3	82	59	11 441
BE	31	12	19	1	7	11	3		1	79	212	13 207
IN	28	1	3		1	6	6	0.3	1	45	22	4 584
RU	12	9	7		7	2	2		1	35	150	4 617
GR	8	10	5		8				1	24	8	990
BR	0.3		4		14	5				24	30	2 322
PT	3	7	2	1	6	1		1		19	17	565
IE	5	1	2		9	3				18	17	2 651
HU	1	10	1	4	3	1				16	32	2 102
SG	13	1	1	1	2					15	16	2 720
UA	1	2	4		1	5	1		1	14	34	777
NZ	3	5	1	1	3	1	2			13	11	1 388
HK	4	4	3		3		1			12	17	1 976
TR	3	3	2		3		1			10	8	566
TH	6	5	4							10	4	253
CZ	2	2	1	1	3	2				8	63	1 788

Table 1.A2.1. **Patenting activity in selected CCMT fields (1988-2007) (cont.)**

	Solar PV	Solar TH	Wind	Geothermal	Hydro/Marine	Biofuels	CO ₂ capture	CO ₂ storage	IGCC	Selected CCMTs	F&N energy	All sectors (TOTAL)
PL	0.2	3	2		3					7	26	1 149
MX	1	1			3	0.3	1			5	15	998
World Total	8 972	1 639	2 232	285	1 902	731	616	54	190	15 755	30 235	2 310 472

Note: Economies selected include those where TOTAL > 1 000 or CCMT > 10 (incl. 27 OECD economies and 10 non-OECD economies). Countries are ordered in descending order by their volume of CCMT patenting. The top five economies in each field are shown in bold. F&N Energy = Fossil-fuel and nuclear energy. TOTAL refers to the entire stock of CP patent applications in PATSTAT with priority dates during the given time period; note that for approx. 8.5% of all CPs the country of the inventor(s) is unknown.

Table 1.A2.2. **CCMT patent intensity**

% share of patenting in an CCMT field on patenting overall (TOTAL), 1988-2007 annual average

	Solar PV	Solar TH	Wind	Geothermal	Hydro/Marine	Biofuels	CO ₂ capture	CO ₂ storage	IGCC	Selected CCMTs	F&N energy
JP	0.57	0.02	0.03	0.00	0.03	0.02	0.02	0.00	0.01	0.68	0.83
US	0.31	0.04	0.08	0.01	0.09	0.03	0.05	0.00	0.01	0.59	1.31
DE	0.28	0.13	0.19	0.01	0.08	0.04	0.02	0.00	0.01	0.72	1.75
KR	0.75	0.01	0.03	0.00	0.02	0.01	0.01	0.00	0.00	0.83	0.55
FR	0.19	0.07	0.07	0.01	0.08	0.04	0.05	0.01	0.00	0.48	2.20
GB	0.25	0.06	0.10	0.01	0.21	0.03	0.03	0.00	0.01	0.67	1.24
IT	0.19	0.11	0.09	0.02	0.16	0.06	0.02	0.00	0.00	0.59	1.83
NL	0.33	0.17	0.19	0.03	0.07	0.04	0.05	0.00	0.01	0.81	1.86
CA	0.14	0.11	0.14	0.03	0.17	0.06	0.05	0.01	0.01	0.66	1.55
CT	0.77	0.05	0.04	0.01	0.07	0.02	0.00	0.00	0.00	0.93	0.59
CH	0.28	0.13	0.06	0.03	0.15	0.04	0.01	0.00	0.02	0.66	2.22
DK	0.06	0.06	1.92	0.03	0.21	0.04	0.01	0.00	0.00	2.23	2.20
ES	0.27	0.39	0.84	0.01	0.24	0.05	0.02	0.01	0.00	1.62	1.64
CN	0.42	0.07	0.10	0.03	0.07	0.06	0.02	0.00	0.01	0.76	0.57
AT	0.21	0.18	0.10	0.05	0.19	0.06	0.01	0.00	0.01	0.72	2.17
SE	0.08	0.06	0.12	0.03	0.13	0.02	0.00	0.00	0.02	0.44	2.57
NO	0.20	0.18	0.43	0.11	0.84	0.00	0.32	0.04	0.03	1.88	2.60
AU	0.40	0.42	0.10	0.01	0.21	0.07	0.03	0.00	0.02	1.10	1.30
FI	0.05	0.04	0.09	0.01	0.05	0.12	0.02	0.00	0.03	0.41	1.98
IL	0.17	0.33	0.08	0.12	0.14	0.03	0.02	0.00	0.03	0.71	0.51
BE	0.23	0.09	0.14	0.01	0.06	0.08	0.02	0.00	0.01	0.60	1.61
IN	0.61	0.02	0.07	0.00	0.02	0.13	0.12	0.01	0.01	0.98	0.49
RU	0.25	0.19	0.16	0.00	0.15	0.04	0.05	0.00	0.01	0.76	3.26
GR	0.79	1.01	0.50	0.00	0.81	0.00	0.00	0.00	0.10	2.41	0.81
BR	0.01	0.00	0.19	0.00	0.60	0.22	0.00	0.00	0.00	1.02	1.30
PT	0.47	1.24	0.32	0.18	1.06	0.18	0.00	0.18	0.00	3.45	2.98
IE	0.18	0.04	0.08	0.00	0.32	0.12	0.00	0.00	0.00	0.69	0.65
HU	0.06	0.45	0.05	0.19	0.14	0.05	0.00	0.00	0.00	0.75	1.50
SG	0.47	0.04	0.04	0.04	0.07	0.00	0.00	0.00	0.00	0.54	0.58
UA	0.13	0.24	0.51	0.00	0.13	0.64	0.13	0.00	0.13	1.78	4.42
NZ	0.24	0.32	0.07	0.07	0.22	0.07	0.11	0.00	0.00	0.92	0.77
HK	0.21	0.18	0.13	0.00	0.14	0.00	0.06	0.00	0.00	0.59	0.87
TR	0.49	0.53	0.27	0.00	0.53	0.00	0.09	0.00	0.00	1.72	1.44
TH	2.17	1.98	1.58	0.00	0.00	0.00	0.00	0.00	0.00	3.75	1.38
CZ	0.08	0.11	0.06	0.06	0.17	0.11	0.00	0.00	0.00	0.48	3.51
PL	0.01	0.22	0.17	0.00	0.26	0.00	0.00	0.00	0.00	0.58	2.31
MX	0.10	0.10	0.00	0.00	0.30	0.03	0.10	0.00	0.00	0.53	1.50

Note: The top five economies in each field are shown in bold.

Table 1.A2.3. **CCMT patenting per unit of GDP**

Number of CCMT claimed priorities per trillion USD in 2000 prices using PPP, 1988-2007 annual mean

	Solar PV	Solar TH	Wind	Geothermal	Hydro/Marine	Biofuels	CO ₂ capture	CO ₂ storage	IGCC	Selected CCMTs	F&N energy	All_sectors (TOTAL)
JP	62.48	2.25	3.10	0.50	3.16	1.78	1.65	0.10	0.59	74.07	91.2	10 967.4
US	7.34	0.97	1.80	0.28	2.18	0.76	1.12	0.11	0.32	14.12	31.2	2 381.8
DE	23.36	11.29	16.29	1.10	6.49	3.32	1.99	0.09	0.68	59.98	146.5	8 382.4
KR	57.70	0.94	2.27	0.07	1.84	0.76	0.68	0.00	0.00	63.67	42.0	7 700.6
FR	8.42	3.07	2.90	0.35	3.60	1.58	2.08	0.30	0.13	21.07	97.1	4 409.0
GB	7.39	1.65	3.03	0.31	6.07	0.94	0.97	0.09	0.38	19.56	36.3	2 933.5
IT	3.17	1.92	1.47	0.27	2.73	0.97	0.31	0.00	0.04	9.86	30.8	1 684.0
NL	11.33	5.98	6.68	1.07	2.56	1.54	1.68	0.12	0.30	27.96	63.8	3 437.6
CA	3.21	2.44	3.08	0.69	3.70	1.39	1.04	0.18	0.15	14.55	34.3	2 217.8
CT	18.97	1.30	1.01	0.18	1.66	0.51	0.00	0.00	0.00	23.04	14.5	2 468.9
CH	17.12	7.96	3.58	1.60	9.03	2.67	0.88	0.30	1.03	40.86	137.1	6 190.3
DK	1.79	1.59	53.68	0.70	5.99	1.23	0.35	0.00	0.00	62.34	61.6	2 793.8
ES	1.80	2.62	5.60	0.06	1.58	0.34	0.11	0.06	0.00	10.85	11.0	669.6
CN	0.88	0.14	0.21	0.06	0.15	0.12	0.04	0.00	0.01	1.56	1.2	206.8
AT	9.20	8.06	4.56	2.45	8.61	2.57	0.28	0.00	0.35	31.99	97.1	4 474.1
SE	5.04	3.89	7.34	1.51	7.56	1.37	0.29	0.00	1.40	26.34	155.2	6 041.7
NO	4.37	3.89	9.30	2.37	18.09	0.07	6.85	0.85	0.74	40.36	56.0	2 151.2
AU	4.17	4.35	1.07	0.10	2.20	0.70	0.32	0.00	0.26	11.43	13.5	1 039.0
FI	4.39	3.24	7.29	1.22	3.85	10.20	1.62	0.00	2.84	33.43	161.6	8 176.6
IL	7.20	14.26	3.38	5.07	6.00	1.13	0.75	0.00	1.13	30.65	22.1	4 292.5
BE	5.80	2.27	3.59	0.19	1.39	2.02	0.57	0.00	0.23	14.88	40.1	2 497.4
IN	0.62	0.02	0.07	0.00	0.02	0.13	0.13	0.01	0.01	1.00	0.5	101.9
RU	0.50	0.38	0.32	0.00	0.29	0.09	0.10	0.00	0.02	1.50	6.4	196.7
GR	2.01	2.57	1.28	0.00	2.05	0.00	0.00	0.00	0.26	6.11	2.1	254.1
BR	0.01	0.00	0.18	0.00	0.59	0.21	0.00	0.00	0.00	0.99	1.3	97.4
PT	0.85	2.23	0.58	0.32	1.91	0.32	0.00	0.32	0.00	6.20	5.4	179.7
IE	2.54	0.54	1.07	0.00	4.55	1.70	0.00	0.00	0.00	9.86	9.2	1 419.8
HU	0.54	3.85	0.41	1.62	1.22	0.41	0.00	0.00	0.00	6.42	12.8	853.0
SG	7.91	0.62	0.62	0.62	1.24	0.00	0.00	0.00	0.00	9.15	9.8	1 687.4
UA	0.18	0.34	0.73	0.00	0.18	0.92	0.18	0.00	0.18	2.54	6.3	142.4
NZ	2.17	2.94	0.65	0.65	1.96	0.65	0.98	0.00	0.00	8.37	7.0	905.6
HK	1.26	1.06	0.76	0.00	0.86	0.00	0.36	0.00	0.00	3.54	5.2	598.0
TR	0.25	0.27	0.14	0.00	0.27	0.00	0.05	0.00	0.00	0.89	0.7	51.5
TH	0.73	0.67	0.53	0.00	0.00	0.00	0.00	0.00	0.00	1.26	0.5	33.7
CZ	0.48	0.64	0.32	0.32	0.96	0.64	0.00	0.00	0.00	2.73	20.1	573.8
PL	0.02	0.34	0.27	0.00	0.41	0.00	0.00	0.00	0.00	0.91	3.6	156.2
MX	0.06	0.06	0.00	0.00	0.17	0.02	0.06	0.00	0.00	0.30	0.8	56.4

Note: The top five economies in each field are shown in bold.

Table 1.A2.4. **CCMT patenting per capita**
 Number of CCMT claimed priorities per ten million inhabitants, 1988-2007 annual average

	Solar PV	Solar TH	Wind	Geothermal	Hydro/Marine	Biofuels	CO ₂ capture	CO ₂ storage	IGCC	Selected CCMTs	F&N energy	All_sectors (TOTAL)
JP	15.65	0.56	0.78	0.13	0.79	0.44	0.41	0.02	0.15	18.55	22.8	2 747.2
US	2.38	0.31	0.58	0.09	0.71	0.25	0.36	0.04	0.10	4.58	10.1	772.3
DE	5.72	2.76	3.99	0.27	1.59	0.81	0.49	0.02	0.17	14.68	35.9	2 052.1
KR	8.76	0.14	0.34	0.01	0.28	0.11	0.10	0.00	0.00	9.66	6.4	1 168.8
FR	2.01	0.73	0.69	0.08	0.86	0.38	0.50	0.07	0.03	5.03	23.2	1 052.6
GB	1.81	0.40	0.74	0.08	1.48	0.23	0.24	0.02	0.09	4.78	8.9	717.4
IT	0.76	0.46	0.36	0.07	0.66	0.23	0.07	0.00	0.01	2.38	7.4	405.9
NL	3.05	1.61	1.80	0.29	0.69	0.42	0.45	0.03	0.08	7.53	17.2	926.1
CA	0.86	0.65	0.82	0.18	0.99	0.37	0.28	0.05	0.04	3.89	9.2	592.2
CT	3.71	0.25	0.20	0.03	0.32	0.10	0.00	0.00	0.00	4.50	2.8	482.3
CH	5.29	2.46	1.11	0.49	2.79	0.82	0.27	0.09	0.32	12.61	42.3	1 910.9
DK	0.48	0.43	14.41	0.19	1.61	0.33	0.09	0.00	0.00	16.74	16.5	750.0
ES	0.36	0.52	1.11	0.01	0.31	0.07	0.02	0.01	0.00	2.14	2.2	132.4
CN	0.03	0.01	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.06	0.0	7.7
AT	2.47	2.16	1.22	0.66	2.31	0.69	0.08	0.00	0.09	8.59	26.1	1 200.6
SE	1.32	1.02	1.93	0.40	1.98	0.36	0.08	0.00	0.37	6.92	40.7	1 586.3
NO	1.46	1.30	3.10	0.79	6.04	0.02	2.29	0.28	0.25	13.47	18.7	718.0
AU	1.08	1.13	0.28	0.03	0.57	0.18	0.08	0.00	0.07	2.97	3.5	270.1
FI	1.06	0.78	1.75	0.29	0.93	2.45	0.39	0.00	0.68	8.04	38.9	1 966.1
IL	1.63	3.24	0.77	1.15	1.36	0.26	0.17	0.00	0.26	6.96	5.0	974.0
BE	1.50	0.59	0.93	0.05	0.36	0.52	0.15	0.00	0.06	3.85	10.4	646.6
IN	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.0	2.4
RU	0.04	0.03	0.03	0.00	0.02	0.01	0.01	0.00	0.00	0.12	0.5	15.8
GR	0.36	0.46	0.23	0.00	0.37	0.00	0.00	0.00	0.05	1.11	0.4	46.0
BR	0.00	0.00	0.01	0.00	0.04	0.01	0.00	0.00	0.00	0.07	0.1	6.9
PT	0.13	0.34	0.09	0.05	0.29	0.05	0.00	0.05	0.00	0.96	0.8	27.7
IE	0.63	0.13	0.26	0.00	1.13	0.42	0.00	0.00	0.00	2.44	2.3	350.9
HU	0.07	0.46	0.05	0.20	0.15	0.05	0.00	0.00	0.00	0.77	1.5	102.6
SG	1.71	0.13	0.13	0.13	0.27	0.00	0.00	0.00	0.00	1.98	2.1	364.2
UA	0.01	0.02	0.04	0.00	0.01	0.05	0.01	0.00	0.01	0.14	0.3	7.8
NZ	0.44	0.60	0.13	0.13	0.40	0.13	0.20	0.00	0.00	1.70	1.4	184.4
HK	0.33	0.28	0.20	0.00	0.22	0.00	0.09	0.00	0.00	0.92	1.4	155.6
TR	0.02	0.02	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.08	0.1	4.4
TH	0.05	0.04	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.08	0.0	2.1
CZ	0.07	0.10	0.05	0.05	0.15	0.10	0.00	0.00	0.00	0.41	3.0	86.9
PL	0.00	0.03	0.03	0.00	0.04	0.00	0.00	0.00	0.00	0.09	0.3	15.0
MX	0.01	0.01	0.00	0.00	0.02	0.00	0.01	0.00	0.00	0.03	0.1	5.3

Note: The top five economies in each field are shown in bold.

Table 1.A2.5. **CCMT patenting per dollar of general R&D**

Number of CCMT claimed priorities per unit of Gross Domestic Expenditures on R&D (GERD) in billion USD
using 2000 prices and PPP, 1988-2007 annual average

	Solar PV	Solar TH	Wind	Geothermal	Hydro/Marine	Biofuels	CO ₂ capture	CO ₂ storage	IGCC	Selected CCMTs	F&N energy	All_sectors (TOTAL)
JP	2.05	0.07	0.10	0.02	0.10	0.06	0.05	0.00	0.02	2.43	2.99	359.8
US	0.28	0.04	0.07	0.01	0.08	0.03	0.04	0.00	0.01	0.54	1.19	90.6
DE	0.97	0.47	0.68	0.05	0.27	0.14	0.08	0.00	0.03	2.50	6.10	349.0
KR	2.06	0.03	0.08	0.00	0.07	0.03	0.02	0.00	0.00	2.27	1.50	274.4
FR	0.38	0.14	0.13	0.02	0.16	0.07	0.09	0.01	0.01	0.95	4.40	199.8
GB	0.40	0.09	0.16	0.02	0.33	0.05	0.05	0.01	0.02	1.05	1.95	157.9
IT	0.29	0.18	0.14	0.02	0.25	0.09	0.03	0.00	0.00	0.91	2.83	154.8
NL	0.61	0.32	0.36	0.06	0.14	0.08	0.09	0.01	0.02	1.49	3.41	183.8
CA	0.18	0.14	0.17	0.04	0.20	0.08	0.06	0.01	0.01	0.80	1.89	122.5
CT	0.81	0.06	0.04	0.01	0.07	0.02	0.00	0.00	0.00	0.98	0.62	105.4
CH	0.65	0.30	0.14	0.06	0.34	0.10	0.03	0.01	0.04	1.56	5.23	235.9
DK	0.09	0.08	2.57	0.03	0.29	0.06	0.02	0.00	0.00	2.98	2.95	133.7
ES	0.19	0.28	0.60	0.01	0.17	0.04	0.01	0.01	0.00	1.16	1.17	71.5
CN	0.13	0.02	0.03	0.01	0.02	0.02	0.01	0.00	0.00	0.23	0.18	30.8
AT	0.49	0.43	0.24	0.13	0.46	0.14	0.01	0.00	0.02	1.71	5.18	238.5
SE	0.14	0.11	0.20	0.04	0.21	0.04	0.01	0.00	0.04	0.72	4.25	165.4
NO	0.26	0.23	0.56	0.14	1.09	0.00	0.41	0.05	0.04	2.44	3.38	129.9
AU	0.27	0.28	0.07	0.01	0.14	0.04	0.02	0.00	0.02	0.73	0.86	66.3
FI	0.16	0.11	0.26	0.04	0.14	0.36	0.06	0.00	0.10	1.18	5.71	289.1
IL	0.19	0.38	0.09	0.13	0.16	0.03	0.02	0.00	0.03	0.81	0.58	113.2
BE	0.32	0.12	0.20	0.01	0.08	0.11	0.03	0.00	0.01	0.81	2.18	135.7
RU	0.04	0.03	0.03	0.00	0.02	0.01	0.01	0.00	0.00	0.12	0.51	15.7
GR	0.39	0.49	0.25	0.00	0.40	0.00	0.00	0.00	0.05	1.18	0.40	49.0
PT	0.12	0.32	0.08	0.05	0.27	0.05	0.00	0.05	0.00	0.89	0.77	25.8
IE	0.22	0.05	0.09	0.00	0.39	0.14	0.00	0.00	0.00	0.84	0.79	121.4
HU	0.06	0.44	0.05	0.18	0.14	0.05	0.00	0.00	0.00	0.73	1.46	97.1
SG	0.24	0.02	0.02	0.02	0.04	0.00	0.00	0.00	0.00	0.28	0.30	51.7
NZ	0.21	0.28	0.06	0.06	0.19	0.06	0.09	0.00	0.00	0.81	0.67	87.1
TR	0.05	0.06	0.03	0.00	0.06	0.00	0.01	0.00	0.00	0.19	0.16	10.8
CZ	0.04	0.05	0.02	0.02	0.07	0.05	0.00	0.00	0.00	0.21	1.56	44.5
PL	0.00	0.05	0.04	0.00	0.06	0.00	0.00	0.00	0.00	0.14	0.56	24.1
SK	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.02	0.00	2.7
ZA	0.00	0.02	0.07	0.00	0.04	0.00	0.00	0.00	0.00	0.13	0.00	15.1
MX	0.02	0.02	0.00	0.00	0.05	0.01	0.02	0.00	0.00	0.08	0.23	15.6
AR	0.05	0.03	0.07	0.00	0.03	0.00	0.02	0.00	0.00	0.16	0.00	13.0
SI	0.07	0.20	0.00	0.00	0.10	0.00	0.00	0.00	0.00	0.37	0.00	90.0
RO	0.03	0.00	0.00	0.00	0.02	0.03	0.00	0.00	0.00	0.09	0.00	16.4
IS	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.00	67.1

Note: Inventor economies selected include those for which GERD data were available. The top five economies in each field are shown in bold.

Chapter 2

The determinants of innovation in electricity generation technologies: A patent data analysis

by

Elisa Lanzi, Ivan Haščič and Nick Johnstone

In this chapter we analyse the determinants of innovation in the electricity generation sector. We present data on the evolution of different types of technologies – renewables, fossil fuel based and nuclear – by considering patent data for 11 OECD countries over the period 1978-2008. We pay particular attention to the role that fossil fuel prices play in inducing innovation in electricity generation. The results show that the effect of the fossil fuel price varies according to the different types of technologies. While the effect on fossil fuel technologies is negative, it is positive on renewables, which suggests that there may be a possible substitution effect. The point at which the substitution effect outweighs the efficiency effect is somewhat less than the peak oil price of the most recent oil price shock.

1. Introduction

While international negotiations on climate mitigation have had a chequered history in recent years, there has been significant increase in national policy efforts targeted at the reduction of greenhouse gas emissions. Much of this focuses on the energy sector, as the main source of emissions. In this context, the importance of the development and use of new mitigation-oriented technologies for the production of electricity is crucial. In particular, the use of fossil fuels for the production of electricity should be based on efficiency-enhancing technologies thanks to which carbon emissions can be reduced. Electricity production accounts for about a quarter of the overall anthropogenic CO₂ emissions, thus greatly contributing to the problem of climate change. Investment in new efficiency-enhancing technologies for power generation – both fossil fuel based and carbon-free – is essential for the realization of policy objectives.

According to the International Energy Agency *Key World Energy Statistics 2010* (IEA, 2010) total world total primary energy supply mostly relies on fossil fuels. In 2009, 37.2% of TPES in the OECD was produced with oil, 24.2% with gas and 19.7% with coal. Nuclear energy accounted for 11.3%, hydro for 2.1%, and renewables for 4.4%. For the world as whole, fossil fuels represented an even more significant share in 2008: 33.2% oil, 27.0% for coal/peat, and 21.1% for gas. Therefore, the invention and diffusion of efficiency-enhancing technologies is crucial, but it is also important that there is a switching from fossil fuels based to carbon free technologies.

Innovation in this sector can be expected to respond to price incentives and particularly to an increase in fossil fuel prices, which can be considered as an indicator of the pressure on the electricity market also deriving from increasing attention to climate change. As fossil fuel prices rise there will be an efficiency effect, inducing innovation in all efficiency-enhancing technologies for electricity generation. However, there may also be a substitution effect driving away innovation from fossil fuel based towards carbon free technologies.

This hypothesis is supported by recent works on directed technical change applied to the environmental sphere, such as Acemoglou *et al.* (2009) and Sue Wing (2006), which shows that substitution between intermediate inputs is the crucial parameter in the determination of innovation. If substitution between energy production sources is easy, then the substitution effect will prevail. In this case, fossil fuel energy will be replaced with carbon free energy and innovation in fossil fuel technologies will decline. Innovation in carbon-free technologies is expected to increase as both the efficiency and the substitution effects will induce more innovation.

The literature on innovation and patents mostly focuses on patenting activity and environmental regulation in specific sectors. Lanjouw and Mody (1996) for example examined the relationship between patenting activity and stringency of environmental policy measured in terms of pollution abatement. They found that pollution abatement induces innovation by increasing the number of patents. Jaffe and Palmer (1997) use R&D

expenditure and patents to study whether changes in regulatory stringency lead to innovation. They do not find evidence that patenting activity responds to environmental regulation. More recently, studies such as Popp (2006) focused on the effect that different policy instruments have on innovation. He finds that command-and-control policy instruments are less effective than market-based instruments. Most of these studies are country-specific or consider a limited number of countries. De Vries and Withagen (2005) instead use cross-country data to investigate the relationship between environmental policy for limiting SO₂ emissions and patenting activity. They find some evidence that the stringency of environmental policies induces innovation.

Only a few papers have focused more specifically on the energy sector. Popp (2002) considers the effect of energy prices on innovation in efficiency-enhancing technologies and finds that energy prices are a determinant of innovation. A recent study by Johnstone *et al.* (2010) uses a panel of OECD economies with data on patents and R&D for different renewable technologies and on different types of environmental regulations to check for the presence of induced innovation. The authors find that different types of policies are effective for different types of renewable technologies.

