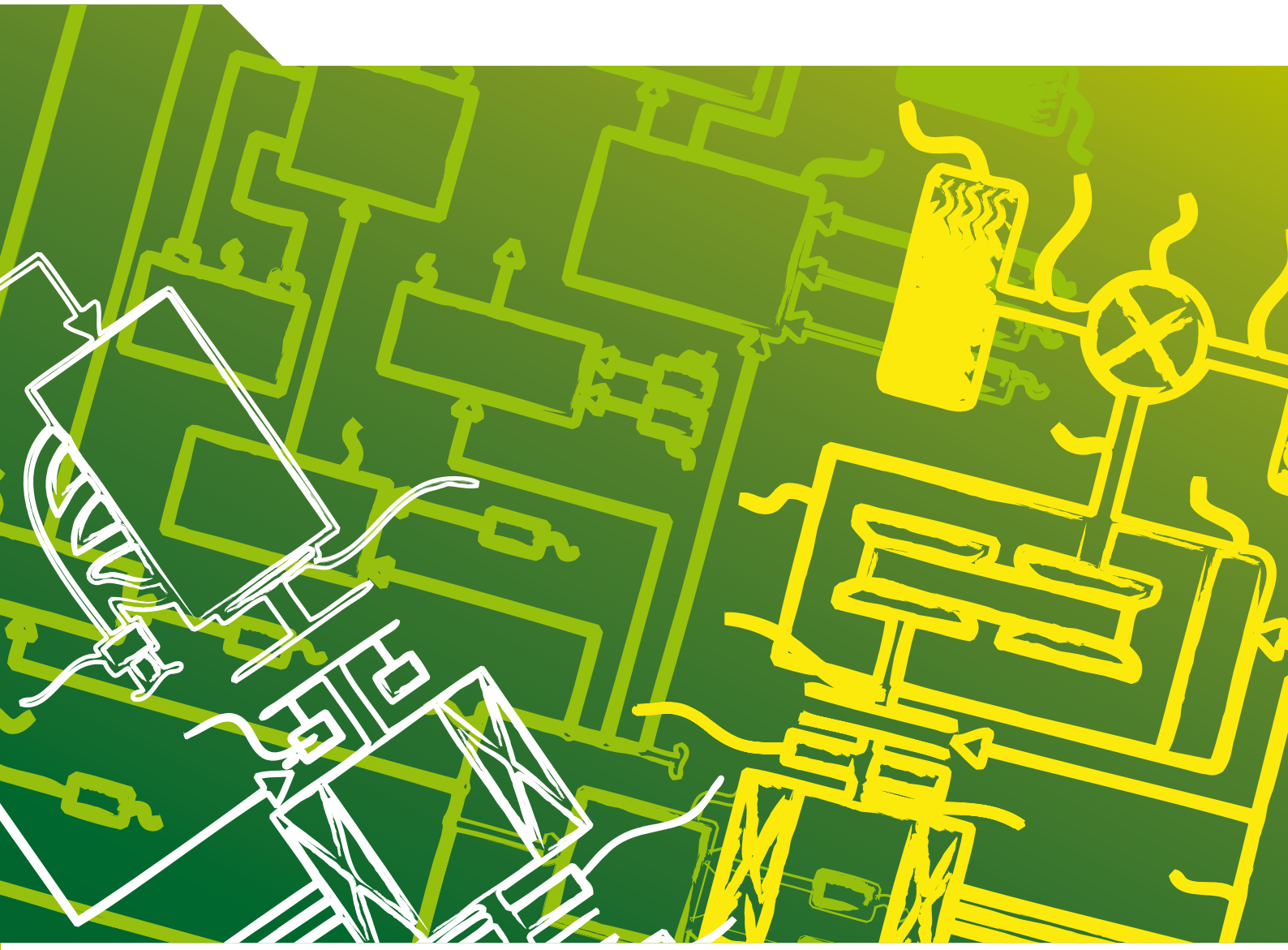
OECD Studies on Environmental Innovation

Invention and Transfer of Environmental Technologies



OECD

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Foreword

Inducing environmental innovation is a significant challenge to policy makers; not least because two types of market failures – environmental degradation (a negative externality) and knowledge spillovers (a positive externality) – co exist and need to be overcome. Efforts to design public policies that address these failures are motivated by the fact that innovations can allow for improved environmental quality at lower cost.