This chapter draws on the work by Johnstone *et al.* (2010) to study the dynamics of innovation between different technology types as induced by fossil fuel prices using a panel of patent data relative to 11 OECD economies over the period 1978-2008. The analysis uses public R&D expenditure, as it is an essential component of an innovation strategy to improve energy efficiency (Nemet and Kammen, 2007). R&D expenditure is expected to have a positive effect on innovation. Innovation also depends on the size of the sector and of the market it is serving. In a large and fast growing market there will be higher potential for inventive talent and stimulus to improve efficiency (see Popp, 2006). Electricity consumption is used to proxy for the growing size of markets and expects that it will have a positive sign. Finally, economies that have a high propensity to patent and a large production of innovative output in general are expected to produce more innovation in specific fields. To control for this effect, the total number of patents is also included as an explanatory variable.

The contribution of this chapter is twofold. First, it illustrates that increasing fossil fuel prices drive innovation in efficiency-enhancing electricity generation technologies. Second, by analysing innovation in different types of technologies, it shows that the effect of fossil fuel prices is not homogenous for all energy generation technologies. This provides insights on the substitutability of innovation efforts between energy types. An increase in fossil fuel prices is therefore likely to have a positive impact on the carbon efficiency of energy, as it both leads to an increase in efficiency-enhancing technologies, and to a switching from fossil fuel towards carbon free technologies.

The chapter is organized as follows. Section 2 describes the data used with a particular focus on patent data, which are analyzed to understand the innovation dynamics. Section 3 illustrates the empirical analysis by specifying the model, the estimation method used, and the empirical results. Section 4 concludes.

2. Patent data in the electricity sector

Patents have emerged as one of the main indicators used for measuring innovation. They are a measure of the output of innovation, and as such reflect the innovative performance of firms and economies (Griliches, 1990). They are a useful indicator as they

can be distinguished by the nature of the applicant and of the invention. This allows for the generation of patent counts by year, country, and technological field. Although not all inventions are patented there are few examples of economically significant inventions that have not been patented (Dernis *et al.*, 2001). Patents are issued by national offices as a means to protect new technologies with property rights within that country. This excludes others from the production for a defined number of years, which varies upon the nature of the innovation and the rules of the national offices. In order to be patented, an innovation needs to be novel, non-obvious, and commercially viable (Dernis *et al.*, 2001).

However, patents are an imperfect measure of innovation. First of all, it is difficult to identify the value of a patent and some patents may have a higher impact on the market than others. For this reason, patents are usually weighted to account for their difference in value, which in this case would consist in appreciably lowering greenhouse gas emissions. The most common procedure to weight patents is to use citations (Popp, 2002).¹ As an alternative methodology, only patents that are protected in multiple countries (so-called “claimed priorities”²) are selected. Previous research has demonstrated that the number of offices for which protection of a given invention is sought is a good indicator of patent value (see Guellec and van Pottelsberghe, 2000; Harhoff *et al.*, 2003).

The second shortcoming in the use of patents is that the propensity to patent, the patent regimes, and the innovative activity change across countries. In this paper, this problem is addressed in two ways: *a*) by including country fixed effects; and *b*) by controlling for the total number of claimed priorities in all technological fields.

The fact that patent data can be disaggregated by technology proves useful for the selection of the technological areas of interest. The International Patent Office (IPO) supplies patent classification codes developed by the World Intellectual Property Organization (WIPO), thanks to which patents are classified into different technological areas and at several hierarchical levels. The International Patent Classification (IPC) (WIPO, 2006) is application-based, thus facilitating the identification of specific technology classes, and particularly for the scope of the present work, of classes including efficiency-enhancing patents for electricity production.

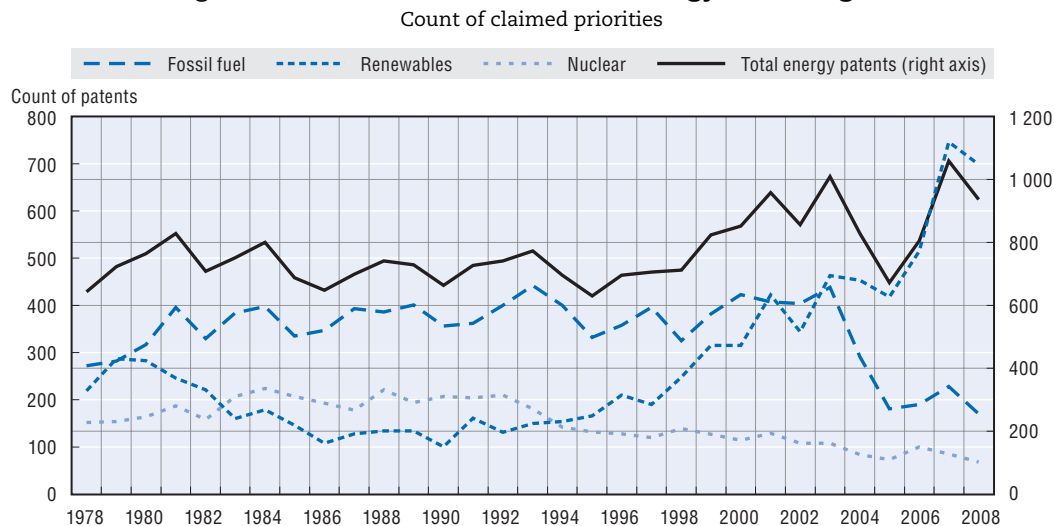
Relevant patent classes have been selected after a careful and extensive review of technological developments in the area of efficiency-enhancing technologies (Lanzi *et al.*, 2011). Thanks to this review a set of technology-specific keywords has been identified. These were then used to determine the appropriate IPC codes related to each of the technologies of interest. The fossil fuel technologies are gas turbines, compressed ignition engines, cogeneration, combined cycles, superheaters, steam engines, boilers, burners and fluidized beds, and the related IPC classes are listed in Annex I. Technology classes for the renewable energy technologies have been taken from Johnstone *et al.* (2010). These include wind, solar, geothermal, ocean, biomass and waste. Finally, IPC classes have been selected for both nuclear fusion and fission.

With the use of the selected IPC classifications, data have been extracted from the EPO/OECD *Worldwide Patent Statistical Database* (usually referred to as PATSTAT). The PATSTAT Database is an extensive and comprehensive database that answers the needs of researchers and policy-makers to combine different data sets for patent-related information.

The patent selection process allowed us to create a database of patent data for the different types of technologies. Thus, it is possible to study innovation in this sector in

aggregate as well as to analyse the dynamics of the different technologies. Figure 2.1 illustrates the development for the world sum of claimed priority counts for efficiency-enhancing patents in aggregate and by technology type for the period 1978-2008. The aggregate number of patents was rather stable until 1997, when it started growing consistently. Interestingly energy patents start to increase rapidly after 1997, the year of ratification of the Kyoto Protocol. The increasing political attention given to the problem of climate change and greenhouse gases emissions may have contributed to stimulate the development of efficiency-enhancing technologies for electricity generation.

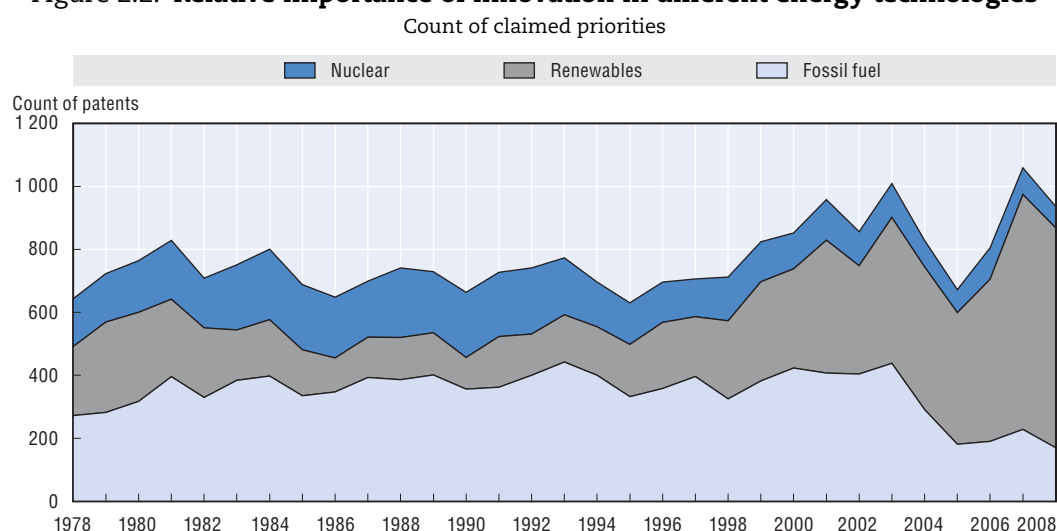
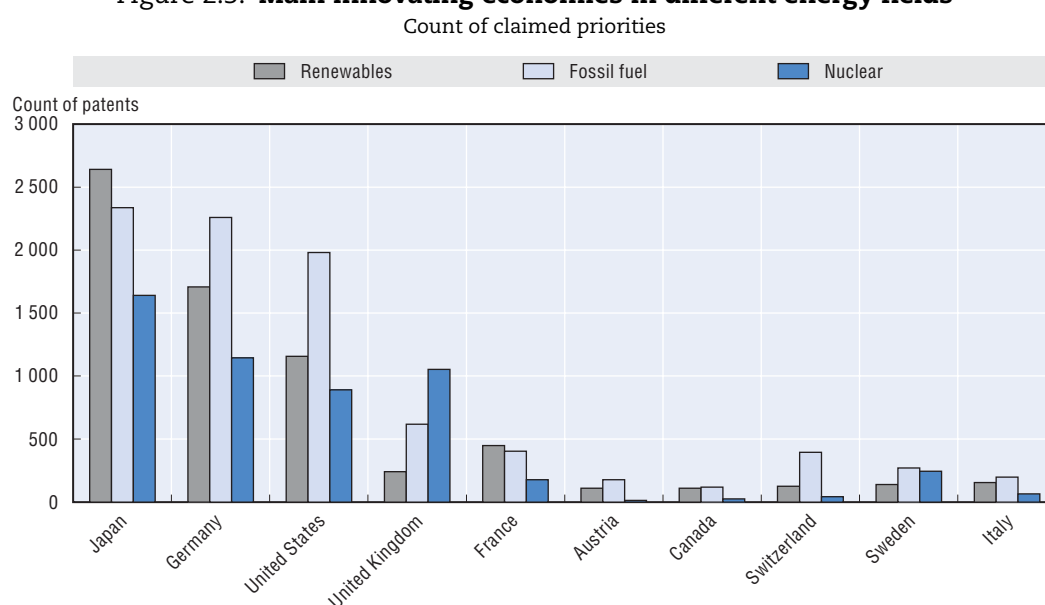
Figure 2.1. **Trends in innovation in energy technologies**



Looking at the different types of technologies aimed at improving energy efficiency it is possible to see that they behave in different ways. Whereas some technologies increase in recent years, other ones appear to be declining. Renewable energy patents had a peak in the late 1970s and early 1980s, and then were stable until late 1990s where they started growing more rapidly. Fossil fuel technologies, though stable over time in the past, have declined in the past decade. Finally, patents relative to nuclear energy exhibit a slow decline starting from the early 90s.

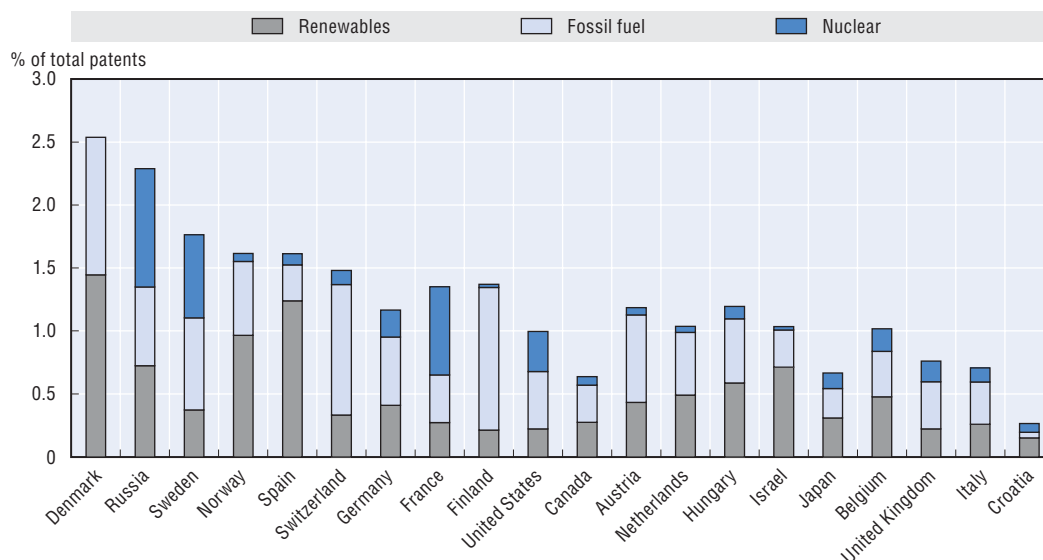
Figure 2.2 illustrates the number of claimed priorities in a stacked area graph that helps identify the relative increase in the different types of patents over time. The graph illustrates that renewables have been increasing more than fossil fuels and nuclear. This is mostly due to the fact that it is a new technology so that more inventions are created. Looking at all technologies together, it is possible to see that the overall investments have been stable while the internal dynamics have slightly changed. In particular, fossil fuel technologies have decreased relative to other technologies.

Figure 2.3 shows the aggregate count of patents over the time period 1978-2008 for the countries with highest number of patents in electricity generation. Main innovating countries are the same for the different types of technologies, although it is possible to see that there is a certain level of specialization. For example, Germany and the USA have a large number of patents in fossil fuel technologies; while the UK has the highest number of patents in nuclear.

Figure 2.2. **Relative importance of innovation in different energy technologies**Figure 2.3. **Main innovating economies in different energy fields**

These values do not control for the effect of relative size of the economies, nor their general ability and propensity to innovate. In order to normalise the relative amount of innovation in these technologies, Figure 2.4 illustrates the number of claimed priorities in electricity generation standardised with the total number of patents. Here it is possible to see that the countries with the highest relative number of patents in electricity generation are Denmark, Russia, and Sweden. Some countries, like Russia, Germany, or the UK, have a homogenous number of patents across the different technology types. For other countries, there is a clear bias towards a certain type of technology, like renewables in Denmark and Spain, or fossil fuels in Switzerland and Finland. The differences between the standardized graph and the one in actual values highlight the importance of taking into consideration the propensity to patent, and the country specific heterogeneities that derive from the different property right systems.

Figure 2.4. **Per cent of energy patents in total patents**
Claimed priorities



3. The determinants of innovation in the sector

The first explanatory variable included in the models estimates is the price of fossil fuels. Higher fossil fuel prices increase production costs of the firms. This encourages firms to invest in new technologies that lower the input of fossil fuels, and thus production costs. Thanks to this efficiency effect, fossil fuel prices produce an increase in innovation in efficiency-enhancing electricity generation technologies.

However, when looking at the single technologies there may also be a substitution effect. With fossil fuel prices increasing, there may be a switching towards carbon free technologies. Thus, fossil fuel prices will have a positive effect on the disaggregated carbon free technologies, while for fossil fuel technologies the effect will depend on the prevalence of the efficiency or substitution effect. Fossil fuel prices have been obtained for coal, oil and gas, using data from the IEA Energy prices and taxes database (IEA, 2009b). Since they are highly correlated, an index of real prices for fuel oil used in industry (2010 = 100) has been used.³

Public R&D investments are also considered as an indicator of the public effort in support of technological development. R&D data are obtained from the *International Energy Agency (IEA)'s Energy Technology Research Development Database* (IEA, 2009c), which national public expenditures on energy R&D disaggregated by type of technology. Therefore, it is possible to create separate measures for the different technologies. It is generally expected that the sign on this variable is positive, as more investment in R&D should lead to a higher innovative activity. Having only public R&D data is a limitation. With full availability of data on both private and public R&D, it would have been possible to study innovation as a two step-estimation in which prices would influence the choice of firms in their R&D investments, and then R&D would have lead to innovation according to its effectiveness. However, the use of public R&D data only in a single equation is unlikely to result in problems of endogeneity.

To control for the electricity market size, which can influence the potential market for innovation, electricity consumption is included as an explanatory variable. Data on household and industry sector electricity consumption are obtained from the IEA's *Energy*

Balances Database (IEA, 2009a). To control for the different propensity to patent, the total count of claimed priorities are considered. Finally, fixed effects control for country specific heterogeneities.

Table 2.1 summarises the descriptive statistics for the explanatory variables included in the panel. For the patent data the mean of the variables are rather similar between all technology types, but the standard deviations differ consistently. There is a higher variation in fossil fuels than in renewable and nuclear. For R&D investment, the highest variation is in nuclear. As the aim of the empirical analysis is to compare the effect of the price index on the different types of technologies, the same panel has been used for all regressions. This facilitates the comparability of results.

Table 2.1. **Descriptive statistics of explanatory variables (1978-2008)**

Variable	Unit of measure	Obs	Mean	Std. dev.
Claimed priorities – Fossil fuels	Number of claimed priorities	123	48.82	39.96
Claimed priorities – Renewables	Number of claimed priorities	123	26.07	21.36
Claimed priorities – Nuclear	Number of claimed priorities	123	23.50	21.76
Claimed priorities – Total	Number of claimed priorities (thousands)	123	12.88	11.97
Oil price index	Price index for fuel oil (2010 = 100)	123	61.10	24.43
Consumption of electricity	Thousand TWh	123	969.99	1049.22
R&D – Fossil fuels	Billion 2000 US\$ – Constant prices and PPP	123	0.03	0.04
R&D – Renewables	Billion 2000 US\$ – Constant prices and PPP	123	0.16	0.25
R&D – Nuclear	Billion 2000 US\$ – Constant prices and PPP	123	0.82	0.89

4. Model specification, estimation method and results

The model is a reduced form equation and is estimated for all energy technologies, as well as for the single technologies:

$$CP_{it} = \beta_0 + \beta_1 R\&D_{it} + \beta_2 P_{it} + \beta_3 P_{it}^2 + \beta_3 CONS_{it} + \beta_4 CPT_{it} + \alpha_i + \varepsilon_{it} \quad (1)$$

where $i = (1, \dots, 18)$ indexes the cross-sectional unit (country) and $t = (1978, \dots, 2008)$ indexes time. The dependent variable, patenting activity $CP_{i,t}$, is measured by the number of patent claimed priorities in the relevant technology areas. The explanatory variables include specific R&D expenditures ($RD_{i,t}$), fossil fuel prices ($P_{i,t}$) as well as the square of fossil fuel prices, growth rate of electricity consumption ($CONS_{i,t}$), and total patent counts ($CPT_{i,t}$). Fixed effects (α_i) are introduced in order to capture unobservable country-specific heterogeneity. All residual variation is captured by the error term ($\varepsilon_{i,t}$). In the estimation of fossil fuel technologies, the squared price index has also been included as for this technology in particular it is reasonable to expect that the effect of prices is non-linear.

The model applies the framework used in Johnstone *et al.* (2010) to explore the effect that fossil fuel prices have on efficiency-enhancing technologies for electricity generation for the single technology types and in aggregate. As fossil fuels are an input for one of the main technology types, they will not only influence innovation in this sector but also in the substitute ones.

Patent data are usually estimated with techniques appropriate for count data models, namely data for which the dependent variable is non-negative.⁴ The classical approach to count data estimation is to use the Poisson regression, assuming that the conditional

distribution of the dependent variable follows a Poisson distribution, as in El Sayyad (1973) and Maddala (1983). However, the Poisson regression is based on the strong assumption of variance-mean equality, which has been rejected in numerous applications.

A relaxed version of this assumption is allowed by the Poisson quasi-maximum likelihood estimator (QMLE), which allows the variance-mean ratio to be any positive constant σ^2 . When $\sigma^2 < 1$, the mean of the distribution is greater than the variance, thus there is underdispersion in the sample. When instead $\sigma^2 > 1$, the mean of the distribution is smaller than the variance, thus there is overdispersion. In the latter case, the distribution corresponds to a Negative Binomial I, which is a particular parameterization of the negative binomial distribution, as explained in Cameron and Trivedi (1986). Given that our sample has a high number of zero counts, it is likely to be overdispersed, and thus the negative binomial estimation is preferable to the Poisson.

Whilst count data models were initially designed for cross-sectional data, extensions have been developed for panel data model, starting with the pioneering work by Hausman, Hall and Griliches (1973), who studied patent applications by firms in terms of R&D spending. This analysis follows their work in using a fixed effect negative binomial estimation technique. A further problem with the data is that it is not just heteroschedastic because of its count data nature, but also heteroschedastic across countries. In fact, because most innovation takes place in a limited number of countries, there is a further problem of heteroschedasticity. This is corrected for by applying a robust estimation.

The model is estimated using the same panel to facilitate the comparison of results, which are illustrated in Table 2.2. The oil price index has different effects across the technology types. Its effect is positive on renewables, non-significant on nuclear technologies, and positive but decreasing over time on fossil fuel technologies.⁵ The non-linear effect on fossil fuel technologies shows that whereas initially a price increase leads to more innovation in energy efficient fossil fuel technologies, as price becomes higher,

Table 2.2. **Estimation results**

	Fossil fuel	Renewables	Nuclear
Oil price index	0.0243 *** (-0.005)	0.0089*** (0.000)	-0.0039 (-0.110)
Oil price index, sq.	-0.0002*** (-0.001)		
R&D fossil fuels	1.1074 (-0.331)		
R&D renewables		0.9723*** (0.000)	
R&D nuclear			0.4403*** (0.000)
Electricity consumption	-0.0009*** (0.000)	0.0006*** (0.000)	-0.0007*** 0.000
Total patents	-.0204*** (-0.008)	.0180* (-0.025)	.0879** (0.000)
Fixed effect	Yes	Yes	Yes
Observations	123	123	123
Log-likelihood	-472.75	-424.65	-403.29
Pseudo R2	0.2144	0.19	0.2136
(Prob > chi2)	0	0	0

p-values are in parentheses. The dependent variable is claimed priorities in fossil-fuel energy-enhancing technologies.

less innovation takes place. This combined with the positive effect on renewable, shows that there is a possible substitution effect between renewable and fossil fuel technologies.

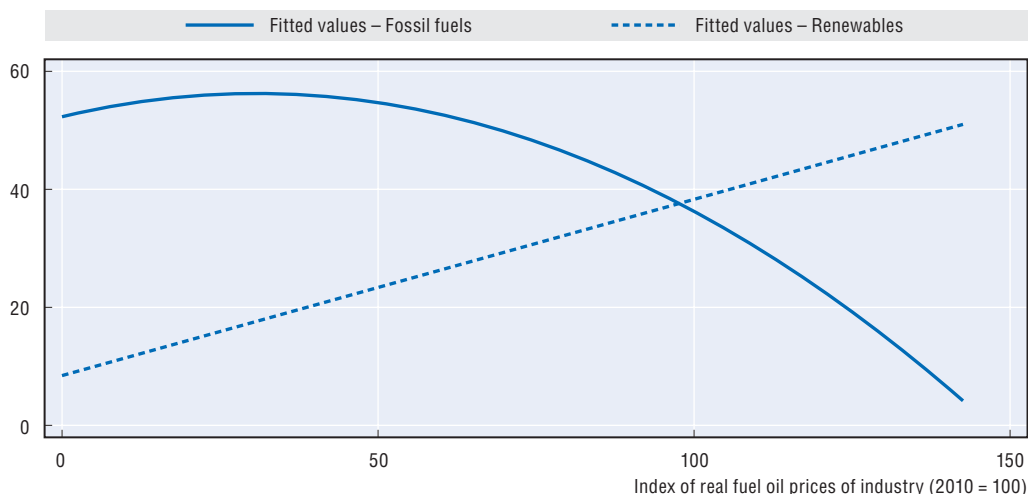
Intuitively, despite the fact that all the technologies considered are aimed at improving the efficiency of using fossil fuels for electricity generation, with increasing prices, political pressure on actions to mitigate climate change, and uncertainty about prices and supply of fossil fuels, innovation decreases in fossil fuels while increasing in carbon free technologies. Fossil fuel prices do not influence technologies regarding nuclear power plants. Innovation in this sector is more influenced by other variables, such as energy consumption.

Public R&D expenditures have a positive and significant effect on innovation in all technologies, but fossil fuels. The effect of electricity consumption is negative and significant for fossil fuel and nuclear technologies, and positive and significant for renewables. The estimated coefficient of the total number of patents is positive and statistically significant for renewable and nuclear, but negative for fossil fuels. This suggests that fossil fuel technologies are not the main focus of the countries with the highest propensity to patent.

For all regressions, values of the likelihood ratio chi-squared test with three degrees of freedom are given. From these it is possible to see that all models are statistically significant. Estimates of the log of the over-dispersion parameter alpha are also obtained in order to check whether the negative binomial estimation is appropriate. The likelihood ratio chi-square tests support the use of negative binomial.⁶

To illustrate the switching between renewable and fossil fuel technologies, we calculate predicted values for these technologies and graphically compare the effect of the price index on innovative activity. Figure 2.5 shows that while the price index has a positive effect on renewables, the effect is only initially positive on fossil fuel technologies. Whereas these increase at first as the price index increases, after a certain level they start declining. The point at which the curves intersect is in the region of oil prices experienced during the most recent oil price shock.

Figure 2.5. **Oil prices and innovation in fossil fuel and renewable energy**



5. Concluding remarks

A panel of OECD economies for the period 1978-2008 is used in order to analyse innovation in energy efficient electricity generation technologies. Different technologies are considered separately in order to study the intra-sectoral dynamics. The empirical results demonstrate that fossil fuel prices induce innovation in energy efficient electricity generation technologies. The results show that the effect is not uniform across the different technologies. Fossil fuel prices have a linear positive effect on renewables, but decreasingly positive effect on fossil fuel technologies and no significant effect on nuclear. This result supports the hypothesis of a substitution effect between fossil fuel and carbon free technologies.

This chapter finds long-run internal dynamics, which could lead to a change in the technology mix for electricity production. From an initial analysis of the effect of fossil fuel prices on innovation it is found that increasing costs of fossil fuels is likely to induce such a change in the energy mix. Therefore, price mechanisms such as emissions trading, and carbon taxes are likely going to lead to a change in the direction of innovation towards carbon-free technologies.

This empirical analysis contributes to the literature by combining and comparing information on innovation in different types of technologies. Whereas this is usually done with applied climate-economy models, the empirical literature analyzing the changes in the direction of innovation is not yet well developed. This chapter underlines the need to explore this topic further by combining empirical analysis with more structural models of directed technical change.

Notes

1. The number of times the patent has been cited in other patent applications. This is an indicator on the importance of the innovation in the technological field.
2. Patents that have only been registered in one patent office are referred to as singulars. Patents that have been registered in multiple offices are instead referred to as claimed priorities. A patent that is registered in an office but that had already been registered before is referred to as a duplicate.
3. More specifically, prices of oil and gas are highly correlated, thus only price of oil is included. The price of coal is not correlated to the other two fuel input prices, and it is rather stable over time. The coal prices data are scarce in terms of number of countries covered and they consistently lower the number of observations in the sample. Thus, as coal price is never found significant in the regressions, and as its omissions does not significantly change the results, it is omitted from the regressions, leaving the price of oil to be the unique measure of fuel input prices.
4. For an overview of count data models see Cameron and Trivedi (1998) or Wooldridge (2002).
5. The squared term on the oil price was statistically insignificant for renewable and nuclear.
6. The test is used to verify whether the overdispersion parameter α is statistically significant from zero. If α equals zero, then there is no overdispersion. If the test is significant zero-truncated negative binomial is preferred to zero-truncated Poisson. In all estimated models the test is significant supporting the choice of estimating with negative binomial.

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ANNEX 2.A1

Selected patent data classes for fuel-based technologies

COAL GASIFICATION	
C10J3	Production of combustible gases containing carbon monoxide from solid carbonaceous fuels
IMPROVED BURNERS	
[Classes listed below excluding combinations with B60, B68, F24, F27]	
F23C1	Combustion apparatus specially adapted for combustion of two or more kinds of fuel simultaneously or alternately, at least one kind of fuel being fluent
F23C5/24	Combustion apparatus characterized by the arrangement or mounting of burners; Disposition of burners to obtain a loop flame.
F23C6	Combustion apparatus characterized by the combination of two or more combustion chambers (using fluent fuel)
F23B10	Combustion apparatus characterized by the combination of two or more combustion chambers (using only solid fuel)
F23B30	Combustion apparatus with driven means for agitating the burning fuel; Combustion apparatus with driven means for advancing the burning fuel through the combustion chamber
F23B70	Combustion apparatus characterized by means for returning solid combustion residues to the combustion chamber
F23B80	Combustion apparatus characterized by means creating a distinct flow path for flue gases or for non-combusted gases given off by the fuel
F23D1	Burners for combustion of pulverulent fuel
F23D7	Burners in which drops of liquid fuel impinge on a surface
F23D17	Burners for combustion simultaneously or alternatively of gaseous or liquid or pulverulent fuel
FLUIDIZED BED COMBUSTION	
B01J8/20-22	Chemical or physical processes (and apparatus therefore) conducted in the presence of fluidised particles, with liquid as a fluidising medium
B01J8/24-30	Chemical or physical processes (and apparatus therefore) conducted in the presence of fluidised particles, according to "fluidised-bed" technique
F27B15	Fluidised-bed furnaces; Other furnaces using or treating finely-divided materials in dispersion
F23C10	Apparatus in which combustion takes place in a fluidised bed of fuel or other particles
IMPROVED BOILERS FOR STEAM GENERATION	
F22B31	Modifications of boiler construction, or of tube systems, dependent on installation of combustion apparatus; Arrangements or dispositions of combustion apparatus
F22B33/14-16	Steam generation plants, e.g. <i>comprising steam boilers of different types in mutual association</i> ; Combinations of low- and high-pressure boilers
IMPROVED STEAM ENGINES	
F01K3	Plants characterised by the use of steam or heat accumulators, or intermediate steam heaters, therein
F01K5	Plants characterised by use of means for storing steam in an alkali to increase steam pressure, e.g. of Honigmann or Koenemann type
F01K23	Plants characterised by more than one engine delivering power external to the plant, the engines being driven by different fluids
SUPERHEATERS	
F22G	Superheating of steam

IMPROVED GAS TURBINES	
F02C7/08-105	Gas turbine plants – Heating air supply before combustion, e.g. by exhaust gases
F02C7/12-143	Cooling of gas turbine plants
F02C7/30	Gas turbine plants – Preventing corrosion in gas-swept spaces
COMBINED CYCLES	
F01K23/02-10	Plants characterised by more than one engine delivering power external to the plant, the engines being driven by different fluids; the engine cycles being thermally coupled
F02C3/20-36	Gas turbine plants characterised by the use of combustion products as the working fuel
F02C6/10-12	Combinations of gas-turbine plants with other apparatus; Supplying working fluid to a user, e.g. a chemical process, which returns working fluid to a turbine of the plant
IMPROVED COMPRESSED-IGNITION ENGINES	
[Classes listed below excluding combinations with B60, B68, F24, F27]	
F02B1/12-14	Engines characterised by fuel-air mixture compression ignition
F02B3/06-10	Engines characterised by air compression and subsequent fuel addition; with compression ignition
F02B7	Engines characterised by the fuel-air charge being ignited by compression ignition of an additional fuel
F02B11	Engines characterised by both fuel-air mixture compression and air compression, or characterised by both positive ignition and compression ignition, e.g. in different cylinders
F02B13/02-04	Engines characterised by the introduction of liquid fuel into cylinders by use of auxiliary fluid; Compression ignition engines using air or gas for blowing fuel into compressed air in cylinder
F02B49	Methods of operating air-compressing compression-ignition engines involving introduction of small quantities of fuel in the form of a fine mist into the air in the engine's intake.
COGENERATION	
F01K17/06	Use of steam or condensate extracted or exhausted from steam engine plant; Returning energy of steam, in exchanged form, to process, e.g. use of exhaust steam for drying solid fuel of plant
F01K27	Plants for converting heat or fluid energy into mechanical energy
F02C6/18	Using the waste heat of gas-turbine plants outside the plants themselves, e.g. gas-turbine power heat plants
F02G5	Profiting from waste heat of combustion engines
F25B27/02	Machines, plant, or systems using waste heat, e.g. from internal-combustion engines

Chapter 3

Technological change, fuel efficiency and carbon intensity in electricity generation: A cross-country empirical study

by

Elena Verdolini, Nick Johnstone and Ivan Haščič

In this chapter we present the results of an empirical analysis of the determinants of energy efficiency in fossil fuel electricity generation across 28 OECD economies over the period 1981-2006. We pay particular attention to the role played by technological development. Results show that the input mix, capacity utilization and new investment in capacity play a significant role in increasing energy efficiency. Increasing the knowledge stock is also associated with higher efficiency levels, with the effect varying significantly depending upon assumptions concerning the extent of international knowledge spillovers. Given the link between increased efficiency and lower CO₂ emissions, we conclude that technological change has a negative effect on carbon intensity, while changing the input mix affects CO₂ intensity both through an increase in efficiency as well as by lowering the input-weighted emission factor.

1. Introduction

A number of studies have reached the conclusion that unless significant global policy action is taken, anthropogenic CO₂ emissions are bound to grow rapidly; oil and gas prices will be high (relative to coal prices); and, energy security concerns will increase. Curbing CO₂ emissions and decoupling economic growth from energy use will not come free of charge. Lower emissions achieved at the cost of reduced economic growth will negatively affect standards of living. In light of this, it is important to target abatement options first in those sectors where the potential for CO₂ emission reductions is higher and the marginal cost of abatement is lower.

The International Energy Agency's recent *Energy Technology Perspective* (ETP) report (IEA 2010) posits that policy interventions to reduce CO₂ emissions from the production of electricity could account for up to 47% of emissions reductions necessary to meet the BLUE Scenario target, namely a halving of emissions with respect to 2005 levels by 2050. Among the different options to lower CO₂ emissions from electricity generation, energy efficiency in production is claimed to be among the least costly options.¹

In this chapter, we study efficiency of fossil fuel based technologies for the production of electricity. This contribution is important for several reasons: first, given the key role of the electricity sector in the global effort to reduce CO₂ emissions, understanding the dynamics of fuel efficiency and its determinants is important to validate the assumptions made about the rate and direction of its change. Second, a number of factors are commonly identified as affecting electricity production efficiency from fossil fuel inputs. These include the choice of fossil-fuel employed in production, the capacity ratio at which the power plants are run and the specific technology used for production. The few studies currently available on this topic are either limited to a single country, or include only descriptive analyses without empirically testing the contribution of the different determinants of fuel efficiency.

In addition, we devote particular attention to constructing new indicators to proxy for technological availability, which we include in the empirical estimation. To our knowledge, this is the first attempt to link technological change (TC) in the energy sector to actual efficiency improvements (and emission reductions). Most of the literature on TC is focused on innovation and its determinants. However, to reduce anthropogenic CO₂ emissions significantly, technological change needs to affect not only the production of ideas, patents and blueprints, but also the efficiency with which goods and services are produced. We explore this topic focusing on the fossil-based electricity sector. As a result, we can examine the importance of technological change as a driver of production efficiency as compared to other important factors such as input mix and capacity utilization. This will shed light on the relative contribution of knowledge and technological availability and will help simulate future efficiency increases.

This chapter presents several important conclusions: first, as expected, it shows that fuel efficiency is negatively correlated with increases in the share of coal over total fossil

fuel input, but positively correlated with higher capacity utilization levels and with new investments in power plants. Moreover, those economies where technological availability is higher consistently show higher levels of fuel efficiency in electricity generation. The estimated coefficient is however fairly small. This calls for some caution with respect to the role of TC in increasing fuel efficiency in the future.

In addition to analyzing the dynamics of fuel efficiency, we also consider the effect of technological development on carbon intensity. Given the relationship between efficiency and carbon intensity of the electricity sector, technological change has a negative and significant, although small, effect on carbon intensity. Finally, we show that changes in the input mix affects carbon intensity in two ways: on one hand, a lower share of coal over total fossil fuels leads to higher fuel efficiency. On the other hand, it also reduces the input weighted emission factor. In both cases, the effect translates in lower carbon intensity of electricity production.

The chapter is organized as follows: Section 2 explains more in detail the potential contribution of the electricity sector to decreased carbon intensity. Section 3 contains a review of the literature on the electricity sector, which points to the abundance of sectoral studies, but to the lack of attention for fuel efficiency dynamics. Section 4 defines fuel efficiency, provides descriptive statistics for the 28 countries included in the analysis and identifies the determinants of efficiency as well as the relationship between efficiency and carbon intensity. Section 5 describes the data and methodology used to build the indicator of technological change. Section 6 presents the result of the empirical estimation on fuel efficiency and describes emission intensity dynamics. Section 7 concludes.

2. The electricity sector and fuel efficiency

This section summarizes recent results both on the role of the electricity sector in increasing future CO₂ emissions in a “no policy scenario” and on its potential for CO₂ reductions under appropriate policy. The ETP report (IEA 2010) shows that in a Business as Usual (BAU) scenario, CO₂ emissions by 2050 will nearly double. Higher emissions are the result of economic growth and continued reliance on coal and gas both for electricity production and on oil for transportation. Without policy intervention to address climate change concerns, by 2050 not only will primary energy use rise by 84%, but its carbon intensity will also increase by 7%, indicating that decoupling of economic activity from energy use will not take place.

Currently, the electricity sector accounts for 32% of total fossil fuel use and 41% of energy related CO₂ emissions. Until 2050, electricity will be the one of the fastest-growing component of total demand and will reach levels 134% higher than in 2007 (IEA 2010). The expected rise in electricity demand is the result of rapid electrification of households in developing economies and of industrial processes around the world. Two thirds of the increased electricity demand will be met with fossil fuels.² As a result, emissions from the electricity sector will increase and the increase in fossil fuel based generation capacity will most likely lock the world into a highly carbon intensive path.

Significant global policy action is called for to counter these trends. With appropriate incentives in place, this sector can turn from one of the largest contributors to rising emissions into a sector that would achieve 44% of emissions reductions necessary to meet reduce emissions by 50% in 2050 with respect to 2007 levels. The means envisioned to achieve the reduction in CO₂ emissions from electricity production include: 1) improving

the energy efficiency of the energy-intensive industrial sectors and of consumer appliances; 2) reducing the emission intensity of electricity generation (de-carbonization) through either substitution of fossil fuels with nuclear and renewable energy sources or the deployment of carbon capture and storage (CCS); and, 3) increasing the fuel efficiency of electricity production from fossil fuels.

The first two of these options face significant challenges. First, increased efficiency of the energy intensive sectors and of household appliances might not reduce overall electricity demand, as rebound effects can increase the overall electricity demand as a result of increased efficiency. Second, a drastic decarbonisation of the energy sector and fast shift towards renewable and nuclear electricity production seems unlikely: fossil-fuels are currently the main input for electricity generation, with coal accounting for more than half of their share (IEA 2010). The life of capital stock (fossil fuel power plants) is very long. Other significant barriers to the widespread deployment of non-fossil energy sources are plant safety, radioactive waste disposal and proliferation concerns for nuclear power, and the restructuring of distribution systems necessary to integrate large amounts of electricity coming from intermittent renewable sources. In many cases, the deployment of renewable energy plants also meets the resistance of local communities (e.g. wind power).

Given that fossil fuels are likely to remain a main input in electricity production, an important component of any CO₂ emissions reduction strategy will be the ability to increase the efficiency of fossil-fuel plants. This is an attractive option also to improve energy security. In addition, energy efficiency is particularly relevant for the deployment of CCS: capturing and storing carbon is an energy-intensive process that reduces the net output of power plants. The application of this technology to plants with low efficiency is not economically viable.

It is thus extremely important to understand its dynamics and determinants. Future scenarios presented so far are based on the assumptions of optimal behaviour on the side of the economic agents. In some cases, such as the widespread deployment of renewable technologies, these assumptions cannot be tested, as data on past performance is still limited. In the case of increased efficiency of the electricity sector, on the other hand, such an analysis is indeed possible: fossil-fuel technologies have not only been used for many years, but their efficiency also increased significantly over time. In addition, there is a good availability of data that allows for the analysis of fuel efficiency for electricity generation in a cross-country setting. A clear understanding of fuel-efficiency dynamics will help in the design of sound policies to address the issue of rising CO₂ emissions.

The recent literature recognizes the importance of fossil fuel efficiency in electricity generation, and a few recent studies on this topic are available. These contributions are however of a descriptive nature: even if fuel efficiency in fossil-fuel generation is compared across countries, these differences are not quantitatively explained and the effects of those determinants that are traditionally indicated as driving the dynamics of fuel-efficiency in fossil-fuel electricity generation are not assessed. The next section summarizes the literature focusing on the electricity sector and points to this lack of empirical evidence.

Measuring technological change and efficiency improvements in thermal power production has been the focus of economic research since the 1960s. This sector represents an ideal case study. First of all, technological change in the sector has been fast and made possible by developments in metallurgy which increased the size of generating units, their pressure and temperature, and introduced the use of reheat cycles in boilers (Belinfante

1978). Secondly, electricity production has the perfect characteristics to study technological change: the output of the production process is homogenous, and measurable in physical amounts, limiting the need to control for product quality in empirical studies.

Since the 1960s, most of the studies on the productivity of the electric industry focused on the generation stage, due to larger data availability and to its high share in the total costs of production. Initially, most of the research was carried out using data for the electricity sector in the United States. Subsequently, the focus shifted from the United States to other countries – Britain and Australia first, and the rest of Europe later. Two main approaches can be distinguished in the empirical literature: studies focusing on total factor productivity and those based on measures of partial productivity, such as GWh per unit of labour or per unit of capital. Most econometric studies of the power sector were primarily aimed at investigating input substitution possibilities, scale economies and technological change. Other relevant topics for the literature on the electricity sector were the impact of rate of return regulation and of environmental controls on the productivity and efficiency of electricity production. Subsequently, changes in the market structure of the electricity sector and in the ownership of utilities allowed the comparison of the efficiency and productivity of government versus privately owned utilities (see Abbott 2005 for a review of the literature). More recently, interest in the energy transformation sector was spurred by its relevance with respect to greenhouse gas emissions and climate change issues.

The first attempt to measure productivity in the electricity industry was set out by Kendrick (1961), who related electricity output measures to labour and capital inputs. He estimated that in the USA total factor productivity increased by 5.5% a year between 1904 and 1953. Barzel (1964) and Galatin (1968) modified the set of input demand functions to incorporate technological change. Barzel (1964) introduced the capacity observed load factor as a regressor in his analysis, and tried to capture the contribution of technological change using dummy variables for different vintages. Galatin (1964) formulated a model in which he took explicit account of the mix of technologies and the degree of capacity utilization. Along these lines, Nelson and Wohar (1983) estimated total factor productivity growth in steam-electric generation for a sample of 50 privately owned utilities over the period 1950-1978. They decomposed changes in TFP into components attributable to technical change, scale economies and regulatory biases.

Among the multi-country studies, Söderholm (1995; 2001) estimates short run interfuel substitution in West European power plants. He shows that although most of the substitution options between fossil inputs is *ex-ante* (before plants are built), there are also several possibilities for *ex-post* substitution. First of all, utilities own plants fuelled by different inputs and therefore can decide which input to burn (if capital utilization is less than 100%). In addition, at the plant level, multi-fired plants allow for burning of different fuels to produce electricity. It is in fact possible to modify a power plant based on coal so that it can burn also gas or oil in the short term and with low capital costs.³ Thus a cost-minimizing electricity generating firm does have some ability to change its fuel input usage in response to changes in relative fuel prices in the short run, although this varies widely by plant configuration.

The studies presented so far are very different from the one proposed here: first of all, they are mostly single-country studies as opposed to having a multi-country focus. In addition, the production and productivity dynamics are studied at the micro level, with the unit of observation being either the single firm or the single plant. Moreover, they often

employ different definitions of efficiency in electricity production, such as TFP or efficiency measures based on capital or labour inputs. Finally, these studies simply characterize technological development with the use of a trend or time dummies.

The studies that more closely related to this one are some recent analyses of fuel efficiency in OECD economies such as Graus *et al.* (2007), Taylor *et al.* (2008) and Graus and Worrell (2009). All these papers build indicators of fuel efficiency in fossil fuel electricity generation, present descriptive analysis of the development of efficiency over time across countries, and calculate the potential CO₂ emission reduction if electricity production plants in all countries operated at the higher levels of efficiency observed. In particular, Graus *et al.* (2007) compare fossil-fired electricity generation for Australia, China, France, Germany, India, Japan, the Nordic countries, South Korea, United Kingdom and Ireland, and United States. Taylor *et al.* (2008) perform a similar analysis for all OECD economies, while Graus and Worrell (2009) look at fuel efficiency in electricity generation in the EU27 with particular attention to the age of fossil fuel power plants. In addition, they describe the changes in energy intensity of the sector over time in their sample.

In a similar vein, this contribution looks at the efficiency of electricity production across 24 countries in the period 1981-2007.⁴ Compared to the analyses of Graus *et al.* (2007), Taylor *et al.* (2008) and Graus and Worrell (2009), this analysis is novel in three respects. First, we assess empirically the contribution of different determinants of fuel-efficiency. Second, we devote particular attention to the issue of technical change and technological availability. Using patent data for carefully selected innovative fossil-fuel technologies for electricity generation, we build an indicator which proxies for technological development in the field of electricity production. Therefore, we do not need to resort to a time trend (or time dummies) to measure technological changes. Third, by formalizing the relationship between fuel efficiency and carbon intensity of the electricity sector, we assess the impact of technological availability and changes in the input mix on CO₂ emissions of the electricity sector.

3. Efficiency in fossil-fuel electricity generation: Definitions and trends

Measurement of fuel-efficiency in electricity production is less problematic than in the case of other industrial sectors. This is because both inputs (fossil fuels) and outputs (electricity) of the production process are highly homogenous compared to other industrial processes.⁵ As a result, it is easier to compare performance of different power plants or countries since there is less concern about the issue of controlling for input and output quality.

In this chapter, we define fuel efficiency in line with previous literature on the topic, namely Graus *et al.* (2007) and Taylor *et al.* (2008). In particular, fuel efficiency (E^{el}) is defined as the ratio between output of the power plants (P) and the amount of fossil fuel inputs (I) that are required to produce electricity.

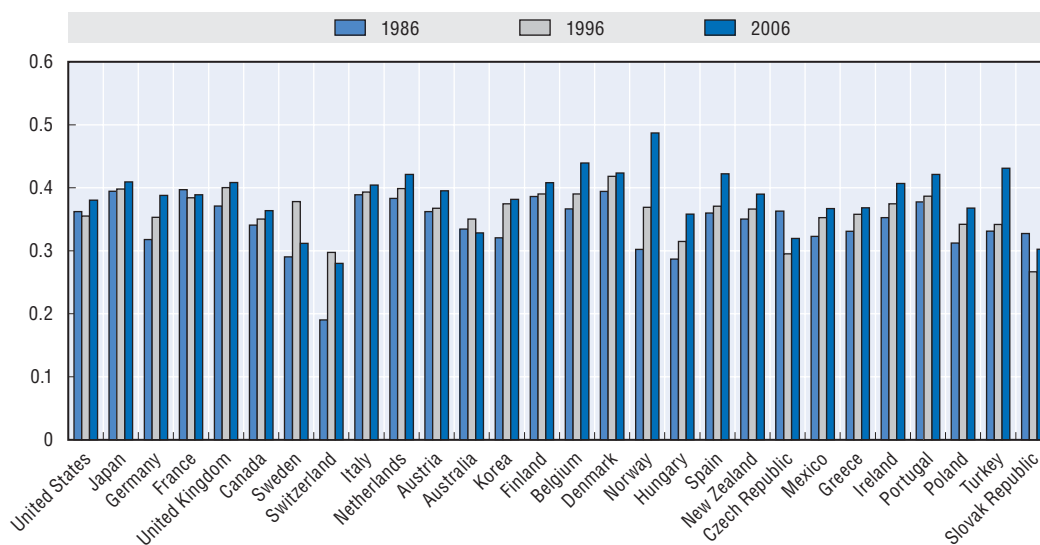
$$E^{el} = \frac{P}{I} = \frac{EL + (H * s)}{I} \quad (1)$$

Note that electricity (EL) can be produced either in traditional power plants or in combined heat and power (CHP) plants, where heat (H) is produced alongside electricity. While the combined production of electricity and heat is more efficient in terms of primary energy than separate production of the two,⁶ the extraction of heat causes efficiency losses

in the electricity production, which depend on the temperature at which the heat is extracted. We follow the literature and apply a correction factor (s) to account for such losses, as shown in equation (1)⁷ where EL and H denote respectively electricity production and heat production from fossil-fuel inputs and s is the above-mentioned correction factor set equal to 1.75.⁸

Data on electricity and heat production as well as on fossil fuel inputs for the 24 countries included in this study are taken from the *IEA Electricity Information Database* (IEA, 2009). Figure 3.1 shows that there are widespread differences in efficiency of electricity production from fossil fuels across the countries in our sample. Moreover, fuel efficiency generally rose with the passing of time, being lower at the beginning of the observation period and higher at the end.