However, the relationship between environmental policy and technological innovation remains an area in which empirical evidence is scant, although this has improved somewhat recently. In addition, it has become apparent that it is not the mere "volume" of innovation induced that matters (as even a "bad" policy is likely to trigger an innovative response). Increased attention should be paid to the design characteristics of public policies that are likely to affect the "type" of innovation thus induced. This area remains still largely unexplored. In an attempt to bridge this gap, the OECD has examined these issues.

The work undertaken is brought together in five substantive chapters: environmental policy design characteristics and their role in inducing innovation, the role of public policies (including multilateral agreements) in encouraging transfer of environmental technologies, followed by three sectoral studies of innovation in alternative fuel vehicles, solid waste management and recycling, and green (sustainable) chemistry. While particular focus has been placed on the role of environmental policy in bringing about the innovation documented, it is recognised that other factors play a key role in inducing innovation which has positive environmental implications.

The book has been prepared by Nick Johnstone and Ivan Haščič (OECD Secretariat) under the guidance of delegates to the OECD's Working Party on Integrating Environmental and Economic Policies. This project has benefited greatly from the contribution of Hélène Dernis and Dominique Guellec of the OECD Directorate for Science, Technology and Industry in the development of the patent database upon which the work depends. The assistance of Barbara Aiello (OECD Secretariat) in the preparation of the final manuscript is gratefully acknowledged.

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List of Acronyms

AFV	Alternative Fuel Vehicles
CCMT	Climate Change Mitigation Technologies
CO_2	Carbon dioxide
CP	Claimed Priority
ECLA	European Patent Classification system
EPO	European Patent Office
GBAORD	Government Budget Appropriations and Outlays for R&D
GERD	Gross Domestic Expenditures on R&D
IPC	International Patent Classification system
IPR	Intellectual Property Rights
ITT	International technology transfer
JPO	Japanese Patent Office
LRTAP	The Convention on Long Range Transboundary Air Pollution
NO_X	Nitrogen oxides
PATSTAT	The *EPO's Worldwide Patent Statistical Database*
PCT	Patent Co operation Treaty
PM	Particulate Matter
PPP	Purchasing Power Parity
R&D	Research and Development
SO_2	Sulphur dioxide
SO_X	Sulphur oxides
TPF	Triadic Patent Family
TRIPS	Trade Related Aspects of Intellectual Property Rights
USPTO	United States Patent and Trademark Office
VOC	Volatile Organic Compounds
WEF	World Economic Forum
WIPO	World Intellectual Property Organisation

Executive Summary

Environmental policy has the potential to bend the direction of innovation towards less environmentally harmful impacts.

It has long been recognised that the characteristics of any **environmental policy framework can affect the rate and direction of innovation** in environmental technologies. Environmental policies have the effect of changing relative input prices. In doing so, they encourage research on technologies which save on the use of the more expensive inputs. The research presented in this publication assesses the role of public policy in inducing environmental innovation in a wide variety of fields, including:

- General environmental management:
  - **Air pollution abatement.**
  - **Water pollution abatement.**
  - **Solid waste management.**
- Specific abatement technologies:
  - Regional air pollutants.
  - **Motor vehicle pollution abatement (including alternative-fuelled vehicles).**
  - Material recycling, solid waste incineration and landfilling.
  - **"Green" chemistry.**

Indicators of inventive activity and international technology transfer are constructed based on data extracted from the *European Patent Office's World Patent Statistical (PATSTAT) Database*. It covers all important intellectual property offices worldwide, with data stretching back over several decades. Our development of indicators for environmental innovation across time and countries represents a significant step forward in our capacity to analyse the potential impacts of environmental policy on innovation. Selected patent-based indicators of environmental innovation are now available on OECD.Stat (*http://stats.oecd.org/index.aspx?queryid=29068*). (For further information see also *www.oecd.org/environment/innovation/indicator*.) While it must be emphasised that patents are an imperfect and incomplete measure of innovation, for the purposes of comparative policy analysis patent data have a number of important advantages relative to alternative measures.