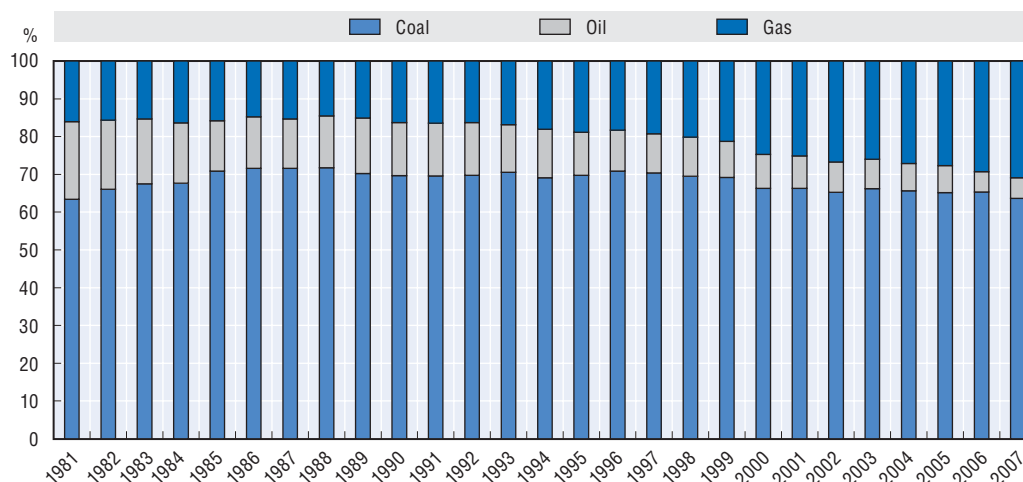
Figure 3.1. **Fuel efficiency in electricity generation**



In order to identify the determinants of fuel efficiency in electricity generation, we take into consideration all those factors that are traditionally indicated in the literature. The first important factor that influences fuel efficiency is the composition of the fossil-fuel input mix: gas-fired plants achieve higher efficiencies than coal-fired plants due to the ability of the respective technology to extract the heat content of the fossil input (IEA 2010). As a result, the different levels of efficiency across countries can be in part attributed to different input mixes, and the increases in efficiency of power plants over time related to changes in the input mix of each country. Figure 3.2 shows how the input mix changed between 1975 and 2006 in the sample considered in our analysis.

Over time, oil has been displaced by gas as an input for electricity production, while coal maintained its predominant role, accounting for the biggest share of fossil fuel input. Changes in the efficiency of the stock of electricity producing plants arise in part from the inherent combustion efficiency of plants using different fuel inputs. In our analysis, the share of coal over total fossil fuel inputs is used to reflect this factor.

Capacity utilization, measured as the ratio of actual to maximum potential output produced, is also an important determinant of electricity production efficiency. Most

Figure 3.2. **Global fossil fuel input mix in electricity generation (1975-2006)**

plants achieve optimal fuel heat rates at capacity utilization ratios of around 80-90%, with a substantial deterioration of the heat rate for capacity utilization ratios of below 50%. Studies based on plant level data show that capacity utilization is higher for base-load plants (more commonly coal-fired) and lower for peak-load plants (more commonly gas-fired) that are turned on quickly in periods of high demand (Belinfante, 1978).

At the level of the individual plant, there is a clear positive relationship between utilization and efficiency since switching on a plant requires a lot of fuel. However, at the country level, we do not have the ability to control for the differences between capacity utilization at the plant level, for example between base-load and peak-load plants: We therefore need to resort to national aggregates. We define aggregate capacity utilization as the ratio between the electricity produced in a given year and the potential for fossil-fuel-based electricity production if all plants were operating at maximum capacity. This indicator captures the effect of a number of factors. First, low capacity utilization of fossil fuel plants at a country level may reflect reliance on other generation technologies, with implications for efficiency. Capacity utilization is lower for those countries, such as France and the Nordic countries, which rely more heavily than others on alternative fuel sources (respectively nuclear and hydro) for the base load, with coal-fired plants used as peak-load sources.⁹ Aggregate capacity utilization also reflects fluctuations of demand for electricity over time: often relying on peak-load plants to meet highly fluctuating demand will result in lower aggregate capacity utilization, *ceteris paribus*.

A further important determinant of increases in fuel efficiency is technological change, or the availability of more efficient technologies on the market. Thermal efficiency improves over time as technology advances and firms invest in new capital or modify existing boilers (Considine, 1999). In particular, plants of different vintages will achieve different efficiency levels, with newer plants being more efficient, for two reasons: on one hand, newer plants embody the latest available technology and will more likely have higher fuel efficiency; on the other hand, older plants have been used for longer periods of time and therefore their capital has in part deteriorated (Nelson 1984). Retrofitting can also significantly improve power plant performance and is especially convenient if the plant stock is relatively young: for instance, the case of Japan and China, where many plants are around 15 years old and, given a lifespan of 40 to 60 years, they will be in operation for another 25 to 45 years (IEA, 2010).

To account for the improvements in technologies for electricity production, we include two proxies for technological development in our analysis. First, we use selected patent data to build several indicators of technological availability at the country level (see discussion below). Second, we account for improvements in fossil fuel technologies for electricity production by constructing a capital stock variable.

Based on the discussion of the determinants of fuel efficiency, we formulate the following log-log specification:

$$\ln E_i^{el} = \ln \frac{P_c + P_o + P_g}{I_c + I_o + I_g} = \alpha_1 + \alpha_{ShC} \ln IM_i + \alpha_{KS} \ln KS_i + \alpha_{CR} \ln CR_i + \alpha_v \ln V_i + \alpha_i \quad (2)$$

where i indicates a given country and the time suffix is suppressed for convenience. Fuel efficiency of electricity generation (E_i^{el}) is defined as in (1), and is a function of a function of the input mix (IM), vintage effects (V), the level of average national capacity utilization (CR) and the indicator of technological change (KS). Country fixed effects are included to control for any remaining country-specific characteristics. Our expectations are that the share of coal over total fossil fuel will be negatively correlated with the level of fuel efficiency in a country, since coal based technologies are less efficient than gas based electricity generation. In addition, increases in installed capacity, higher levels of capacity utilization and greater availability of technology on the market should positively affect the level of fuel efficiency.

As said, data regarding electricity generation, fossil fuel inputs and capacity utilization are taken from the *IEA Electricity Information Database* (2009). Capacity utilization (CR) is defined as $(MWh/Mwe \cdot 8\,766)$ where MWh is electricity produced, Mwe is capacity installed and 8 766 is the number of hours in a year. Wishing to control for the vintage effects of power plants in an aggregate analysis, we calculate the average age of a Mwe installed in any given country. The construction of the knowledge stock to proxy for technological development is explained in detail in the next section.

Given the definition of fuel efficiency, it is important to point out two limitations of the present contribution. First, we cannot take into consideration some important determinants of fuel efficiency at the plant level, such as the cooling method or the outside temperature. However, in the empirical analysis this is captured through the inclusion of country fixed effects. Second, we abstract from the contribution of labour to changes in fuel efficiency in power plants. This is dictated by the lack of appropriate data. However, in the fossil-fuel electricity sector, fuel efficiency improvements are less likely to come from learning-by-doing and from disembodied technical change than from embodied technical change and improvements in metallurgy and combustion. In addition, as pointed out in the literature, capital and fuel inputs make up the majority of the costs of electricity production.¹⁰

4. Patent data on fuel-efficiency innovation

To build an index proxying for technological availability we use information on patent applications relative to fossil fuel based efficient technologies for electricity production. Patents are a set of exclusionary rights (territorial) granted by a state to a patentee for a fixed period of time (usually 20 years) in exchange for the disclosure of the details of a given invention. Patents are granted by national patent offices on invention (devices, processes) that are judged to be new (not known before the application of the patent),

involving a non-obvious inventive step and that are considered useful or industrially applicable.

The use of patent data as proxy for innovation has a long history in the field of innovation economics. Griliches (1990) argues that patents are imperfect but useful indicators of inventive activity. For the present study, the use of patents as indicators of the supply of fuel-efficient technologies in the market is justified by the fact that patenting is a costly procedure that is undertaken by firms that have the intention of marketing a patented good and benefiting from the temporary monopoly power granted by the patent itself. They are not however, ideal measures of innovation. Their main limitations are linked to the facts that not all innovations are patented, not all patented innovations have the same economic value, and that propensity to patent may vary across countries and technological fields.

The identification of patents that are relevant to fossil-fuel electricity generation technologies is explained in detail in Lanzi et al. (2011). As in Lanzi et al. (2011), we exploit the differences between inventor country and patenting office and we build three different indexes using patent applications from the *PATSTAT Database*. First, we build a global indicator of technologies in the market by considering all patent applications (claimed priorities and singulars) in fossil based efficient technologies for the production of electricity, independent of the countries where they are protected. This indicator is not country-specific, and it is meant to measure the increased availability of better technologies over time. Second, we use information on singular and claimed priorities applications by national inventors. Third, we build market-specific indicators by taking into account all the patent applications (claimed priorities, singulars and duplicates) at the national application authority.¹¹

The three indexes are built using patent counts and following previous studies such as Popp (2002) and Bottazzi and Peri (2005) and Verdolini and Galeotti (2011). We use the perpetual inventory method to construct a measure of knowledge stock for each time t :

$$KS_t = Pat_t + (1 - \delta)KS_{t-1} \quad (3)$$

where the initial stock ($t = t_0$) is calculated as follows:

$$KS_0 = \frac{Pat_0}{\bar{g} + \delta} \quad (4)$$

In all cases, $t_0 = 1958$, equals the average growth rate in patenting during the three years preceding the analysis (1955-1957), and δ is a 10% discount rate.¹² In the empirical analysis, the discounted stream of knowledge is lagged by five years to account for temporal differences between invention and deployment. We carried out a sensitivity analysis of the technological availability indexes by using different lags (from 3 to 10 years) and found that this did not qualitatively affect the empirical results. In the next section, we turn to presenting the empirical results of the estimation of equation (1).

5. Estimation results

The empirical analysis is carried out using a panel covering the period 1980-2006 (27 years) and 28 OECD economies¹³ Table 3.1 presents descriptive statistics. The estimation method is pooled OLS with heteroskedasticity-robust standard errors.

Table 3.1. **Descriptive statistics of variables used in model**

Variable	Obs	Mean	Std. dev.	Min.	Max.
Efficiency	756	0.360	0.045	0.129	0.523
Share of coal in fossil inputs	756	0.562	0.280	0	0.995
Capacity ratio	717	0.43	0.15	0.03	0.76
Technological availability (global)	756	16 612.96	4 307.88	7 659.79	20 788.25
Technological availability (local inventor)	756	144.819	384.715	0.282	2 276.969
Technological availability (local application authority)	756	536.654	851.467	0.500	4 568.211
CapStock	756	19 580.85	46 474.30	0	284 386.90

The empirical results of the estimation of (2) are shown in Table 3.2. Specifications I through III include the input mix, the level of capacity utilization and different indexes of technological availability, respectively global (specification I), own innovators (specification II) and own patent office (specification III). Specifications VII through IX also include the variable proxying for the capital stock in fossil fuel generation. The estimated coefficients are in line with expectations outlined above. In all specification, the elasticity of fuel efficiency with respect to the coal share is estimated between 0.026 (specification II) and 0.041 (specification VII). A 1% decrease in the share of coal over total fossil input translated in efficiency levels that are between 0.026% and 0.041% higher.

Table 3.2. **Results of models of fuel efficiency (log)**

	(I)	(II)	(III)	(VII)	(VIII)	(IX)
Share of coal in fossil inputs	-0.0403*** (0.0100)	-0.0261** (0.0104)	-0.0311*** (0.0110)	-0.0409*** (0.00980)	-0.0284*** (0.0101)	-0.0312*** (0.0108)
Capacity ratio	0.0611*** (0.0106)	0.0751*** (0.0130)	0.0773*** (0.0141)	0.0622*** (0.0107)	0.0742*** (0.0130)	0.0785*** (0.0142)
Index of technological availability (global)	0.128*** (0.00921)			0.127*** (0.00913)		
Index of technological availability (own)		0.0308*** (0.00423)			0.0316*** (0.00444)	
Index of technological availability (market)			0.0226*** (0.00781)			0.0183** (0.00785)
lnCapStock				0.0306** (0.0148)	0.0560*** (0.0166)	0.0469*** (0.0172)
Country FE	yes	yes	yes	yes	yes	yes
Constant	-2.249*** (0.0897)	-1.225*** (0.0324)	-1.181*** (0.0657)	-2.612*** (0.200)	-1.926*** (0.214)	-1.727*** (0.216)
Nr of cases	704.000	704.000	704.000	703.000	703.000	703.000
R-Square	0.802	0.758	0.740	0.806	0.766	0.745

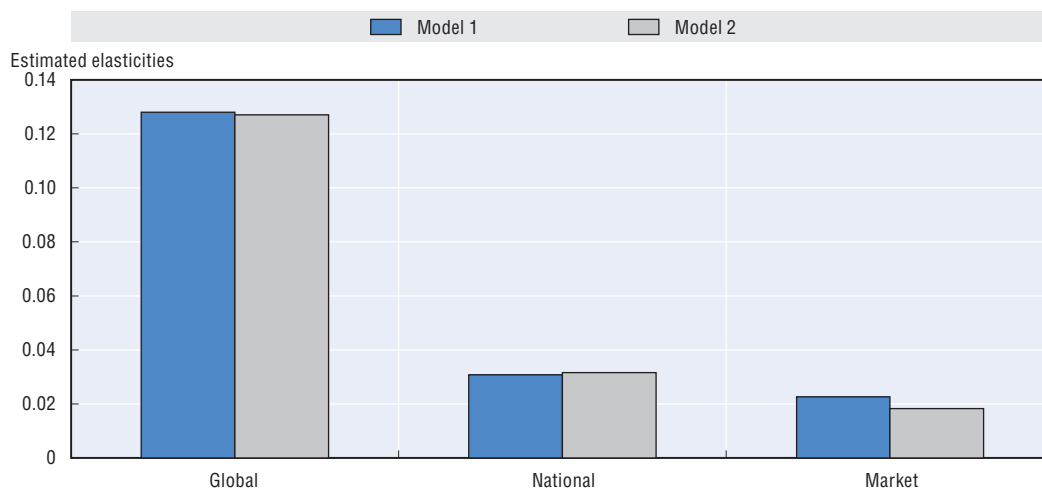
Standard errors in parentheses

* = p < 0.1; ***p < 0.01

Conversely, higher capacity utilization is associated with higher levels of fuel efficiency in electricity production: a 1% increase in average capacity utilization at the country level is associated with an increase in fuel efficiency between 0.061% (specification 1) and 0.079% (specification VI), depending on the specification employed. This suggests that efficiency gains can be achieved in economies where electricity production is lower than the maximum installed capacity. However, such efficiency gains may not be easy to achieve, if the lower capacity utilization is a sign that fossil electricity generation is used as peak load, for example to compensate for the fluctuation of intermittent renewable sources. This result also points to the possibility of increasing efficiency through demand-side policies aimed at smoothing electricity consumption and demand over time.

The results related to the technological availability indexes are particularly interesting (see Figure 3.3). The first index, indicating the global availability of more efficient technologies, indicates that a 1% increase in the knowledge stock is associated with an increase of around 0.12% in combustion efficiency. The second index, indicating the stock of innovation produced by home inventors, associates a 1% increase in technological availability with an increase of efficiency between 0.031% and 0.032%. The third index, indicating all the innovation available in any national market for technology, shows that a 1% increase in the stock of innovation is associated with an increase of between 0.018% and 0.023%.

Figure 3.3. **Effects of assumptions concerning technological availability**



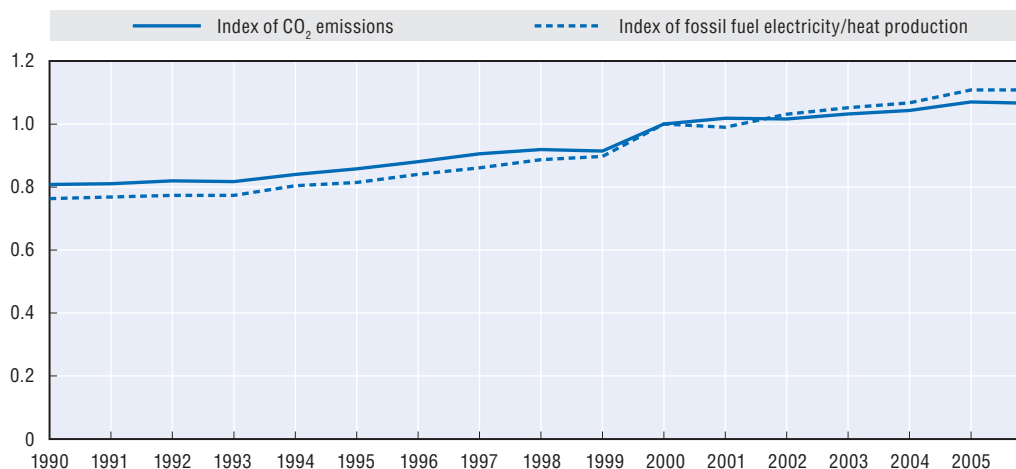
The explanatory power of the first indicator of technological availability (global knowledge) seems to be the highest, while the other two perform equally well but the associated coefficients are lower. This is an interesting finding. The global knowledge stocks works exactly as a time trend in the equation, since it is increasing over time and common to all economies. Conversely, the market specific indicators show that the impact of technological availability over time is much lower. This can be because the global index picks up additional effects rather than only the ones linked with technological availability.

Specifications IV through VI include the capital stock of fossil generation electricity. In general, the estimated coefficient shows that the higher the stock of capital (thus, the higher the investment in new generation capacity), the higher combustion efficiency.

6. Efficiency determinants and carbon intensity

Increasing the efficiency of fossil fuels based electricity also results in decreased CO₂ emissions. Using the emission factors associated with the fossil fuel input (see the Appendix), we calculate the CO₂ emissions associated with the production of electricity in our sample during the period 1991-2006.¹³ Figure 3.4 shows the growth rate of CO₂ emissions together with that of electricity production, with 2000 as the base year. Between 1991 and 2006, electricity and heat output increased by 44% in our sample, with an average annual increase of around 2.5%. Conversely, CO₂ emissions increased over the same period by about 30%, with an annual average increase of 1.8%.

Figure 3.4. **CO₂ emissions from fossil fuel electricity production, 1990-2006**



Therefore, electricity and heat production have been rising faster than the associated CO₂ emissions, leading to a decrease in emission intensity of fossil fuel electricity production. This trend indicates that in a capital intensive sector technological change only happens slowly over time. In addition, it clearly points to the necessity to increase significantly investment in more efficient technologies if the goal to be reached is higher efficiency and reduced emissions from fossil fuel based electricity.

The link between fuel efficiency and carbon intensity is straightforward. In particular, given three inputs in the production of electricity (coal, oil and gas), CO₂ intensity (CI) indicates the emissions per GWh of electricity production and can be defined as follows:

$$CI = \frac{F_c * I_c + F_o * I_o + F_g * I_g}{P_c + P_o + P_g} \quad (5)$$

where I is the input of fossil fuel, F is the corresponding emission factor and P is production of both electricity and heat. The relationship between fuel efficiency and carbon intensity becomes apparent transforming the above equation as follows:

$$CI = \frac{F_c * I_c + F_o * I_o + F_g * I_g}{P_c + P_o + P_g} \cdot \frac{I_c + I_o + I_g}{I_c + I_o + I_g} = \bar{F} * \frac{I_c + I_o + I_g}{P_c + P_o + P_g} = \bar{F} * \frac{I}{E^{el}} \quad (6)$$

Carbon intensity can be thought of as the product of the inverse of fuel efficiency and $\bar{F}$, the input weighted emission factor. As a result, by empirically assessing the impact of the determinants of fuel efficiency, we are also able to comment on the effect of the carbon intensity of the electricity production process. For example, the coefficient associated with the knowledge stock variable in the fuel efficiency equation speaks the impact of knowledge stock on fuel efficiency, but also the impact of increased technological availability on the carbon intensity of the electricity industry:

$$\frac{\partial \ln CI}{\partial \ln KS} = \frac{\partial \ln CI}{\partial \ln E^{el}} * \frac{\partial \ln E^{el}}{\partial \ln KS} = - \frac{\partial \ln E^{el}}{\partial \ln KS} = -\alpha_{KS} \quad (7)$$

Conversely, the input mix affects carbon intensity in two ways: on the one hand, it has an indirect effect through changes in fuel efficiency; on the other hand, the input mix has a direct effect on the input weighted emission factor.

7. Conclusion

The impact of the input mix, the level of capacity utilization, the quality of the fossil-fuel power plant stock, as well as several alternative indicators of technological availability on the level of fuel efficiency of fossil-fuel power plants has been estimated for a sample of 28 OECD economies over the period 1981-2006. We show that, while higher coal shares in the input mix are associated with lower fuel efficiency levels, higher capacity utilization, newer power plants and higher levels of technological availability are associated with higher levels of efficiency. Therefore, the results presented in this chapter shed light on the relative importance of all the options currently presented as ways to reduce CO₂ emissions associated with fossil-fuel electricity production. However, it is important to bear in mind that a general decrease in carbon intensity has not resulted in overall CO₂ emissions reductions for the sector.

Therefore, it is important to keep in mind that, unless significant changes come about on the demand side (energy conservation) or on the supply side (production of electricity from alternative sources), increases in the available stock of knowledge will not be sufficient to both reduce carbon intensity and the overall level of CO₂ emissions. In addition, a key finding is that assumptions concerning the extent of international knowledge spillovers have important implications for resulting efficiency gains. If perfect spillovers are assumed the effect of changes in the technological frontier on energy efficiency are over five times greater than if knowledge is constrained to the national level.

Notes

1. Other options to lower CO₂ emissions from the power sector include coupling coal and gas with CCS, co-firing of fossil inputs with biomass, and switching to non-fossil electricity sources such as wind, solar, or nuclear power.
2. Coal-based electricity generation is predicted to increase by 149% above 2007 levels, and will account for 44% of all electricity generation.
3. Belinfante (1978) points out that plants are built to burn alternative fuels interchangeably upon short notice. The adaptation of coal plant to handle gas or oil is rather inexpensive, but the adaptation of a gas or oil plant to burn coal is on the other hand rather expensive and requires more time. Coal burning plant requires generally 10-15% more capital investment, primarily in coal ash handling equipment and more expensive design. See also Söderholm (1997; 1998; 2000; 2001).

4. Countries included in this analysis are: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, and the United States.
5. Although there is variation in the calorific value both between fossil fuels (coal as opposed to gas) and within fossil fuel (hard coal as opposed to brown coal), fossil fuel inputs are still rather homogenous as compared to other production processes.
6. According to Ko and Dahl (2001), combining gas turbines with a series of steam generating units (combined cycle), although more capital intensive, can raise efficiency of gas over 50% because of reuse of waste heat. Coal has higher capital costs and needs to be stored and crushed. Moreover, particulate matters need to be removed.
7. Electricity, heat and fossil fuel inputs are measured in TJ.
8. We test the results with correction factors between 1.5 and 2.
9. For example, average capacity ratio for France over in the period 1981-2006 is 0.20 versus a 0.43 average capacity in the overall sample.
10. For example, Cowing (1974) suggests that in a usual plant fuel, capital and labor proportions in total costs are respectively 50%, 40% and 10%. According to Belinfante (1978), for the USA the average shares of total cost of production are 49% fuel, 39% capital, operation labor 7% and maintenance 5%. Fuel cost for a typical firm is about 80% of total variable generation costs, including expenditures on coal, natural gas and petroleum products.
11. For details on patenting procedures and on different patents, see the Introduction to this volume, as well as www.oecd.org/environment/indicator.
12. This is in line with the literature, see e.g. Bottazzi e Peri (2005).
13. This sample contains a total of $28 \times 27 = 756$ observations. However, in 13 cases the share of coal over fossil fuel equals zero and in 39 cases there is not information about installed capacity. The total number of observations are thus 704. In addition, there is 1 missing observation due to lack of information specifically with respect to the capital stock variable. The countries covered are: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, and the United States.

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ANNEX 3.A1

Emission factors (tonne of CO₂/TJ)

Input	Emission factor
Crude oil	73.30
Orimulsion	77.00
Natural gas liquids	64.20
Motor gasoline	69.30
Aviation gasoline	70.00
Jet gasoline	70.00
Jet kerosene	71.50
Other kerosene	71.90
Shale oil	73.30
Gas/diesel oil	74.10
Residual fuel oil	77.40
Liquefied petroleum gas	63.10
Ethane	61.60
Naphtha	73.30
Bitumen	80.70
Lubricants	73.30
Petroleum coke	97.50
Refinery gas	57.60
Other petroleum products	73.30
Anthracite	98.30
Coking coal	94.60
Other bituminous coal	94.60
Sub-bituminous coal	96.10
Lignite	101.00
Oil shale and tar sands	107.00
Brown coal briquette	97.50
Patent fuel	97.50
Coke oven coke and lignite coke	107.00
Gas coke	107.00
Coal tar	80.70
Gas work gas	44.40
Coke oven gas	44.40
Blast furnace gas	260.00
Oxygen steel furnace gas	182.00
Natural gas	56.10
Peat	106.00
Charcoal	112.00

Source: www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf.

Chapter 4

Increasing the penetration of intermittent renewable energy: Innovation in energy storage and grid management

by

Nick Johnstone and Ivan Haščić*

Intermittent renewable energy sources (wind, solar, ocean) present significant challenges to electricity grid management. In this chapter we present empirical results on the factors which encourage innovation and investment in energy storage and grid management technologies in order to increase grid flexibility. We argue that focussing policy incentives on innovation in these areas may obviate some of the problems associated with targeting R&D at specific generating technologies. Drawing upon a rich worldwide database of patent applications, with a dataset on 28 countries over three decades, we present preliminary analysis of the effects of different economic and structural factors on innovation in energy storage and grid management.

* This chapter will also be published in the forthcoming Handbook on Energy and Climate Change, edited by Roger Fouquet, 2013, Edward Elgar Publishing.

1. Introduction

Many governments have introduced policies to support the development and adoption of renewable energy technologies as a means of mitigating climate change. However, a significant barrier to the increased penetration of renewable energy arises from the “intermittent” nature of the electricity produced. While some sources are “dispatchable” (e.g. hydro, geothermal, and biomass), wind, solar and wave/tide power are subject to varying weather and ecological conditions.