Making a rigid distinction between market-based instruments and direct forms of regulation can be misleading.

Economists have long argued that directly changing the relative price of polluting inputs (or products) through market-based instruments, such as taxes or tradable permit schemes, is the most effective way to induce innovation. While there is no question that "pricing" pollution is a necessary condition for encouraging innovation, drawing a stark contrast between market-based instruments and direct forms of regulation can be misleading since there can be as much variation within policy types as across them. In this book, it is argued that it is more helpful to think in terms of the more general characteristics of different instruments, and what effect each individual characteristic has on innovation. The relevant characteristics include:

- **Stringency** – How ambitious is the environmental policy objective relative to business-as-usual?
- **Predictability** – What effect does the policy measure have on investor uncertainty; is the signal consistent, foreseeable, and credible?
- **Flexibility** – Does it let the innovator identify the best way to meet the objective (whatever that objective may be)?
- **Depth** – Are there incentives to further improve one's performance regardless of the level of performance already achieved (down to zero emissions)?
- **Incidence** – Does the policy target directly the externality, or is the point of incidence a "proxy" for the pollutant?

While many taxes and tradable permit systems score well on most of these criteria, there is no hard and fast rule which allows for a unique mapping from instrument type (*e.g.* taxes, regulations) to each of these five characteristics. For this reason, **assessment of the effects of environmental policy on technological innovation requires a close analysis of both the characteristics of the environmental policy framework and the technological areas** which it is likely to affect. In this book, we report on research in which the policy framework is represented in a variety of different ways, and in a manner which is suitable for empirical analysis. This includes the results of surveys of business representatives, reviews of specific national regulations and directives, and the contents of international environmental agreements.

Stringency of environmental policy is important but predictability and credibility of policies in the longer run matter as well.

In the first part of this volume, the potential impacts of environmental policy on innovation are analysed in the context of general environmental management (covering a broad range of air, water, and waste management technologies). A number of key conclusions emerge from this work:

- Not surprisingly, it has been found that **policy stringency plays a significant role in inducing innovation**. More specifically, based on evidence from a broad cross-section of countries, it is found that the stringency of environmental policy has a positive impact

on the likelihood of developing innovative means of mitigating environmental impacts (such as air and water pollution and managing solid waste). A more ambitious policy will provide greater incentives for polluters to search for ways to avoid the costs imposed by the policy. This finding is largely confirmed by the research presented on the more specific policy measures and technology fields assessed in the second part of this volume.

- However, it is not just the "level" of the price of polluting which matters. **Predictability and credibility of the price over the longer term are also important.** Signals that are difficult to predict over time encourage investors to postpone investments, including the risky investments which lead to innovation. In the face of unpredictability there is an advantage to "waiting" until the policy dust settles. By adding to the risk which investors face in the market, an "unpredictable" policy regime can serve as a "brake" on innovation, both in terms of technology invention and adoption. Frequently changing policy conditions impose a cost, and such instability should be avoided.
- In addition, the more "**flexible**" **(or technology-neutral) a policy regime is, the more innovation takes place**. Since future trajectories of technological change cannot be foreseen, it is important to give innovators the incentive to search across a wider "space" to identify the best means of complying with regulations. Flexibility unleashes efforts to search for new innovations, some of which may be only improvements on existing technologies. This implies that rather than prescribing certain abatement strategies (such as technology-based standards), wherever possible governments should give firms stronger incentives to seek out the best means to meet a given environmental objective.

Flexibility of policy regimes encourages innovation and ensures that markets are not fragmented across different countries.

Research in other fields has identified **international technology transfer as an important means of bringing about improved welfare**. This is particularly true in the case of environmental technologies where many negative impacts cross borders. Based on results presented in this book, two environmental policy factors appear to have an influence on the flow of technologies internationally: A) the degree of flexibility of the domestic policy framework in both the source and the recipient countries; and B) the degree of international policy co-ordination. If environmental policy is prescriptive and unco-ordinated this can result in fragmented technology markets, with the potential market for any innovations split across different policy jurisdictions.