Output from individual plants can vary on a scale of seconds to minutes, as well as over several hours. The extent to which the 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 the need for such capacity increases. In effect, with system flexibility held constant, the real contribution of intermittent renewable energy sources to generating capacity decreases with the level of penetration.

System “flexibility” can be increased through factors such as the integration of grids and trade in electricity services, or the use of a more diverse and dispersed mix of intermittent sources. However, flexibility can also be introduced into the system through increased energy storage capacity and improved grid management, both of which allow for improved matching of electricity supply and demand.

The motivation for the chapter arises out of a concern to provide policymakers with guidance on the targeting of public R&D support and other policy incentives. There are good reasons to believe that there are benefits of targeting R&D expenditures at storage and grid management technologies rather than directly at intermittent generating technologies. At least three related reasons can be cited:

- It is more parsimonious with respect to information requirements for the government. Since innovation in “enabling” technologies (such as storage and grid management) is an important complement to innovation in all intermittent renewable generating technologies;
- The technologies are at a relatively early stage of development in comparison with the most important generating technologies, with greater returns on public R&D in the presence of learning curves; and,
- Such technologies are subject to important network externalities, implying that the rents from private investment will not be fully captured, and thus sub-optimally provided.

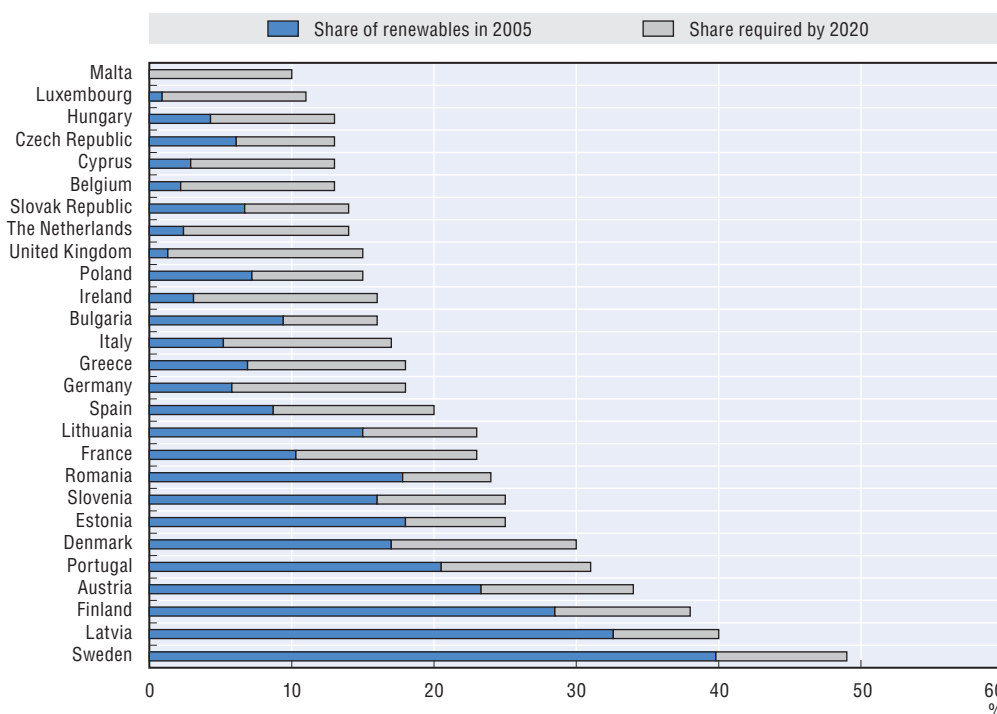
In this chapter, preliminary empirical results are presented on the factors that encourage innovation in system flexibility (energy storage and grid management technologies). The study draws upon a rich database of patent applications and IEA data on energy research expenditures, prices, capacity and production.

2. Intermittency in renewable energy generation and system flexibility

A number of OECD (and other) governments have identified the increased penetration of renewable energy sources as a primary means of mitigating the emissions of greenhouse gases. Policy targets for renewable energy exist in at least 73 countries. Most national targets are for shares of renewable energy supply in total electricity production, typically 5-30%, but ranging all the way from 2 to 78% (REN21 2008).

For instance, the European Union Directive of 2008, which succeeds the one from 2001, requires member states to increase their shares of renewable energies to meet a 20% overall energy target by 2020. The Directive set a series of interim targets, known as “indicative trajectories”, in order to ensure steady progress towards the 2020 targets. EU countries are free to decide their own mix of renewables, allowing them to account for their different potentials, while Brussels reserves the right to enact infringement proceedings if states do not take appropriate measures to reach their targets. Figure 4.1 gives the 2020 national targets for renewable use in EU as compared to the 2005 share of renewables in total energy supply.

Figure 4.1. **Renewable energy targets in Europe**
Share in final energy by 2020 as compared to share of renewables in 2005



- Footnote by Turkey: The information in this document with reference to « Cyprus ;» relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognizes the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the “Cyprus issue”.
- Footnote by all the European Union member states of the OECD and the European Commission: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

Source: EurActiv (2010).

In order to meet such targets specific policies need to be introduced. By 2009, at least 64 countries had some type of policy to encourage renewable power generation (REN21 2008). Such government policies target different stages of the industrial process, ranging from the research and development (R&D), through the investment in physical capital (plants and equipment) up to the production and sale/consumption of energy. However, the penetration of renewable energy remains relatively low. More than 80% of produced electricity comes from coal, natural gas and nuclear power plants, while renewable energy sources rank fourth, and most of this comes from hydro (IEA, 2009b). Cost is, of course, the main reason. Despite many policy initiatives, the cost of renewable electricity generation remains prohibitively expensive, although there are exceptions. However, a significant additional barrier to the increased penetration of renewable energy arises from the “intermittent” nature of the electricity produced. While some sources are “dispatchable” (e.g. hydro, geothermal, and biomass), wind, solar and wave/tide power are subject to varying weather and ecological conditions.¹

Output from individual plants can vary on a scale of seconds to minutes, as well as over several hours. The extent to which the grid as a whole can accommodate such variations is a function of its capacity to adjust to supply and demand shocks (power system flexibility), and as the penetration of intermittent renewable sources increases the need for such capacity rises as well. Moreover, since those renewables which are the most promising sources of future increases in capacity (e.g. offshore wind, tidal/stream, wave energy and solar photovoltaics) are intermittent in nature, the need to be able to adjust output levels and sources on short notice is likely to rise (see Infield and Watson, 2007; Sinden, 2007).

In a sense, all plants have “variable” output, insofar as there is some probability of a breakdown that puts the plant off-line for a period of time. Since power outages can impose significant economic costs, most regulators have a target “loss of load probability” (LOLP). For instance, in the United Kingdom this is set at nine (i.e. nine outages per century). This is met by building in a system margin, allowing the system to meet unexpected decreases in supply from some plants and/or unexpected increases in demand.

The introduction of intermittent renewable energy plants increases the required system margin in order to meet the target LOLP since they are able to contribute less to peak demand (Neuhoff 2005).² This can be measured as a capacity credit – i.e. the amount of electricity (expressed in terms of conventional thermal capacity) that can be served by intermittent plant without increasing the LOLP. For instance, while wind plants generally have a capacity factor in the region of 20% to 40% (relative to 80%-90% for conventional fossil fuel-fired plants) the capacity credit is less, reflecting the high variability of output through time. At 20% wind power penetration, Gross *et al.* (2007) estimate a capacity credit of 19%-26% for a plant with an average annual capacity factor of 35%. On the basis of a formula developed by Gross *et al.* (2007) this can be converted into a “reliability cost”³ of approximately £ 4/MWh, which can be considered as an “externality cost” arising out of intermittency.

In the face of such vulnerability, some governments have even sought to cap the penetration of intermittent renewable energy sources in the grid (see IEA 2008). Moreover, as penetration levels of intermittent renewables rise still further the ratio between capacity credit and capacity factor falls, reflecting increased vulnerability of the system. The extent

to which the penetration of intermittent renewables increases LOLP is a function of the flexibility of the system. Flexibility can be introduced into the system in six ways:

- *Improved weather forecasting.* Improved forecasting of meteorological and other ecological conditions (ocean wave activity, solar radiation, etc.) can help system operators efficiently balance the amount of dispatchable and different intermittent power sources in the grid (see e.g., IEA, 2008; APS, 2010).
- *Geographic dispersal of intermittent renewable energy plants.* Since spatial dispersion will likely reduce the extent of correlation amongst the output of different plants, this will “smooth” system-wide output (see e.g., Inage, 2009).
- *Diversity in the portfolio of renewable energy sources.* Since output variations between types of renewable is unlikely to be strongly correlated this will also smooth output (see e.g., Sinden, 2007; Gross et al., 2007; Infield and Watson, 2007).
- *Trade in electricity supply services.* The reasoning is analogous to the point made above, but with imperfect grid connections between countries it is worth highlighting. Even within continental Europe there are significant lacunae (e.g. France↔Spain) (see Milborrow, 2007; IEA, 2008).⁴
- *Improvements in grid management.* The development of “intelligent” grids allows for improved balancing of demand and supply, and more flexible transfer between sources of supply (see e.g., IEA, 2008; Duff and Green, 2008).
- *Energy storage.* Historically the primary back-ups (or reserves) have been fossil fuel plants, which can come on-line relatively quickly. However, this can be costly and as a consequence pumped hydro plants have been commonly used as a reserve source of energy. In recent years there have been significant innovations with respect to different types of energy storage of sufficient scale to serve as back-up for the grid (see e.g., Hall and Bain, 2008; IEA, 2005; IEA, 2008).

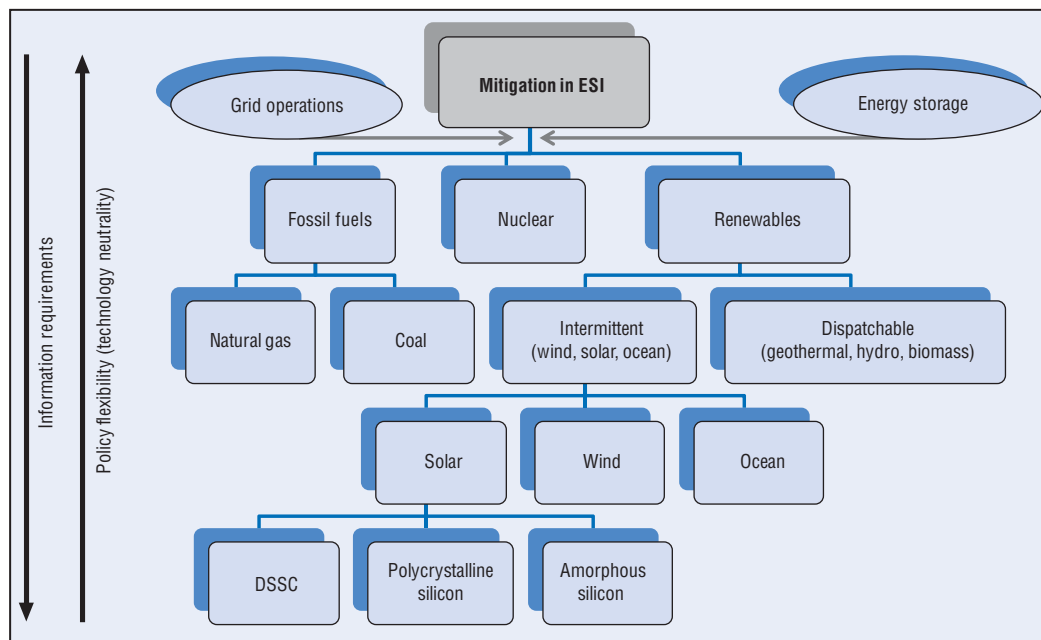
It is developments in grid management and storage that is the primary focus of much on-going work, and this chapter focuses on the case of innovation in these areas. Both improved storage and grid management have beneficial consequences for the delivery of electricity services more generally, irrespective of the supply mix. For instance, they can increase the reliability of supplies in the face of unexpected shocks (i.e. due to extreme weather events or earthquakes). They can also reduce transmission losses and increase efficiency more generally. However, by allowing for improved spatial and temporal balancing of supply and demand, improved storage and grid management have particular benefits for renewable energy. Exploiting such possibilities is, of course, dependent upon the implementation of institutional and regulatory measures that allow for such balancing in the market.⁵

Inage (2009) and IEA (2005) highlight a number of different storage technologies (in addition to pumped hydro) which are “efficient” at scales of 1MW and above. These include compressed air energy storage, superconducting magnetic energy storage, advanced lead acid batteries, lithium-ion batteries, and flow batteries. However, it remains the case that efficient energy storage is a significant constraint on the penetration of renewable energy sources in the market. The increased availability of energy storage at reasonable cost is, therefore, one of the strategies, which a government can pursue in order to increase penetration of renewables in the electricity supply industry. Publicly-supported innovation efforts which reduce the cost of storage may be a cost-effective strategy to bring about reduced CO₂ emissions.

As noted above, improved grid management becomes increasingly important as the penetration rises to 15%-20% of the grid. Technologies such as flexible AC transmission systems (FACTS) enhance transmission networks. High-voltage DC systems are particularly valuable for remote generating facilities (i.e. offshore wind). High-temperature superconductors reduce transmission losses and improve generation efficiency. In addition, a variety of information and communication technologies enables more efficient management and use of the grid. Advanced metering infrastructure (AMI) that allows for two-way communication will enable the transfer of information (and incentives) from users to suppliers (see IEA, 2011).

Moreover, there are good reasons to believe that public research efforts targeted at storage and grid management are likely to be more cost-effective. Why? The information requirements (for governments) are more limited than would be the case in allocating public resources across different generating technologies. By targeting innovation “upstream”, flexibility with respect to the choice of generating technology is retained downstream. This point is represented in the schema presented below (Figure 4.2). In effect, energy storage technologies and grid operations can serve as an “enabling” technology, allowing for increased power system flexibility. This increases the competitiveness of all intermittent renewable energy sources relative to dispatchable sources (renewable and other), without specifically favouring one intermittent source over another (i.e. neutrality). It is a form of “local” general purpose technology (GPT) within the basket of intermittent renewable energy sources.⁶

Figure 4.2. Policy incidence and local general purpose technologies

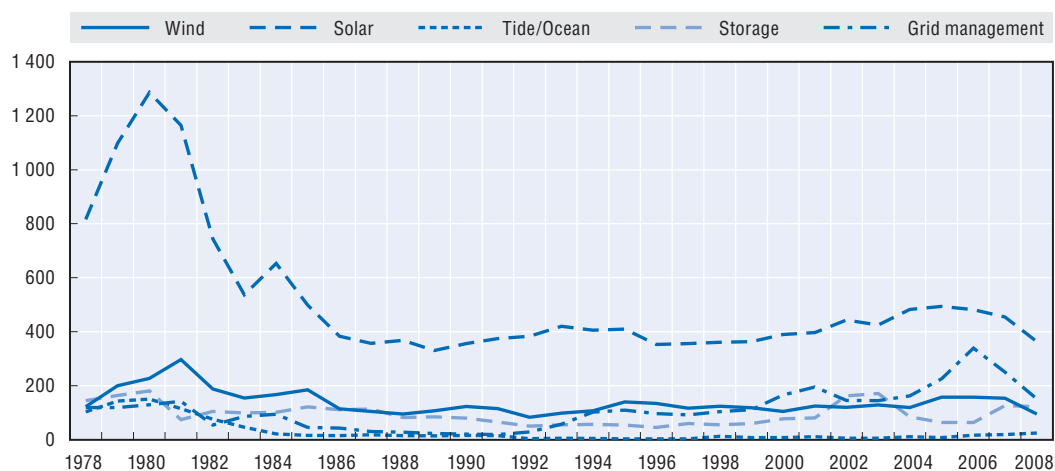


Moreover, Popp *et al.* (2010) have argued that improved electricity transmission systems benefit all technologies and will “typically not reap great rewards for the innovator”. Therefore, there is less likely to be crowding out of private R&D investment if

support is targeted at energy storage and grid management than if intermittent generating technologies are targeted directly.

For these reasons, targeted support for innovation in storage and grid management technologies (rather than generating technologies) may avoid some of the potential pitfalls associated with public R&D subsidies. Moreover, redirecting support from generating technologies to storage technologies is likely to have a significant impact since the scale of public R&D going to storage and grid management technologies is small relative to generating technologies (see Figure 4.3). However, R&D on grid management has been increasing recently.

Figure 4.3. **Trends in public RD&D on energy storage, grid management and electricity generation from intermittent renewables (1978-2008, OECD economies)**

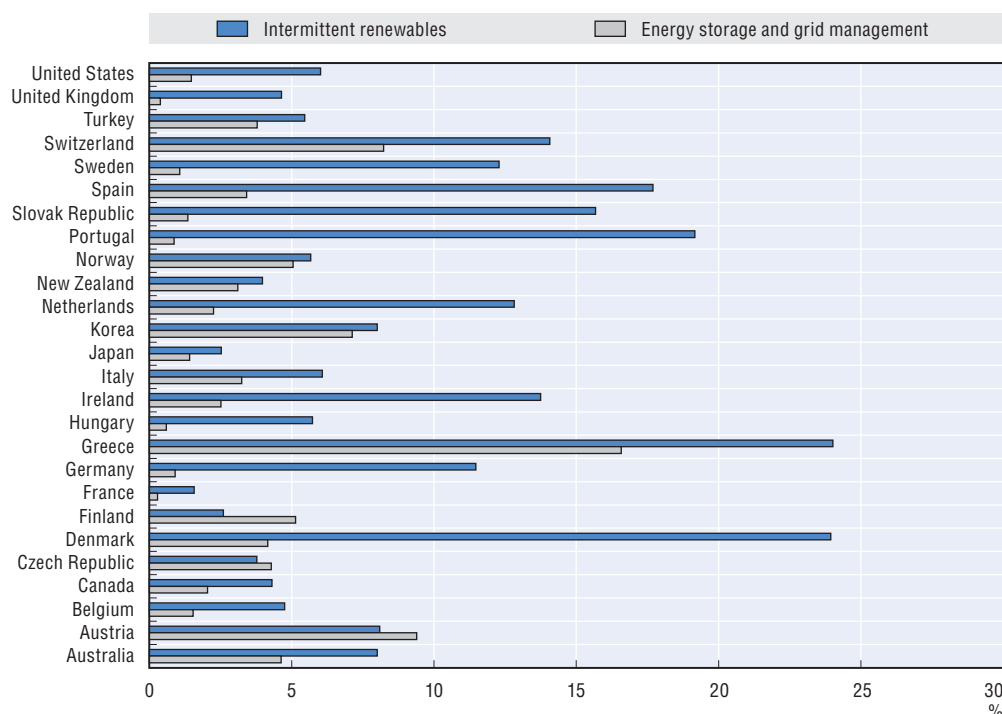


Source: Energy Technology RD&D Budgets (IEA 2011).

The percentage of total energy RD&D expenditures devoted to both intermittent generating and storage and grid management technologies varies widely across countries. Switzerland, Greece and Austria target more than 8% of energy R&D at storage and grid management (Figure 4.4). France and Japan have very low investment in both intermittent renewable and storage and grid management R&D. Only three countries (Austria, Czech Republic and Finland) have greater investment in storage and grid management R&D than intermittent renewable R&D. It is interesting that the two countries with the highest relative level of investment in intermittent renewable R&D (Denmark and Greece) have very different levels of investment in storage and grid management R&D. This may be due in part to differences in their capacity to use other strategies to increase system flexibility (e.g. grid interconnections).

Figure 4.4. **Public R&D on energy storage, grid management and electricity generation from intermittent renewables by country**

% of total energy RD&D 1978-2008



Source: Energy Technology RD&D Budgets (IEA, 2011).

3. Innovation in energy storage and grid management

As a measure of innovation in energy storage (and generating) technologies, patent counts have been developed. Patents are a set of exclusionary rights (territorial) granted by a state to a patentee for a fixed period of time (usually 20 years) in exchange for the disclosure of the details of a given invention. Patents are granted by national or regional patent offices on invention (devices, processes) that are judged to be new (not known before the application date of the patent), involving a non-obvious inventive step and that are considered useful or industrially applicable. The use of patent data as proxy for innovation has a long history in the field of innovation economics. Griliches (1990) argues that patents are imperfect but useful indicators of inventive activity. Their main limitation is linked to the facts that not all innovations are patented, not all patented innovations have the same economic value, and that propensity to patent may vary across countries and technological fields.

The patent data used in this chapter have been extracted from the *European Patent Office's (EPO) World Patent Statistics Database*, or PATSTAT (EPO, 2010). PATSTAT is unique in that it contains data from more than 90 patent offices and on over 70 million patent documents. Patent documents are categorized using the international patent classification (IPC) and some national and regional classification systems, including the European classification scheme (ECLA). In addition to the basic bibliometric and legal data, the database also includes patent descriptions (abstracts) and citation data.

Data have been extracted on patent applications filed from 1975 to 2008. The relevant inventions have been identified using specially developed tagging codes for climate change mitigation technologies (see Table 4.1). This tagging scheme (Y02) has been developed by a team of patent examiners at the European Patent Office, with inputs from collaborating researchers (including the authors) and has now been implemented into the ECLA system.

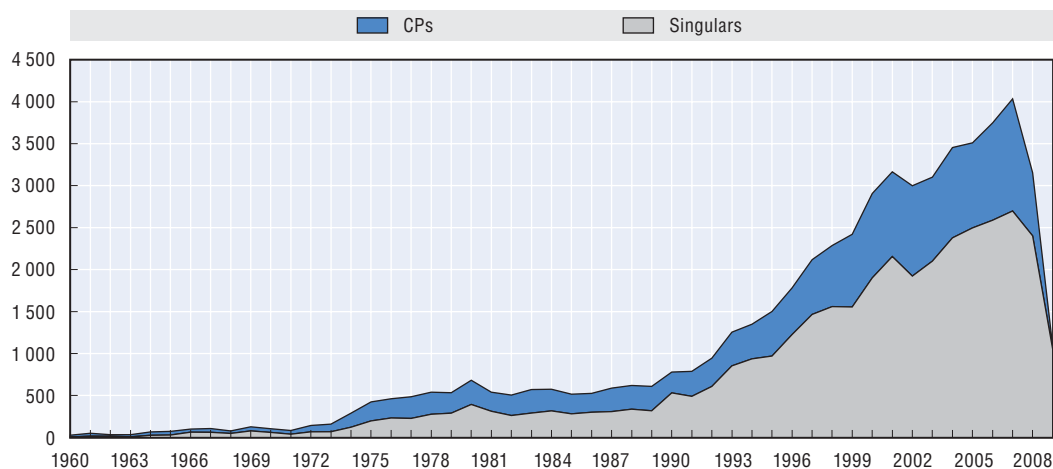
Table 4.1. Patent classification codes for energy storage and grid management

ENERGY STORAGE	
Battery technology	Y02E60/12
Lithium-ion batteries	Y02E60/12B
Alkaline secondary batteries, e.g. NiCd or NiMH	Y02E60/12D
Lead-acid batteries	Y02E60/12F
Hybrid cells	Y02E60/12H
Ultracapacitors, supercapacitors, double-layer capacitors	Y02E60/13
Thermal storage	Y02E60/14
Sensible heat storage	Y02E60/14B
Latent heat storage	Y02E60/14D
Cold storage	Y02E60/14F
Pressurised fluid storage	Y02E60/15
Mechanical energy storage, e.g. flywheels	Y02E60/16
Pumped storage	Y02E60/17
GRID MANAGEMENT	
Flexible AC transmission systems	Y02E40/12-16
Active power filtering	Y02E40/22-34
Arrangements for reducing harmonics	Y02E40/40
Arrangements for eliminating or reducing asymmetry in polyphase networks	Y02E40/50
Superconducting generators	Y02E40/62
Superconducting or hyperconductive transmission lines or power lines or cables or installations thereof	Y02E40/64
Superconducting transformers or inductors	Y02E40/66
Superconducting energy storage for power networks, e.g. SME, superconducting magnetic storage	Y02E40/67
Protective or switching arrangements for superconducting elements or equipment	Y02E40/68
Current limitation using superconducting elements	Y02E40/69
Methods and systems for the efficient management or operation of electric power systems	Y02E40/7
... characterised by remote operation, interaction, monitoring or reporting system, e.g. smart grids	Y02E40/72

Figures 4.5-4.6 present data on patented inventions in the area of energy storage. Data are presented for both “claimed priorities” (CP) (i.e. inventions for which protection is sought in at least two countries) and “singulars” (i.e. inventions protected only in one country). This distinction is useful because it indicates different market value of the inventions patented (see OECD, 2011). With respect to energy storage, there was significant “take-off” around 1990, with a six-fold increase in singulars since that point. Claimed priorities have tripled in the same period.

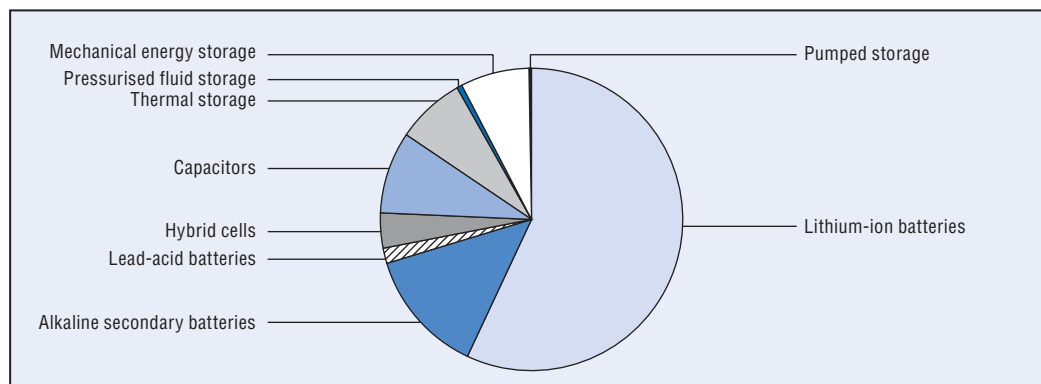
Over the period 1978-2008, the most important inventor countries in terms of “claimed priorities” were Japan, United States, Germany and Korea, which together are responsible for approximately three-quarters of total applications. Switzerland is amongst the top ten. Figure 4.6 breaks down the energy storage data in terms of technology type. Lithium-ion batteries are the most prevalent technology type, followed by alkaline batteries. While pumped hydro storage is very important in terms of system flexibility, there are few patents in this area since it is a very mature area and most of the inventions are likely to

Figure 4.5. Innovation in energy storage technologies
 Claimed priorities (CP) and singular patent applications by in-sample countries



have more general applications. Pressurised fluid storage (often referred to as compressed air energy storage) represents a very small percentage of the total.

Figure 4.6. Innovation in energy storage by technology type
 Claimed priorities 1978-2008

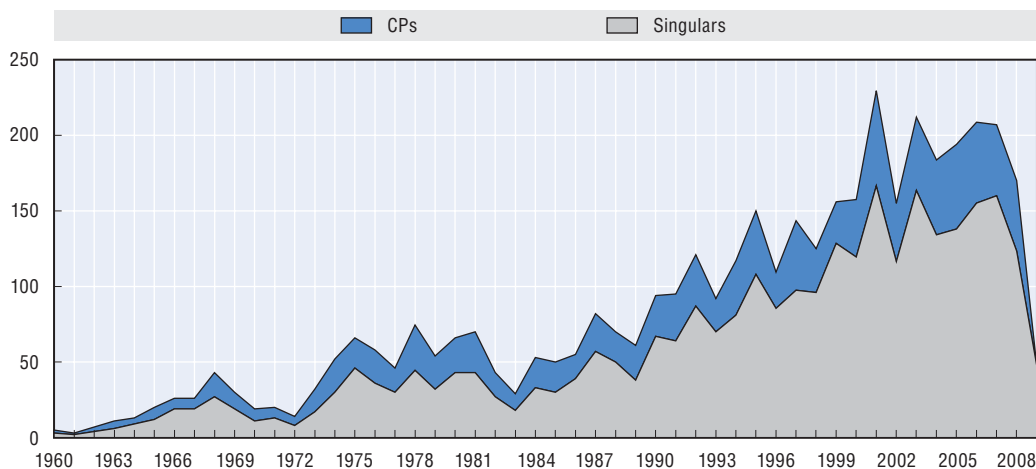


In terms of grid management innovations, Figure 4.7 indicates that the absolute level of patented inventions is more than an order of magnitude lower than in storage. There has been no obvious acceleration in the rate of invention. CPs represent a somewhat higher percentage of total counts than is the case for energy storage.

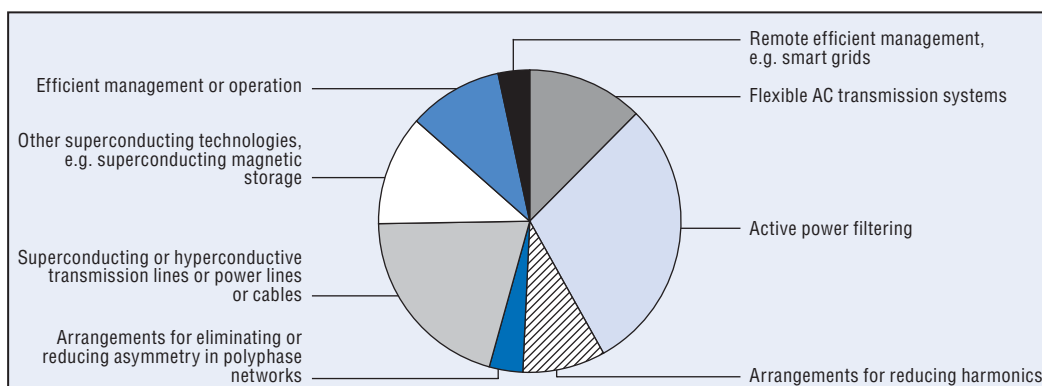
In terms of countries, Korea is much less prevalent than in the case of energy storage. The converse is true of France. Both Sweden and Switzerland have relatively higher counts than is generally found in other fields. In terms of technology types, active power filtering, superconducting transmission lines and flexible AC transmission systems make up almost two-thirds of the total claimed priorities (Figure 4.8).

Figure 4.7. **Innovation in electricity grid management**

CP and singular patent applications by in-sample countries

Figure 4.8. **Innovation in grid management by technology type**

Claimed priorities 1998-2008



4. Determinants of innovation in energy storage and grid management

Our principal objective in this section is to assess the factors that affect innovation in storage and grid management technologies. This is a first (and necessary) step in determining whether public support for RD&D in the area of energy storage and grid management will lead to increased penetration of renewable energy in the grid. Based on the discussion above, innovation in system flexibility (energy storage and grid management) is specified by means of the following equation:

$$\begin{aligned}
 & CNT_EP_STORGRID_{it} \\
 &= f(R\&D_STORGRID_{it}, POLICY_{it}, INTR_PERC_{it}, INTR_CONC_{it}, ELEC_TRADE_{it}, CNT_EP_TOTAL_{it}, \omega_i) \quad [1] \\
 &+ \varepsilon_{it}
 \end{aligned}$$

where i indexes country and t indexes year. The dependent variable ($CNT_EP_STORGRID$) represents the number of patent applications deposited at the European Patent Office, classified by inventor country⁷ and priority year⁸. We have used EPO patent applications because the search strategy is based on the Y-tags developed by the EPO, and alternative

counts would be biased since the coverage of Y-tags for applications from other offices is uneven. (The data source is PATSTAT as discussed above.)

As a control, a variable reflecting the propensity to invent and patent technologies in general (CNT_EP_TOTAL) is included as an explanatory variable. This variable is constructed in a manner analogous to the dependent variable (a count of patent families by inventor country and priority year) with the difference that all types of technologies (not only storage and grid mgmt) are covered.⁹ Ideally, we would estimate the model using a two-stage procedure where total patenting activity is first estimated. This approach was followed in (Johnstone *et al.*, 2011) and it was found that results from the two-stage estimation were closely comparable with those from a reduced-form model. Since many observations would be lost with such an approach, in this case we have decided to adopt this strategy.¹⁰

Public sector expenditure on R&D in energy storage and grid management (R&D_STORGRID) is included as an explanatory variable, expressed in million USD using 2008 prices and PPP. Assuming that such expenditures either result in patented innovations by the public sector, or contribute to patented innovations by the private sector the sign is expected to be positive. The data source is the IEA's *Energy Technology RD&D Budgets* (IEA, 2010).

The data for energy storage covers government expenditures for RD&D on batteries, super-capacitors, superconducting magnetic, water heat storage, sensible/latent heat storage, photochemical storage, kinetic energy storage, and other means (excluding hydrogen and fuel cells). The data for grid management covers RD&D on "electricity transmission and distribution". It covers solid state power electronics, load management and control systems, super-conducting cables, AC and DC high voltage cables and transmission, other transmission and distribution R&D related to integrating distributed and intermittent generating sources into networks, and all high temperature super-conducting research not covered elsewhere.¹¹

We also include a variable that reflects policy incentives. This is based upon a database of public policies aimed at developing renewable energy sources compiled at the IEA. A composite policy dummy variable is constructed equal to one when any of the six policy types were in place and zero otherwise (these include investment incentives, tax measures, feed-in tariffs, voluntary programmes, obligations, and tradable permits; see also Johnstone *et al.*, 2010).

Trade in electricity services (ELEC_TRADE) is included as a binary variable reflecting whether or not there was any trade (exports or imports) in electricity in the year in question. This variable is intended to capture the extent to which economies are able to compensate for intermittency by importing or exporting electricity services. In the absence of trade, the incentives for innovation in system flexibility are greater. An alternative variable in which trade is constructed as the maximum of imports or exports over total generation was also used, but the results remain qualitatively the same. The source of the data is the IEA's *Electricity Information* (IEA, 2009b).¹²

The percentage of "intermittent" energy sources (wind, solar, ocean/tidal) in total electricity supply (INTR_PERC) is included to reflect the vulnerability to intermittency. The expected sign is positive. In addition, since the vulnerability to intermittency may be obviated through a more diverse portfolio of sources, a variable is constructed to reflect this variation. The variable INTR_CONC is constructed as the squared sum of the differences between the percentage dependence on each intermittent source and mean

dependence for all intermittent sources. This is then normalised by percentage of intermittent sources in the grid to isolate the effect of concentration. The expected sign is positive. The source of the data is the IEA's *Renewables Information* (IEA, 2009c).¹³ Descriptive statistics are set out in Table 4.2.

Finally, country fixed effects account for omitted country-variant effects that influence the dependent variable in a time-invariant manner. Most notably, this would capture the effect of geographical area, and thus potentially smoothing of intermittent sources. All the residual variation is captured by the error term.

Table 4.2. **Descriptive statistics**

Variable	Obs	Mean	Std. dev.	Min.	Max.
CNT_EP_STORGRID	674	22.167	56.337	0	435.667
R&D_STORGRID	674	9.778	22.861	0	244.139
POLICY	674	0.616	0.487	0	1
INTR_PERC	674	0.593	2.027	0	18.319
INTR_CONC	674	0.546	0.454	0	1
ELEC_TRADE	674	0.838	0.368	0	1
CNT_EP_TOTAL (in 1 000's)	674	3.344	6.476	0	35.465

Note: The estimation sample includes data on 28 OECD economies (AT, AU, BE, CA, CH, CZ, DE, DK, ES, FI, FR, GB, GR, HU, IE, IT, JP, KR, LU, NL, NO, NZ, PL, PT, SE, SK, TR, US) for the period 1974-2007.

Our dependent variable represents the number of patent applications – patent counts. Count data models, such as the Poisson and negative binomial, have been suggested for estimating the number of occurrences of an event, or event counts (see e.g., Wooldridge, 2002; Cameron and Trivedi, 1998; Hausman, Hall and Griliches, 1984; Maddala, 1983:51). Formally, the Poisson model is derived by assuming that a random variable y is Poisson-distributed with the conditional density of y equal to $(y|x) = (e^{-\theta} \theta^y) / y!$, where $\theta = E[y|x]$. The log of the mean θ is assumed to be a linear function of a vector of independent regressors x : $\ln \theta = x'\beta$, where β is a parameter vector. This specification ensures non-negativity of θ (Cameron and Trivedi, 1998). However, the Poisson specification imposes a heavy restriction on the data – the equality of conditional mean and conditional variance, $E[y|x] = V[y|x] = \theta$, referred to as the equidispersion property of the Poisson. Indeed, as with most empirical data, casual inspection of the sample mean and sample variance indicates that their conditional counterparts are likely to be different for both dependent variables, indicating over-dispersion.

One way to account for over-dispersion is the negative binomial model suggested by Cameron and Trivedi (1998). They derive a negative binomial model from a Poisson-gamma mixture distribution (C&T: 100–102). In addition to y being conditionally Poisson-distributed, parameter θ is assumed to be the product of a deterministic term and a random term, $\theta = e^{x'\beta + s} = e^{x'\beta} + e^s = \mu v$. In other words, the unobserved error parameter (v) introduces heterogeneity in the variance, and the intensity parameter (μ) is explained (in log) by a vector of explanatory variables (x). Therefore, by assuming a gamma distribution for v (mean 1, variance α) Cameron and Trivedi show that the marginal distribution of y is the negative binomial with the first two moments $E[y|\mu, \alpha] = \mu$ and $V[y|\mu, \alpha] = \mu + \alpha\mu^2$ (for the NB2 variance function, C&T:63). It follows that as $\alpha \rightarrow 0$ the NB model converges to the Poisson distribution with intensity μ . The dispersion parameter α is to be estimated.

The results of the estimation are presented in Table 4.3. The total sample is a maximum of 676 observations, with an unbalanced sample of 28 countries and 34 years. In

Table 4.3. **Estimated coefficients of the system flexibility innovation models**

	Model 1 (base model)	Model 2 (lagged policy)	Model 3 (without USA)	Model 4 (just storage)	Model 5 (just grid mgmt)
R&D_STORGRID	0.004***		0.008***		
Lag1_R&D_STORGRID		0.006***			
R&D_STOR				0.006**	
R&D_GRID					0.003
POLICY	0.804**		0.720***	0.789***	0.761***
Lag1_POLICY		0.650***			
INTR_PERC	0.055***	0.055***	0.058**	0.038**	0.126***
INTR_CONC	0.335**	0.368***	0.362***	0.253***	0.778***
ELEC_TRADE	-0.516***	-0.362	-0.466**	-0.510**	0.172***
CNT_EP_TOTAL	0.087**	0.088***	0.086***	0.094***	0.044
Number of Observations	674	666	641	676	674
Log pseudo-likelihood	-1 617.8	-1 612.3	-1 449.7	-1 579.8	-617.7

* p < 0.050, **p < 0.025, ***p < 0.010 based on robust standard errors. Fixed effects are included in all models but are not reported here. The estimation sample includes data for 28 OECD economies and 34 years (1974-2007).

total five models are estimated, in addition to the base model. Model 2 includes lagged R&D and policy variables. Model 3 is estimated on the post 1985 data since demand for system flexibility before that point may have been less acute. Model 4 excludes the US sample since the pattern of R&D expenditures for the US is quite distinct. In Models 5 and 6 storage and grid management are estimated separately.

As expected public RD&D has a positive and significant impact. Based on the estimated elasticities (Table 4.4), a 10% increase in public sector R&D results in approximately 0.4%-0.5% increase in patents in the base model. The effect is relatively small, and further work will be undertaken to determine whether such investments result in significant increases in the efficiency of storage and grid management technologies, as well as increases in renewable energy penetration. Indeed, it is interesting to note that the coefficient reflecting the effect of the introduction of renewable energy support measures (POLICY) is highly significant and much larger in magnitude. Countries that are encouraging renewable energy penetration in their grid are also innovating in storage and grid management. Moreover, as the penetration of intermittent renewable energy in the supply mix rises, innovation in storage and grid management increases. However, other findings indicate that this is conditioned by other factors. For instance, greater diversity in the mix of wind, solar and ocean-tide energy reduces innovation rates in storage and grid management. In addition, greater trade will have the same effect. Interestingly, when disaggregated one can see that this is only true of storage (Model 5) and not grid management (Model 6). This is likely because many aspects of grid management are complementary with improved capacity to exploit trade in electricity services.

Table 4.4. **Estimated elasticities for base model**

R&D_STORGRID	Public R&D expenditures on storage and grid management	0.040
POLICY	Renewable energy support measures	0.451
INTR_PERC	Percentage of intermittent energy sources	0.027
INTR_CONC	Concentration of intermittent energy sources	0.172
ELECT_TRADE	Trade in electricity	-0.121
CNT_EP_TOTAL	Total patents	0.299

Note: Based on conditional marginal effects evaluated at sample means.

5. Conclusions and further research

Insufficient system “flexibility” is a significant constraint on the penetration of intermittent renewable energy sources in the grid. Imperfect and uncertain matching of supply and demand means that the “real” contribution of increased capacity of wind, solar, and ocean/tide power is less than the nominal capacity, and sometimes very much less. Improved energy storage and grid management can overcome this constraint by increasing system flexibility.

There are good reasons to believe that there are benefits of targeting public R&D expenditures at storage technologies rather than directly at intermittent generating technologies. At least three related reasons can be cited:

- It is more parsimonious with respect to information requirements for the government. Since innovation in “enabling” technologies (such as storage and grid management) is an important complement to innovation in all intermittent renewable generating technologies;
- The technologies are at a relatively early stage of development in comparison with the most important generating technologies, with greater returns on public R&D in the presence of learning curves;
- Such technologies are subject to important network externalities, implying that the rents from private investment will not be fully captured, and thus sub-optimally provided.

In this chapter, preliminary results have been presented on the determinants of innovation in energy storage and efficient grid management. The results are consistent with our expectations, with an important role played by both underlying technological factors (i.e. penetration and concentration of renewables) and policy factors (i.e. policy incentives and public R&D expenditures). However, this is just a first step. Further work is required to assess whether public support for R&D is better targeted directly at the specific intermittent generating technologies or at supporting technologies that are of wider benefit to system flexibility. Such an evaluation would require an assessment of the impact that such innovation has on generating costs, and thus penetration of renewable energy in the grid.

Notes

1. The IEA (2008) prefers the terms “firm” and “variable”. Sinden (2007) uses the terms “dispatchable” and “non-dispatchable”. The key factors are: what is the source of generating capacity; whether there is significant variation in the potential output of the source; and whether this variation is a consequence of exogenous factors beyond direct control (i.e. ecological conditions).
2. However, there are some “intermittent” variables which correlate with peak demand (e.g. solar photovoltaic and air conditioning). See Heal (2009) and Gross *et al.* (2007).
3. The difference between the fixed cost of energy-equivalent thermal plant minus the fixed cost of thermal plant displaced by capacity credit of the intermittent plant.
4. While 20% of Danish electricity is generated by wind, only 9% is consumed domestically with the balance exported to Norway and Sweden. Since the power exported to Norway and Sweden displaces power that is itself partly carbon neutral (e.g. hydro) the benefits in terms of carbon reduction may be limited (see CEPOS, Wind Energy: The Case of Denmark).
5. For instance, some (e.g. Swift-Hook 2010) have argued that storage does not facilitate penetration of intermittent renewable energy since as a low-marginal cost sources they will be the last to be

stored by operators. However, as Wilson *et al.* (2011) point out this would not be the case if storage operators are able to exploit price differential through inter-temporal trading.

6. With “locality” restricted to the basket of intermittent renewable energies. Such a strategy would favour intermittent over dispatchable renewable (e.g. hydro, geothermal) energy. Moreover, it would favour renewable energy in the electricity supply industry over other means of carbon abatement.
7. “Fractional” counts are generated in cases when inventors from multiple countries are listed.
8. “Priority date” indicates the earliest application date worldwide (within a given patent family).
9. This is achieved by extracting data on all EPO patent applications with an (any) ECLA code assigned.
10. In the sample used for econometric analysis, storage patents represent on average only 0.2% of total patents. Nevertheless, in order to avoid any concern over possible endogeneity, regressions are estimated on the difference between the patent total and the dependent variable.
11. http://wds.iea.org/wds/pdf/documentation_RDD.pdf.
12. http://wds.iea.org/wds/pdf/doc_Electricity_2009.pdf.
13. <http://wds.iea.org/WDS/tableviewer/document.aspx?FileId=1315>.

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Chapter 5

International technology agreements for climate change: Analysis based on co-invention data

by

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This chapter examines the effect of multilateral energy technology initiatives, so called “Implementing Agreements”, on international research collaboration in seven important climate change mitigation technologies. The analysis is conducted using patent data on 33 OECD countries during the period 1970-2009. We find that co-invention is significantly affected by the membership in the Implementing Agreement. Joining an agreement would increase co-invention by between 150% and 200% in the case of the agreements which relate to carbon capture and storage and solar photovoltaics, and approximately 100% for biofuels, fuel cells, and wind power. Given the urgency to develop effective international mechanisms to mitigate climate change, these results are encouraging and the topic is an important area for further policy research.

1. Introduction

A global effort is required to reduce emissions of greenhouse gases. This can only be achieved by accelerating the development and utilization of climate change mitigation technologies (CCMT) on an international scale. The issues of technology and knowledge transfer have received special attention in recent discussions on climate mitigation. A number of commentators have seen international technology-oriented agreements as a potentially useful complement to emissions-based agreements at the international level (see, De Coninck *et al.*, 2007; Popp, 2011; Ockwell, 2010). In particular, measures that support international collaborative research activities across economies can be a helpful mechanism to encourage the development and diffusion of climate mitigation technologies internationally.

In order to measure collaborative research activities, we build on previous work undertaken by the OECD Environment Directorate on identifying environmental and climate change mitigation technologies using patent data. Based on the search algorithms developed in close collaboration with patent examiners at the European Patent Office we are able to identify those patents that are directly relevant to climate mitigation. Moreover, the documentation allows us to identify those patents for which “inventors” are residents of different countries – i.e. so called co-inventions.

This is of particular interest since until recently, studies on the internationalization of technology and knowledge focussed on foreign direct investment or international trade. Knowledge transfer through co-invention remains under-researched, and has not been examined at all in the context of climate mitigation technologies, except in a qualitative manner. In this chapter we look at the specific role of the International Energy Agency’s “Implementing Agreements”.¹

The organization of the chapter is as follows. In the second part, it reviews the economics literature on the internationalization of research and diffusion of technologies. In the third part, the role of international research collaboration for climate change mitigation will be discussed. In the next section, the links between co-invention of climate mitigation technologies and Implementing Agreements are discussed. In the fifth part, the modelling strategy will be explained and the results of the econometric estimation presented. The chapter concludes with some tentative conclusions and discussion of further work.

2. Literature review

The general literature on the internationalization of technology is large, often using firm-level internationalization of R&D expenditures as a measure (e.g. Guellec and Zuniga 2006). This strand of literature presents the internationalization as the product of the exploitation of a firm’s own knowledge assets or of knowledge external to it, usually undertaken by multinational companies (UNCTAD 2005). It reflects joint involvement of the headquarters with research facilities of affiliates or subsidiaries based in a different

country (intra-firm collaboration), or research joint ventures amongst several firms or institutions in at least two different countries (inter-firm collaboration).

In an advanced country-level analysis Guellec and Zuniga (2006) investigate the motives for globalization of cross-border R&D investment by MNCs since the early 1990s. The authors identify two motivations:

- The dominant one being that companies source for knowledge abroad, by “tapping talents”, to make up for a lack of technological competences. Joint research endeavours allow companies to overcome shortages of resources by hiring complementary knowledge from abroad, at lower cost.
- The second, and perhaps less prominent, motivations for the globalization of activities is product adaptation to local characteristics with which market access will be increased.

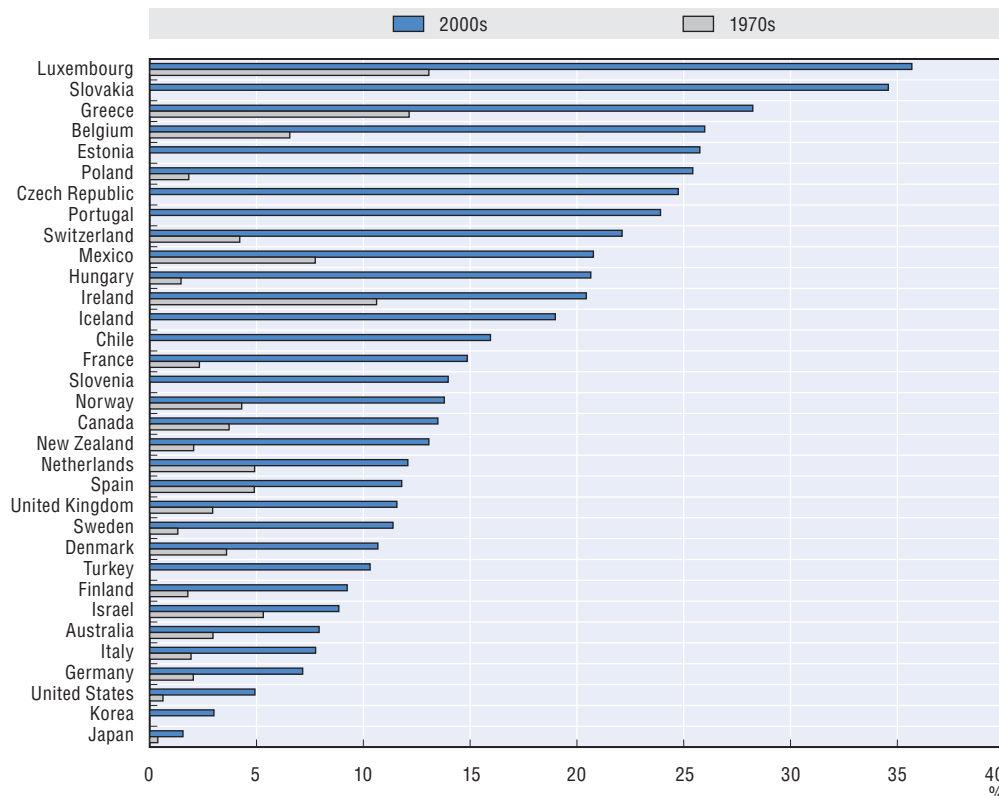
Archibugi and Iammarino (1999) developed a taxonomy of the internationalization of innovation and technology, which has been applied by subsequent researchers. Nonetheless, investigations of patterns of internationalization of research are relatively new and remain descriptive. However, an influential paper by Guellec and Van Pottelsberghe (2001) uses patent data to understand major trends in international patenting. By creating three patent-based indicators of internationalization of technology, they find an increasing trend of globalization of technology within the OECD area. They support previous findings which indicate that for applications filed at the United States Patent and Trademark Office as well as at the European Patent Office the share of cross-border inventions in total inventions was between one and two per cent until the 1980s (Bergek and Bruzelius, 2005). In recent years however, this share increased rapidly, reflecting the globalization of technology due to increases in FDI or R&D investment abroad by MNCs, or simply a higher propensity to patent.