- The effect of the flexibility of national policy regimes on the international diffusion of environmental technologies has been assessed. The results confirm that **flexibility of policy regimes not only increases domestic rates of innovation, it also ensures that markets are not fragmented across different countries**. With prescriptive regimes the market will be fragmented into different regulatory silos. Given the risks associated with expenditures on research and development, and the economies of scale required to recover such expenditures, it is important that regulatory regimes in "source" countries not constrain the potential markets for any induced innovations. In addition, flexible policy regimes in "recipient" countries allow potential adopters of innovations to access a much wider range of technologies available on international markets.

- We assessed the role of international policy co-ordination through adherence to multilateral environmental agreements. More specifically, we examined whether adherence to a series of international agreements on reducing SO_X and NO_X emissions (the Convention on Long-Range Transboundary Air Pollution (LRTAP), and the related Protocols) has induced the transfer of technologies between signatories. We argue that transfer of technology between signatories to an agreement can be a way of encouraging adherence, providing an inducement for upwind countries to participate. Some descriptive evidence is presented but more formal analysis might be addressed in future work.

While general policy conditions are clearly important factors driving the development and international diffusion of environmental technologies, a more precise assessment of the effects of policy on innovation requires an analysis of the effects of specific policy instruments. The second part of this volume includes detailed case studies of the potential impacts of environmental policy on innovation in specific fields (incl. regional air pollutants, motor vehicles, solid waste and recycling, green chemistry). A number of conclusions emerge from the different "sectoral" studies.

- First, in follow-up work on the role of multilateral environmental agreements in inducing international technology transfer, we assessed the specific role of the LRTAP Protocols in encouraging transfer of air pollution abatement technologies between signatories. The major finding is that **there is a positive effect on technology transfer between pairs of countries which have both joined the LRTAP Protocols**. It must be emphasised, however, that the while the Protocols place emphasis on co-operation across signatories, there are few explicit incentives. The finding presented may be due to the simple sharing of information on available abatement technologies through intensive co-operation – that is, through regular conferences and sharing of documentation. While on the face of it removing information gaps may seem relatively unimportant relative to other factors, improved information flows across borders might have been pivotal in introducing more ambitious national policies.

Appropriate sequencing of policy measures is important.

- Second, in many cases **different instruments are introduced in combination**, sometimes with different but related environmental objectives. In this vein, work has been undertaken in the area of alternative-fuelled vehicles to assess the relative importance of fleet-level fuel-efficiency standards, after-tax fuel prices, and public support for R&D. Based on precise characterisations of the policy instruments implemented in different countries, the results indicate that relatively minor changes in a performance standard or automotive fuel prices would yield effects that are equivalent to a much greater proportional increase in public R&D budgets. However, there are significant differences between types of technologies – electric and hybrid vehicles. For example, in the case of electric vehicles the role of after-tax fuel prices is statistically insignificant, but standards play an important role. Conversely, for hybrid vehicles it is after-tax fuel prices which are statistically significant and not standards. R&D plays a much more important role for electric than hybrid vehicles.

These results may indicate **the importance of the sequencing of policy measures**. Relative prices may have a lesser role to play than ambitious performance standards or significant

public support for research the further a technology is from being directly competitive with the incumbent technology (petrol- and diesel-driven technologies). While in theory a price sufficient to induce an equal level of innovation for such technologies could be introduced, such a measure would likely be politically infeasible in practice. Moreover, even if introduced, it may not be perceived as credible over the longer-term.

For technologically mature sectors, behavioural and organisational innovations are the most likely responses to greater environmental stringency.

- Third, a case study of material recycling and waste management technologies has been conducted through a descriptive analysis of the correlation between the introduction of important policy measures and patent counts for different waste streams. The results indicate the possibility that the first wave of policies (end of the 1980s, beginning of the 1990s) has produced an innovation response, but their effect is now less pronounced. This result is underlined in the analysis of specific waste streams (end-of-life vehicles, packaging, composting), where there seems to be a strong and positive link between policy action and innovation performance at the beginning of the 1990s, but this link is less clear in the last fifteen years.