There is a branch of the literature which uses co-invention data in the context of network and spatial analysis to quantify geographically localized spillovers (see e.g. Jaffe *et al.*, 1993; Breschi and Lissoni, 2009; Cowan *et al.*, 2007). For example, Ejermo and Karlsson (2006) quantify localized knowledge spillovers in interregional inventor collaboration networks in Sweden by analysing co-authorship of patents (i.e. interregional co-invention). Broekel *et al.* (2011) find positive evidence of inter-regional collaboration and increases in firms’ innovation performance in Germany. Regional innovation systems are also investigated by Maggioni *et al.* (2007) who use co-invention data as one aspect in their exploration of the importance of traditional “geographical” spillovers *vis-à-vis* “relational” spillovers. Fontana and Geuna (2008) investigate determinants of the governance structure for a sample of successful collaborative inventive activities and find that firm size and spillovers have a positive impact on the probability to co-invent. In a study of a particular patent class, Stolpe (2002) found that 969 of 1 398 patents (69%) listed more than one inventor, and only 246 of 2 115 inventors (12%) had always patented without help of collaborating inventors.

Amongst these patents, there is a sub-group in which at least two inventors reside in different countries. Those internationally co-invented patents will be the subject of our investigation. Within the OECD (OECD, 2009), the world share of co-invented patents more than doubled between 1990 and 2000 to over five per cent (Guellec and van Pottelsberghe, 2001; see also Ma and Lee, 2008). Other papers have found that co-invention is subject to large heterogeneities across time, countries, industries and firms (Guellec and van

Pottelsberghe, 2001; Bergek and Bruzelius, 2005). Large differences in the share of co-inventive activity between inventors in different countries show that it is the smaller and less developed economies, i.e. those with lower technological intensity, that have the higher degree of technological internationalization (Guellec and van Pottelsberghe, 2001; OECD 2008), such as Belgium, Ireland, the Czech Republic, Hungary and Poland. These studies also establish that inventors from two countries are more likely to collaborate if they are closer geographically and have similar technological specialization. Figure 5.1 gives co-invention data for the sample of OECD economies.

Figure 5.1. **Co-invention rates in OECD (2000s compared with 1970s)**



Source: The Figure shows cases with at least 10 inventions per year on average (in all technological fields). Constructed based on data prepared for this paper; for further details see the discussion below.

Overall, the rate of co-invention among OECD economies has increased significantly since the 1970s, with the highest increases in Slovakia and Poland and the lowest increases in Israel, Japan and Korea. However, in some countries co-invention has actually gone down, particularly in Chile and Turkey.

To our knowledge, there has not yet been a quantitative analysis of co-invention in fields relevant to climate change mitigation. This paper provides the first step in this direction.

3. International research collaboration in CCMTs

The benefits of international research collaboration may be particularly important in sectors that require large-scale investments and/or a diverse mix of research capability. In

the context of climate change, many of the research efforts involve significant expenditures of resources and a wide variety of expertise.

National policy incentives are motivated in large part by commitments made at the international level in the context of the UNFCCC. However, the protracted and unpredictable nature of climate change negotiations has encouraged researchers to examine the role of international technology-oriented agreements and mechanisms (see De Coninck *et al.*, 2007, for a discussion.) This approach is justified by previous theoretical research: Golombek and Hoel (2011) find that – in the light of the shortcomings of the Kyoto protocol in inciting countries to reduce emissions – the probability of collaboration on climate-friendly technologies is higher than that on emission reductions.

In the study by De Coninck *et al.* (2007)² technology-oriented agreements are classified as:

- knowledge-sharing and co-ordination;
- research, development and demonstration and cost-sharing;
- technology transfer; and,
- technology mandates and incentives.

The International Energy Agency has established a range of multilateral energy technology initiatives in various areas such as energy efficiency, fossil fuels, fusion power and renewable energy technologies from 1975. The creation of new initiatives and increases in member numbers can be closely linked to national policy priorities: While their activities reflect patterns of close collaboration in fossil fuels in the 1980s, since the 1990s focus has been on energy savings, GHG emissions, climate change, technology transfer and renewable energies (IEA, 2010). For an excellent summary of the governance of the Implementing Agreements see Figueroa (2010).

These so called “Implementing Agreements” (IAs) have the objectives of sharing knowledge about these technologies across borders and creating research collaboration synergies. Membership includes member and non-member economies, businesses, industries, international organisations and non-government organisations (see Figueroa 2010). An increase in participation has been observed coming from non-IEA member countries, in particular China and India since 2007.

IAs are closest in nature to the first two classes of technology-oriented agreement set out above, but can have important implications for the objectives (technology transfer and standards) related to the latter two types of agreement as well. Through activities such as joint development of energy related technologies, exchanges of scientists and information and undertaking joint studies, IAs provide a unique platform to foster co-invention in CCMTs.

In 2010, 42 active initiatives had been registered, amongst which we will focus on seven agreements since they are closely related to climate change mitigation and they can be “married” to search algorithms developed for the extraction of patent data:

- *Advanced motor fuels*: The objective of this IA is to promote understanding of alternative motor fuels, to assess their economic and environmental impacts, and to facilitate harmonization of legislation and standards.
- *Greenhouse gases*: The goals of this IA go beyond dissemination of information, and comprise instead the evaluation of technologies, preparation of R&D proposals and projects. “Activity under the program initially focused on the capture and storage of carbon dioxide from power stations and has since broadened to explore a range of

opportunities for reducing emissions of greenhouse gases. [Two of the] research and development [annexes initiated are]: geological storage of carbon dioxide, [...] and modelling of ocean storage of carbon dioxide.” This has become the core focus of the agreement.

- *Advanced fuel cells*: This IA advances co-operative research to reduce cost and improve performance of advanced fuel cells, by establishment of expert networks, and information exchanges. According to the website, these have “strengthened national capabilities and are expected to lead to the achievement of significant technical objectives”.
- *Photovoltaic (PV) Power Systems*: This IA contributes to the cost reduction of PV applications, increases awareness of their potential and value, fosters their market deployment by removing technical and non-technical barriers, and enhances technology co-operation with non-IEA economies.
- *Hydrogen*: The work of the Agreement is “directed towards the development of advanced technologies, including direct solar production systems, low-temperature metal hydrides, and room-temperature carbon nano-structures for storage.” The agreement covers “research, development and demonstration stages, [over] validation of environmental and economic performance, to final market deployment”. Amongst other achievements, activities have led to the establishment of a database of metal hydride material properties.
- *Energy storage*: The goal of this IA is to develop and demonstrate various advanced energy storage technologies for application, to encourage their use by formulation of case studies, demonstrations, deployment measures and design tools. “The work program includes a range of tasks relating to development of underground thermal energy storage systems in the buildings, industrial and agriculture sectors; examination of the potential role of electrical storage technologies in optimizing electricity supply and use; examination of the role of phase-change materials and thermo-chemical reactions in energy systems; and development of procedures and screening and decision tools to facilitate the adoption of energy storage in project designs.”
- *Wind energy systems*: “The Agreement has a purpose to produce objective information and analysis that will inform government policy.”

IAs potentially contribute to achieving faster technological innovation at lower cost, since the financing works through cost sharing or task sharing of the participating countries. Collaborations bring the benefit of scale, and permit research in instances where the scale or scope is too large for a national project (The Royal Society, 2011). Experiences and results of the IAs are accessible and hence create a knowledge pool and infrastructure that enhances the efficiency of future collaboration by avoiding replication of errors, duplication of efforts etc. Dissemination of information, on which a strong emphasis lies, happens by various means such as technology bulletins, and monthly or yearly publications about achievements and outputs. The activities often require the organization of conferences, workshops, and the maintenance of informative websites about proceedings and working papers (IEA, 2010).

According to the IEA (2003 and 2010) the benefits of signing an Implementing Agreement, include:

- shared costs and pooled technical resources;

- avoided duplication of effort, reduce technological and research risk, and repetition of errors;
- harmonized technical standards, protection of intellectual property rights;
- active network of researchers;
- stronger national R&D capabilities;
- improved effectiveness of future research programs;
- accelerated technology development and deployment;
- better dissemination of information;
- easier technical consensus;
- boosted trade and exports.

The financial cost of participation depends upon the agreement. A potentially more significant concern is loss of rents associated with knowledge diffusion. However, special provisions are applied to protect intellectual property rights (IPRs), “existing proprietary information, as well as inventions and patents developed under the IA are appropriately protected” (IEA 2010). This indicates that in principle there are no IPR-related disincentives from the establishment of genuine partnerships.

The Framework for International Energy Technology Co-operation of the IEA provides the legal structure and establishes the commitments of the participants to the IAs. For example, annual reports on achievements and resources need to be published while the centralized Committee on Energy Research and Technology of the IEA (CERT) reviews and evaluates those activities. The duration of every IA is time-delimited and since extensions only happen on “exceptional circumstance and sufficient justification”, the problem of inactive initiatives is reduced.

The benefits of being a member of an Implementing Agreement are supported indirectly by previous literature on the benefits of research partnerships. Scott (2003) uses patent cross-citations to test his hypothesis that research partnerships expand firms’ absorptive capacities. He finds that efficiency gains are produced, since scarce research resources of multiple organizations are brought together, extending the range of potential outputs. Geyer et al. (2004) and Philibert (2004) investigate one Implementing Agreement on solar energy (SolarPACES) and confirm that even if international policy may not be substitutable to domestic policies; international energy technology collaboration “plays an important role [...] in reducing costs and multiplying benefits of many R&D efforts thanks to cost-sharing collaboration and information exchanges”.

This paper evaluates cross-country collaborative research activity in the seven climate change mitigation technologies in a panel data framework. In doing so, it bridges a gap in the literature on cross-country comparisons of co-inventive activity in climate change mitigation technologies. The recent availability of co-invented patent data for climate change mitigation technologies makes it possible to investigate the following hypothesis:

Does membership in an Implementing Agreement in selected sectors of climate change mitigation technologies lead to an increase in international research collaboration?

4. The implementing agreements and co-invention in CCMTs

To investigate this hypothesis, we assembled the data to construct a variable for each Implementing Agreement. Since there is no source that provides the adherence dates of

signatory countries in a disaggregated manner, information was collected from the respective websites and annual reports that were complemented with information communicated by the IEA Secretariat directly.³

As noted, we rely on patent data to develop our measure of co-invention. Patents are exclusive rights to an invention providing protection for a period of usually 20 years, granted by national or regional patent offices. This invention can be a device or process and is required to meet three patentability conditions: be “new” (novelty), involve a non-obvious inventive step (non-triviality) and be considered industrially applicable (usefulness) (see OECD, 2008). The earliest application date worldwide is referred to as the priority year (Dernis, Guellec and Van Pottelberghe de la Potterie, 2001).

The advantages of using patent data for tracking the internationalization of technology are numerous. First, the documentation provides a complete description of the invention. In addition, a classification of the invention in technology fields is possible. Finally, information on the inventor(s) name(s) and address(es) are registered as well as dates and a variety of other data (OECD 2009 Patent Statistics Manual). The inventor is always an individual, usually a researcher employed by the patent applicant.

For the purpose of this paper, co-invention occurs when two, or more, of the registered inventors declare different countries of residence. The indicators of co-invention are constructed as frequency counts of co-invented inventions. In doing so, care is taken to consider inventor information only once for each patent family in order to avoid double counting. Exploiting the inventor data can tell us much about the geographical organization of co-inventions.

Some care needs to be taken when analyzing international co-invention activity using patent data. The first set of limitations is conceptual and relates to the definition of what constitutes co-invention. In particular, the definition of co-invention as adopted in this paper restricts the range of hypotheses that can potentially be examined. For example, it is impossible to exclude inventions from two inventors of the same nationality but located in different countries. In addition, since submission of company information, i.e. ownership or country of origin is not required in patent applications, co-invented patents may not be perfectly accurate indicators for international research collaboration. For example, a patent may be classified as co-invented, if it results from common efforts of two laboratories of the same company, located in different countries and listed as inventors' addresses. Decisions within a company of whom to mention as listed inventor certainly play a role.

The second set of limitations is more general in nature and relates to the usual set of limitations concerning the use of patent data to measure innovation (see Griliches, 1990). For example, care needs to be taken to control for differences in propensities to patent across industries, technological sectors, and countries. These may emerge due to differences in regulations between countries or the use of alternative strategies of protection other than patents (e.g. secrecy, reputation, or lead-time) which changes across industries. Equivalently in panel data settings, differences in the propensity to patent over time within one country or industry, i.e. due to changes in the breadth of protection of patents or in the protected technologies, need to be controlled for in the analysis. In the same spirit, patents from different patent offices may have different “breadth” and are thus not strictly comparable to each other. As explained below, we control for these concerns econometrically.

Finally, the third set of limitations relates to data quality issues. As with many other sources of data, patent databases do not always contain complete information (i.e. some patents included in the database may have missing attributes) and, more broadly, their coverage may vary over time and across countries (i.e. some patents may not be included in the database, compared with the “true” population of patents worldwide). While the availability of data on inventors appears to be of particular importance in our case, the broader question of idiosyncratic coverage is relevant as well – an aspect frequently overlooked in empirical studies using patent data. Again, we control for both of these issues econometrically.

In this paper, indicators of co-invention are constructed using data extracted from the *European Patent Office’s Worldwide Patent Statistical Database*, or PATSTAT (EPO, 2010). The data set was created by extracting patent information using search strategies defined by the OECD’s indicator of environmental technologies (ENV-Tech). The indicator covers a broad range of environment-related technology fields. Identification of such technologies is possible using the International Patent Classification (IPC) system as well as its extension the European Classification (ECLA).

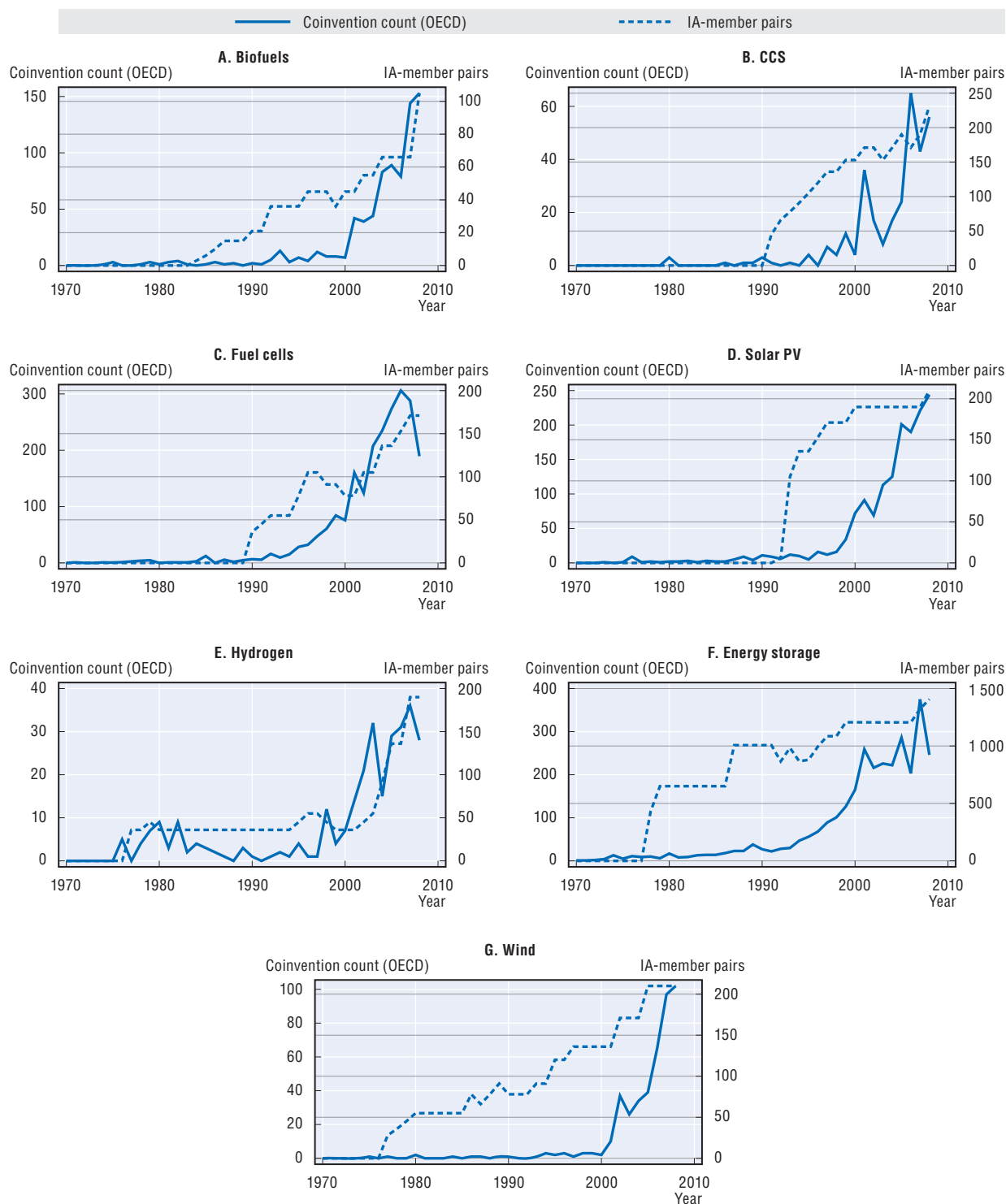
As noted above, in this paper patent data are used to construct indicators of co-invention in seven technological fields that are the primary focus of IAs, including wind energy, solar photovoltaics, energy from biofuels, energy storage, hydrogen, fuel cells, and carbon capture and storage (CCS). These selected fields are relevant to climate change-mitigation in energy generation. (For a list of the search strategies applied see www.oecd.org/environment/innovation and Appendix 1.A1.)

Table 5.1 indicates that there are large differences in co-invention counts between the sectors analyzed. An additional “control sector” is included and this allows us to compare the co-invention shares of the selected CCMTs with shares for all technologies overall (TOTAL). Three CCMTs – biofuels, CCS, and fuel cells – have higher co-invention rates than what is found for all technologies overall. What might explain the relative ranking? Two factors come to mind: The degree of technology maturity and the extent to which benefits of technology development have public versus private good aspects.

Table 5.1. Co-invention rates by technology field

	Co-inventions	All inventions	% Co-inventions
Biofuels	603	6 286	9.6
CCS	253	3 501	7.2
Fuel cells	1 985	34 713	5.7
Solar PV	1 160	22 327	5.2
Hydrogen	252	5 035	5.0
Energy storage	2 511	54 422	4.6
Wind	390	10 060	3.9
PATSTAT TOTAL (all tech. fields)	454 998	8 457 380	5.4

The double y-plots presented in Figure 5.2 show the change in the number of member country-pairs over time and the total co-invention counts for the OECD sample. There are very few cases in which countries exit the Implementing Agreement. Furthermore, they have been established as early as the mid-70s (hydrogen, energy storage, and wind) and as late as 90 (CCS, fuel cells, and solar PV). The biofuels IA was signed in the mid-80s. Most of the sectors display a short lag between the establishment of the implementing agreement

Figure 5.2. **IA membership and trends in co-invention rates**

and the increases in co-invention. Since in the areas of biofuels and wind this lag is greater than ten years, one might surmise that Implementing Agreements may be less effective in inducing co-invention in these cases. Interestingly, not all IAs grow in terms of

membership in a similar fashion. Hydrogen displays 15 years of little growth, where no additional member country pairs joined the agreement.

Bearing in mind the descriptions of the Implementing Agreements, it is not surprising to find important discrepancies in the descriptive data. In the case of Wind Energy Systems, which has the sole objective of producing and sharing information, co-invention rates are low. The Photovoltaic Power Systems (PPS) IA encompasses a large array of different activities, and co-invention rates are higher. This may indicate that the effect of information dissemination has a slower effect on co-invention; while the effect of PPS, since it emphasize development and deployment, leads to faster results in co-invention.

When investigating top co-inventing country pairs by levels, the United States and Germany stand out, while Japan, which is a top-inventor country, is relatively under-represented. This indicates that there may be major differences in inventive activities and co-inventive ones: Countries that have a high propensity to innovate do not necessarily have a high share of co-invented patents. The converse is also true. For instance, Denmark and New Zealand feature as first and second in selected fields in Table 5.2.

Table 5.2. **Top 10 co-inventor country pairs, levels (2000-2008)**

Sector rank	Biofuels	CCS	Fuel cells	Solar PV	Hydrogen	Energy storage	Wind	PATSTAT TOTAL
1	DK-US	CA-US	JP-US	JP-US	DE-US	GB-US	DK-GB	GB-US
2	NL-US	NL-US	CA-US	DE-US	JP-NZ	CA-US	DE-US	DE-US
3	CA-US	GB-US	DE-US	GB-US	CH-DE	DE-US	CA-US	CA-US
4	DE-US	FR-US	GB-US	CH-DE	IT-US	JP-US	DE-NL	CH-DE
5	CN-DK	DE-US	CN-US	AT-DE	CA-US	JP-KR	NL-US	JP-US
6	DE-GB	AU-NL	KR-US	CA-US	CH-US	FR-US	DE-DK	FR-US
7	GB-US	DE-GB	FR-US	CN-US	FI-SE	CH-DE	IN-US	NL-US
8	CH-DE	GB-NL	CH-DE	DE-FR	DE-FR	CA-FR	BE-ZA	DE-FR
9	GB-NL	NO-US	CA-FR	DE-NL	DE-GB	CN-US	RU-US	CH-FR
10	JP-US	CN-US	CA-DE	GB-IT	IN-US	KR-US	DK-ES	CH-US

Source: The two-letter standard international country codes refer to: Austria (AT), Australia (AU), Belgium (BE), Canada (CA), Switzerland (CH), China (CN), Germany (DE), Denmark (DK), Spain (ES), Finland (FI), France (FR), United Kingdom (GB), India (IN), Italy (IT), Japan (JP), Korea (KR), the Netherlands (NL), Norway (NO), New Zealand (NZ), Russia (RU), Sweden (SE), the United States (US), and South Africa (ZA).

Amongst the emerging economies, it is also interesting to note that China is amongst the top 10 co-inventor pairs in five of the technologies examined, and India in the remaining two technologies. Russia is also present (wind), as is South Africa (wind). Conversely, no BRICS country figures in the top ten co-invention pairs for all technologies, indicating that collaboration in CCMTs may be particularly important for them.

5. Modelling strategy and results

5.1. Modelling strategy

The goal of this paper is to assess the effect of participation in Implementing Agreements on co-inventive activity between OECD economies. In order to correctly specify this relationship it is however important to control for other factors that may motivate international research collaboration. In our reduced-form model these factors are controlled for through the use of variables which reflect inventive capacity in the specific

field, as well as propensity to collaborate in general. The following empirical model is specified:

$$COINV_{ij,t} = f(IA_{ij,t}, RD_{ij,t}, TOTALCOINV_{ij,t}, \alpha_i, \alpha_j) + \varepsilon_{ij,t}$$

where ij indexes country-pairs and t indexes time (1970-2009). The models are run separately for each technological field, and country dummies are included. The maximum sample consists of 514 country-pairs (including 33 OECD member economies) over the period of 40 years (1970-2009) and contains 8 610 observations. However, we have only retained those observations in which there is evidence of at least some co-invention in any field.

The dependent variable $COINV$ is the count of bilateral co-inventions in each technological field. It measures the number of patented inventions (claimed or unclaimed priorities) whose inventors come from at least two different countries, specifically countries i and j . The priority date of the invention (i.e. the earliest date when an application for patent protection has been made worldwide) defines year t .

IA is a binary variable indicating whether both countries were members of the relevant energy technology “Implementing Agreement” in year t . In addition to the joint membership dummy (IA_BOTH), in some model specifications we also include a dummy for the case when only one of the countries participated (IA_EITHER). The sign of these variables is expected to be positive.

RD controls for research & development capacity and is constructed in two alternative ways. First, a variable (RD_EXP) is constructed as an unweighted sum of R&D expenditures by the two countries (i and j) for the budget category that most closely relates to the technology field in question. This data has been obtained from the *IEA Energy Technology R&D Database* (IEA, 2010). In an alternative specification, we include a covariate (RD_INV) which measures the sum of patented inventions (claimed or unclaimed priorities) in the specific technological field registered by inventors from country i or j . This variable is constructed using data extracted from the *PATSTAT Database* discussed above. Sample sizes are slightly larger in the latter case due to some missing R&D expenditure data.

$TOTALCOINV$ is the count of bilateral co-inventions in all technological fields (that is, not only climate-related). It is important to point out that this variable is constructed in exactly the same manner as the dependent variable. This variable reflects co-invention patterns in patenting activity overall, and not only in a specific field. As such, it controls for the differences in general propensity to co-invent and patent over time and across countries. It thus captures all of the more general economic factors that are likely to influence patented co-invention (e.g. openness, common language, geographic distance, FDI, labour mobility, regional trade agreements, etc.), but that are not specific to a narrow technological field.⁴ In addition, perhaps most importantly, it controls for database idiosyncrasies (coverage, completeness of data) as discussed above. The sign of this covariate is expected to be positive.

Since the dependent variable is the count of bilateral co-inventions, the analytical framework is within the realm of discrete dependent variable regression models and specifically within the sub-category of count models. The variable displays frequent zero counts and low integer values. In this paper we primarily present results based on the estimation of negative binomial models, but a number of other count data models were estimated with similar results (incl. the conditional fixed-effects negative binomial and the zero-inflated negative binomial model). (For general references on count data models see Wooldridge, 2002; Cameron and Trivedi, 1998; Hausman, Hall and Griliches, 1984).

The model is estimated only on those observations where (any) co-invention actually occurred. That is, all models are estimated on a sample where total co-invention is non-zero ($\text{TOTALCOINV}_{ij,t} > 0$). This is because we are interested in whether IA “bends” the direction of co-invention towards more climate-related technologies. This gave us a maximum sample size of 8610 observations. See Table 5.3 for summary statistics.

Table 5.3. **Descriptive statistics for the full estimation sample**

Variable	Obs	Mean	Std. dev.	Min.	Max.
COINV					
_Biofuels	8 610	0.073	0.664	0	24
_CCS	8 610	0.031	0.413	0	24
_Fuel cells	8 610	0.213	1.656	0	39
_Solar PV	8 610	0.148	0.881	0	21
_Hydrogen	8 610	0.025	0.226	0	8
_En.Storage	8 610	0.272	1.629	0	36
_Wind	8 610	0.038	0.449	0	17
IA_BOTH					
_Biofuels	8 610	0.115	0.320	0	1
_CCS	8 610	0.258	0.437	0	1
_Fuel cells	8 610	0.222	0.416	0	1
_Solar PV	8 610	0.293	0.455	0	1
_Hydrogen	8 610	0.194	0.396	0	1
_En.Storage	8 610	0.437	0.496	0	1
_Wind	8 610	0.363	0.481	0	1
IA_EITHER					
_Biofuels	8 610	0.434	0.496	0	1
_CCS	8 610	0.352	0.478	0	1
_Fuel cells	8 610	0.393	0.488	0	1
_Solar PV	8 610	0.324	0.468	0	1
_Hydrogen	8 610	0.503	0.500	0	1
_En.Storage	8 610	0.259	0.438	0	1
_Wind	8 610	0.468	0.499	0	1
RD_EXP					
_Biofuels	7 066	1.61	5.48	0	65
_CCS	7 066	20.10	247.45	0	4 121
_Fuel cells	7 066	10.69	36.18	0	344
_Solar PV	7 066	31.51	47.89	0	439
_Hydrogen	7 066	6.74	26.227	0	269
_En.Storage	7 066	12.29	30.20	0	462
_Wind	7 066	15.01	21.12	0	219
RD_INV					
_Biofuels	8 610	15.24	48.45	0	565
_CCS	8 610	5.21	20.22	0	269
_Fuel cells	8 610	79.26	239.57	0	2 619
_Solar PV	8 610	51.49	138.24	0	1 465
_Hydrogen	8 610	8.16	26.51	0	311
_En.Storage	8 610	136.59	302.41	0	2 647
_Wind	8 610	23.46	56.10	0	703
TOTALCOINV	8 610	58.014	224.00	1	3 468

5.2. Base model results

The base model results support the principal hypothesis that membership in Implementing Agreements (IA) increases international research collaboration and leads to higher co-invention. All coefficients of IA_BOTH are positive and statistically highly significant, with the exception of hydrogen (Table 5.4). For example, the results indicate that a change in the IA_BOTH variable from 0 to 1, and holding all other variables constant, increases the count of co-inventions by 0.0155 for biofuels (per year and per country-pair). The biggest impacts are for solar PV, fuel cells, and energy storage. Effect of the key control variable TOTALCOINV is, as expected, positive and significant in all of the models estimated, while effect of R&D expenditures varies.

Table 5.4. **Estimated marginal effects of co-invention (model A)**

	A1	A2	A3	A4	A5	A6	A7
	Biofuels	CCS	Fuel cells	Solar PV	Hydrogen	En. Storage	Wind
IA_BOTH (d)	0.0155** (0.0059)	2.93e-05*** (5.59e-06)	0.0512*** (0.0112)	0.104*** (0.0175)	1.33e-04 (1.60e-04)	0.0433*** (0.0126)	1.42e-03** (4.78e-04)
TOTALCOINV	6.72e-06** (2.32e-06)	7.12e-09*** (2.14e-09)	3.11e-05*** (9.44e-06)	2.95e-05** (1.01e-05)	4.34e-07** (1.37e-07)	1.52e-04*** (3.78e-05)	1.62e-06*** (4.08e-07)
RD_EXP	2.34e-04*** (6.86e-05)	1.82e-09 (9.44e-10)	1.32e-04*** (4.04e-05)	-1.48e-04*** (4.59e-05)	2.93e-06** (9.34e-07)	3.50e-05 (6.28e-05)	-2.99e-06 (3.88e-06)
Country dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ln(alpha)	2.58***	1.32***	1.09***	0.95***	1.27***	1.11***	2.38***
AIC	2 287.1	1 161.4	4 003.3	3 846.6	1 264.9	5 467.3	1 488.7
BIC	2 506.7	1 381.1	4 222.9	4 066.2	1 484.5	5 686.9	1 708.3
N	7 066	7 066	7 066	7 066	7 066	7 066	7 066

Note: *p < .05; **p < .01; ***p < .001 based on robust standard errors (in parentheses). The estimates give the predicted number of events on the margin, evaluated at sample means. For binary regressors (d) indicates effect for a discrete change from the base level. The estimation sample includes an unbalanced panel of 368 country-pairs (including 27 OECD economies) over a period of 36 years (1974-2009).

Next, we replace the RD_EXP covariate with RD_INV as an alternative measure of research capacity (Table 5.5). As a consequence, the marginal effects of IA_BOTH decrease

Table 5.5. **Estimated marginal effects of co-invention using an alternative model specification (model B)**

	B1	B2	B3	B4	B5	B6	B7
	Biofuels	CCS	Fuel cells	Solar PV	Hydrogen	En.Storage	Wind
IA_BOTH (d)	0.0046** (0.0017)	1.94e-07*** (4.18e-08)	0.0248*** (0.0058)	0.0404*** (0.0066)	1.26e-04 (9.72e-05)	0.0158* (0.0082)	8.17e-05* (3.59e-05)
TOTALCOINV	1.24e-06* (5.56e-07)	2.17e-08*** (6.34e-09)	1.22e-05** (4.67e-06)	1.26e-05* (5.34e-06)	8.28e-08 (6.16e-08)	7.23e-05*** (2.08e-05)	5.79e-08** (1.85e-08)
RD_INV	2.18e-05*** (3.07e-06)	5.05e-07*** (1.12e-07)	2.00e-05*** (4.67e-06)	5.76e-05*** (1.01e-05)	4.58e-06*** (8.57e-07)	9.01e-05*** (1.67e-05)	4.87e-07*** (8.32e-08)
Country dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ln(alpha)	2.51***	1.15**	1.02***	0.75***	1.19***	0.96***	1.79***
AIC	2422.1	1143.6	4167.6	4052.0	1344.2	5800.3	1421.8
BIC	2690.4	1411.9	4435.9	4320.3	1612.5	6068.6	1690.1
N	8610	8610	8610	8610	8610	8610	8610

Note: *p < .05; **p < .01; ***p < .001 based on robust standard errors (in parentheses). The estimates give the predicted number of events at sample means. For binary regressors (d) indicates effect for a discrete change from the base level. The estimation sample includes an unbalanced panel of 514 country-pairs (including 33 OECD economies) over a period of 40 years (1970-2009).

in magnitude but remain positive and significant in all models except, again, for hydrogen. The RD_INV variable is positive and significant in all models estimated, suggesting that having active research capacity in a given field is one factor that determines the level of international co-invention.

5.3. Extensions and tests of robustness

Having only considered situations in which both co-invention partners were members of the Implementing Agreement, we lost information about research collaboration between members and non-members. In order to be able to take into account also those country-pair relationships, we consider a specification in which we keep the interaction term previously called IA_BOTH in the regressions. Recall:

- IA_BOTH =1 if [1;1]
- IA_BOTH =0 if [0;1] or [1;0] or [0;0]

Now, an additional term is added which takes on the value 1 if and only if either one of the countries is a member, and 0 if both or neither are:

- IA_EITHER =1 if [0;1] or [1;0]
- IA_EITHER =0 if [1;1] or [0;0]

The results suggest that while the IA_BOTH variable is still positive and significant in all models but hydrogen, IA_EITHER is significant only for biofuels, fuel cells, solar PV and energy storage (Table 5.6). The impact of either co-invention partner being member of the agreement leads to an increase in co-invention counts of approximately half of the magnitude, *ceteris paribus*, of that if both co-invention partners are members. The difference between the two coefficients is statistically significant (Wald test rejects the null hypothesis that both coefficients are equal), except for the case of hydrogen.

Table 5.6. **Estimated marginal effects of co-invention using two policy variables (model C)**

	C1	C2	C3	C4	C5	C6	C7
	Biofuels	CCS	Fuel cells	Solar PV	Hydrogen	En.Storage	Wind
IA_BOTH (d)	0.0237* (0.0094)	5.35e-05*** (1.16e-05)	0.0918*** (0.0196)	0.1184*** (0.0219)	2.25e-04 (1.90e-04)	0.0670*** (0.0168)	0.0021* (0.0009)
IA_EITHER (d)	2.87e-03* (1.24e-03)	1.05e-05 (5.43e-06)	0.0371*** (0.0081)	0.0509*** (0.0125)	9.58e-05 (1.12e-04)	0.0390* (0.0194)	3.67e-04 (4.11e-04)
TOTALCOINV	4.96e-06** (1.67e-06)	8.12e-09*** (2.16e-09)	2.11e-05** (6.90e-06)	2.29e-05** (7.42e-06)	3.75e-07** (1.20e-07)	1.40e-04*** (3.68e-05)	1.52e-06*** (3.72e-07)
RD_EXP	1.82e-04** (6.03e-05)	2.15e-09* (1.06e-09)	9.57e-05** (3.03e-05)	-1.20e-04** (3.80e-05)	2.47e-06** (8.02e-07)	3.02e-05 (5.86e-05)	-3.47e-06 (3.83e-06)
Country dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes
ln(alpha)	2.54***	1.32***	0.98***	0.90***	1.26***	1.07***	2.38***
AIC	2 280.8	1 158.2	3937.6	3 802.3	1 266.1	5 455.8	1 489.4
BIC	2 507.3	1 384.6	4 164.1	4 028.8	1 492.6	5 682.3	1 715.9
N	7 066	7 066	7 066	7 066	7 066	7 066	7 066

Note: *p < .05; **p < .01; ***p < .001 based on robust standard errors (in parentheses). The estimates give the predicted number of events at sample means. For binary regressors (d) indicates effect for a discrete change from the base level. The estimation sample includes an unbalanced panel of 368 country-pairs (including 27 OECD economies) over a period of 36 years (1974-2009).

Intuitively, the finding that the propensity to co-invent is significantly higher if both co-invention partners are members suggests that the agreement facilitates research collaboration between members to a higher degree, e.g. due to more symmetric cost and cost sharing and access to the knowledge pool provided by the agreement. If an outside country co-invents with a member then maybe access to the benefits of the IA are restricted.

We also estimated conditional fixed effects models (xtnbreg) with fixed effects for the country-pairs, rather than individual countries. The results are qualitatively similar. However, it should be noted that the xtnbreg regression uses only a sub-sample of observations and the subsample used differs somewhat across the various technologies, rendering the results not strictly comparable. Results from all models are summarized in Table 5.7. Overall, the findings are rather consistent in that the marginal effect of joint membership (IA_BOTH) is greatest for solar PV, fuel cells, energy storage and biofuels, but less for wind, hydrogen and CCS.

Table 5.7. **Summary of marginal effects of the IA variables from the various models estimated**

			a. IA_BOTH						
Model			Biofuels	CCS	Fuel cells	Solar PV	Hydrogen	En.Storage	Wind
A	nbreg	RD_EXP	0.0155***	2.93e-05***	0.0512***	0.104***	1.33e-04	0.0433***	1.42e-03**
B	nbreg	RD_INV	0.0046***	1.94e-07***	0.0248***	0.0404***	1.26e-04	0.0158*	8.17e-05*
C	nbreg	RD_EXP	0.0237*	5.35e-05***	0.0918***	0.1184***	2.25e-04	0.0670***	0.0021*
D	nbreg	RD_INV	0.0084**	5.79e-06***	0.0460***	0.0513***	2.73e-04	0.0327**	8.23e-05*
E	xtnbreg	RD_EXP	0.0676***	0.1214***	0.3266***	0.4233***	0.0606*	0.1525***	0.0681***
F	xtnbreg	RD_INV	0.0716***	0.1174***	0.2928***	0.3513***	0.0413	0.0779**	0.0591***
G	xtnbreg	RD_EXP	0.1284***	0.1589***	0.5412***	0.5342***	0.0791	0.2769***	0.0764**
H	xtnbreg	RD_INV	0.1449***	0.1609***	0.5092***	0.4479***	0.0946*	0.1929***	0.0753**

			b. IA_EITHER						
Model			Biofuels	CCS	Fuel cells	Solar PV	Hydrogen	En.Storage	Wind
C	nbreg	RD_EXP	2.87e-03*	1.05e-05	0.0371***	0.0509***	9.58e-05	0.0390*	3.67e-04
D	nbreg	RD_INV	0.0012**	1.29e-06*	0.0186***	0.0235***	1.10e-04	0.0288*	1.18e-05
G	xtnbreg	RD_EXP	0.0553***	0.0623	0.2944***	0.2777***	0.0187	0.2335***	0.0115
H	xtnbreg	RD_INV	0.0590***	0.0759	0.2880***	0.2543***	0.0512	0.2282***	0.0249

Note: *p < .05; **p < .01; ***p < .001 based on robust standard errors. Given that IA_BOTH and IA_EITHER are binary regressors, the values indicate effect for a discrete change from 0 to 1.

5.4. Policy simulations

What do these results tell us about the economic significance of technology agreements? What would be the benefits to non-members of joining the agreements? To provide some indication we simulate two policy scenarios, taking the observed joint-membership as given (baseline). First, we compare co-invention activity in the baseline with a scenario that no country was a member of an IA (scenario 1). Second, we compare co-invention activity in the baseline with a scenario that non-member country-pairs accede to technology agreements (scenario 2). In both cases, we calculate the average proportional change in co-invention implied by such shifts in joint membership for the relevant sub-sample of country-pairs (that is, for those that change membership status). The results for both scenarios are reported in Table 5.8.

Table 5.8. **Simulated effect of joint membership relative to the baseline prediction**
%

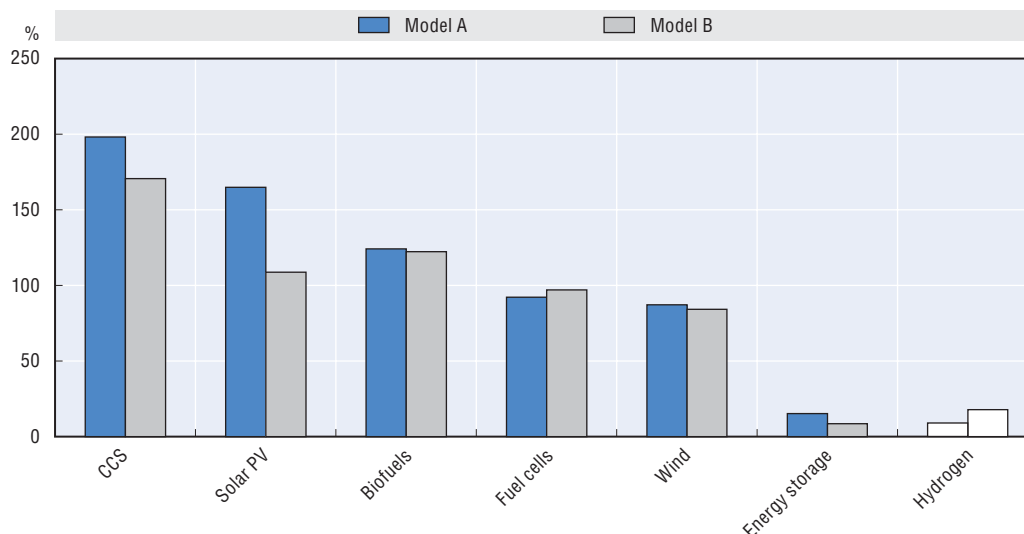
	Biofuels	CCS	Fuel cells	Solar PV	Hydrogen	En.Storage	Wind
Members:							
Model A	77	83	74	64	24	28	68
Model B	74	79	73	69	33	18	66
Non-members:							
Model A	124	198	92	165	9	15	87
Model B	122	171	97	109	18	8	84

Note: These values indicate the average effect under the policy scenario relative to the baseline prediction, evaluated at observed sample values.

Based on results from our preferred model, we find that the effect of joint-membership (as observed – scenario 1) on co-invention has been greatest for CCS (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%). (The effect for hydrogen is statistically insignificant.) These differences 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.

Concerning the simulated impact for non-members (scenario 2), we find that adherence of countries to an IA 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 (Figure 5.3). However, these figures represent only the direct impacts on co-invention. Additional impacts on domestic inventive activity may occur through spillovers. The overall impact of technology agreements may thus be higher.

Figure 5.3. **Predicted effect of joint membership on co-invention**



Note: These figures show the predicted proportional change in y for a change in x (a discrete change in joint membership from 0 to 1). Bars shown “without fill” represent estimates that are not statistically significant at the 5% level. Co-invention is measured using patent data extracted from the *European Patent Office’s Worldwide Patent Statistical (PATSTAT) Database*, using search algorithms developed by the OECD.

6. Conclusions

This chapter has investigated the relationship between the international policy mechanism of “Implementing Agreements” and co-invention. We found good evidence to support our hypothesis that IAs have an impact on co-inventive activities between inventors residing in different member states. They have a lesser impact on encouraging co-invention between an inventor residing in a member of the agreement and those in non-member countries. However, the impacts vary widely across the different agreements, with solar PV and wind at opposite extremes. These differences 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.

An important avenue for further research would involve the assessment of the value of co-inventions relative to purely domestic inventions. Does international research collaboration help economies develop their innovation capacity by giving them greater access to foreign knowledge and expertise? And does this have positive impacts downstream? For instance, in the area of wind and solar power it would be interesting to assess whether economies benefit particularly from international research collaboration in terms of reduced electricity generating costs or increased market penetration.

Eventually, these activities may create lasting knowledge pools and research infrastructures that lead to increases in innovation and absorptive capacities. This may be particularly valuable for emerging and developing economies. Since the achievement of significant reductions in greenhouse gas emissions at an international scale is also dependent upon mitigation in fast-growing non-OECD economies, further work could focus on the role of IAs in which emerging economies are members.

Indeed, it is interesting to note that countries such as India and China have started to play increasingly important roles in those IAs which have important implications for the development of climate mitigation technologies. Moreover, based on Table 5.2 above, it is clear that they have become important co-inventing partners with a number of emerging economies featuring amongst the top ten bilateral relationships in different fields.

Notes

1. www.iea.org/techno/.
2. See also Hagedoorn *et al.* (2000), for a more general discussion.
3. The provision of the relevant data by Anne Lechartier of the Office of the Legal Counsel at the IEA is very much appreciated.
4. In a related manner, Johnstone *et al.* (2012) estimate sector-specific models for innovation in selected environmental technologies and use total invention to control for these generic factors. To address the concern that estimating a reduced-form model may not sufficiently control for these general economic factors they also estimate a two-stage model. Using a two-stage model they confirm that “although the coefficient of the predicted total patents is smaller in magnitude, the expected positive sign and statistical significance persist. The findings suggest that an estimation of the reduced-form model, where total patents are considered to be exogenous, provides closely comparable results with those of the two-stage estimation.”

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Chapter 6

Energy and climate policy: Conclusions and further policy research

by

Nick Johnstone and Ivan Haščič

In this chapter we present suggested areas for further policy research. Additional work on the identification of the innovation impacts of alternative policies is clearly required. This will necessarily involve modeling 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.

In the theoretical literature, a strong case has been made for the use of market-based instruments (e.g., taxes, tradable permits), rather than direct regulation (e.g., technology-based controls) in order to induce innovation. The hypothesis is that if more “prescriptive” policies are applied, technology invention and adoption decisions are constrained by the precise characteristics of the standard. Thus, in order to induce search for the optimal technology to meet a given environmental objective, governments should seek to allow for more flexibility in their policy regimes when this can be achieved at reasonable administrative cost.

While the theoretical case for the use of well-targeted market-based instruments (and performance standards) as a means of inducing innovation is very strong, the review of the empirical evidence presented in the first chapter of this volume is mixed. This may be due in part to a number of methodological issues. Firstly, it can arise from measurement error – it can be more difficult to identify the innovations arising from more flexible instruments since, by their very nature, such measures are likely to induce a wide (and unknown) range of innovations. Identification of innovations arising from more prescriptive measures is much more straightforward. One of the great advantages of market-based instruments – their flexibility – makes assessment more difficult for the researcher.

Despite these caveats, there is little question that flexible market-based instruments are efficient tools to induce innovation in the energy-climate sphere. Indeed, the empirical results presented in Chapter 2 of this book provides further support that fossil fuel prices induce innovation in energy efficient electricity generation technologies. Moreover, the results show that the effect is not uniform across the different technologies. Fossil fuel prices have a linear positive effect on renewables, but decreasingly positive effect on fossil fuel technologies and no significant effect on nuclear.

This result supports the hypothesis of a substitution effect between innovation in fossil fuel and carbon-free technologies. It is found that increasing costs of fossil fuels is likely to induce such a shift in research efforts. On the basis of the evidence presented, the point at which innovation in renewable exceeds that of fossil fuel efficiency technologies in the region of oil prices experienced during the most recent oil shock. Therefore, price mechanisms such as emissions trading, and carbon taxes are likely going to lead to a change in the direction of innovation towards carbon-free technologies.

Innovation can take many forms. Even within “carbon” technologies, innovation is likely to drive down emissions through incentives for changing the input mix, the level of capacity utilization, and the quality of the fossil-fuel power plant stock. These factors have been assessed in Chapter 3. We show that, while higher coal shares in the input mix are associated with lower fuel efficiency levels, higher capacity utilization, and newer power plants are associated with higher levels of efficiency.

In addition, a key finding is that assumptions concerning the extent of international knowledge spillovers have important implications for the resulting efficiency gains. If perfect spillovers of knowledge across countries is assumed the effect of changes in the

technological frontier on energy efficiency are over five times greater than if knowledge is constrained to the national level. The results presented shed light on the relative importance of all the options currently presented as ways to reduce CO₂ emissions associated with fossil-fuel electricity production. However, it is important to bear in mind that a general decrease in carbon intensity has not resulted in overall CO₂ emissions reductions for the sector.

Prices may not always be sufficient to bring about the necessary innovation to shift onto a low-carbon trajectory. This is particularly true if there are associated market failures and barriers that “blunt” the effect of prices on incentives for innovation. Perhaps the most significant “secondary” market barrier relates to possible path dependency. Path dependency can arise from structural characteristics of the market and policy failures, as well as from learning-by-searching through research or learning-by-doing through adoption. This implies that new, less environmentally-damaging technologies may have difficulty displacing more polluting incumbent technologies in the market. In such conditions, exclusive reliance on relative price differences may not suffice to bring about substitution between the two technologies, at least for a period of time.

A number of studies have emphasised that public R&D support may be a necessary complement to encourage innovation. Targeted support for innovation in specific technologies may be warranted. However, this can be risky in a world of imperfect information. One possible strategy to reduce such risks has been discussed in Chapter 4 in the context of public support for research on intermittent renewable energy sources (wind, solar, ocean). It is well-known that insufficient system “flexibility” is a significant constraint on the penetration of intermittent renewable energy sources in the grid. Imperfect matching of supply and demand means that the “real” contribution of increased capacity of wind, solar, and ocean/tide power is less than the nominal capacity, and sometimes very much less.

Improved energy storage and grid management can overcome this constraint by increasing system flexibility. Preliminary results have been presented on the determinants of innovation in energy storage and efficient grid management. Our results are consistent with expectations, with an important role played by both underlying technological factors (i.e. overall penetration rates and concentration of specific renewable energy types). However, policy factors also play a role. While it is not surprising to find that targeted R&D support encourages innovation, it is revealing that policy measures that are primarily designed to support generating technologies have a positive effect on innovation in grid management and advanced energy storage.

Just as ecological systems are increasingly intertwined on a global scale, so are innovation systems. In the final chapter of this volume, the relationship between multilateral technology agreements and international research collaboration has been assessed. We found good evidence to support our hypothesis that the International Energy Agency’s “Implementing Agreements” have an impact on co-inventive activities in “green” technologies between inventors residing in different member states. Indeed, it is interesting to note that countries such as India and China have started to play increasingly important roles in those IAs that have important implications for the development of climate mitigation technologies.

In conclusion, 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.

A further challenge relate 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 further important avenue for research would involve 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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Energy and Climate Policy

BENDING THE TECHNOLOGICAL TRAJECTORY

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

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Please cite this publication as:

OECD (2012), *Energy and Climate Policy, Bending the Technological Trajectory*, OECD Studies on Environmental Innovation, OECD Publishing.

<http://dx.doi.org/10.1787/9789264174573-en>

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