One possible explanation for this finding is that the sector is technologically mature, relative to other areas of environmental innovation, a point which is reflected in the data presented in the first chapter. Rates of innovation have been declining, with the exception of some emerging economies. However, even there the rates are lower than for innovation overall. Nonetheless, in many countries recycling rates have increased and waste generation per unit of economic activity is beginning to fall. **For mature sectors, responses to environmental policy shocks may be reflected in behavioural and organisational innovations, rather than in terms of technological inventions.**

- The final case study focuses on "green" chemistry, which is different insofar as the nature of the patent classification system did not allow for the identification of the "population" of green chemistry patents. However, some specific fields were identified. Among these, biochemical fuel cells and green plastics were the two areas that have shown the most growth. Other areas are past their innovation peak: notably, totally chlorine-free pulp and paper technology and biodegradable packaging. The trends in selected areas of industrial biotechnology are interesting in that this is a cornerstone of green chemistry, and it is hoped that many future green technologies will emerge from this area. While patenting in industrial biotechnology has increased, it has not increased more than the rate for the chemistry sector overall.

Qualitative review of the role of public policy indicates that **innovation in this area requires avoiding differentiated treatment of new *versus* existing chemicals**. If producers are allowed to continue relying on "grandfathered" existing chemicals, incentives for development of new, less environmentally harmful substances will be undermined.

In addition, the frequent use of support measures (R&D support, public procurement, grants, and awards) to encourage innovation in this area means that policy makers face a difficult task in identifying particular technologies or activities to be supported in the face of imperfect information and uncertainty over future trajectories. As with other areas, a balance of policy flexibility and predictability is essential.

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Chapter 1

Environmental Policy Design Characteristics and Innovation

by
Nick Johnstone, Ivan Haščič and Margarita Kalamova (OECD Environment Directorate)*

It is often argued that market-based instruments are a preferable means of encouraging innovation than direct forms of regulation, drawing a stark contrast between the two. In this chapter it is argued that it is more helpful to think in terms of the more general characteristics of different policy instruments, including policy stringency, predictability, flexibility, depth and incidence. Some of these questions are further examined empirically drawing upon a rich database of patent data. It is found that while stringency of environmental policy is important, predictability and flexibility of policies indeed matter as well.

* The contribution of Julie Poirier and Marion Hemar (ENSAE ParisTech) in developing the search strategy is gratefully acknowledged. In addition, Christian Michel (University of Heidelberg) provided valuable inputs in the initial stage of this research.

Introduction

It has long been recognised that the characteristics of the environmental policy framework can affect the rate and direction of innovation in pollution abatement technologies. This argument is an extension of a more general postulate that public policy may induce innovation by changing relative factor prices or introducing production constraints. The idea was first raised by Hicks (1932), who observed that a change in the relative prices of factors of production will motivate firms to invent new production methods in order to economise the use of a factor which has become relatively expensive. Originally developed in the context of labour economics, this idea came to be known as the "induced innovation hypothesis". Applied to the public policy framework, it implies that if governments could affect relative input prices, or otherwise change the opportunity costs associated with the use of environmental resources, firms' incentives to seek improvements in production technology which save on these inputs would be increased. Since markets often fail to put a price on environmental resources, the opportunity costs of many environmental assets is to a large extent formed by government regulation.

Empirically, the role of environmental policy on technological innovation has been assessed in a number of recent papers (see, for example, Johnstone and Labonne, 2006). However, different policy measures are likely to have different impacts on innovation. There is a large body of literature which assesses the role of environmental policy instrument choice on the rate of innovation, with the common finding that market-based instruments (*e.g.* taxes, tradable permits) are more likely to induce innovation than direct forms of regulation (*e.g.* technology-based controls, performance standards) (see Popp *et al.*, 2009 for a literature review) (Johnstone *et al.*, 2010b assesses the role of six different instrument types on innovation in renewable energy). In particular, it is argued that the rate of innovation under market-based instruments is likely to be greater, since a greater proportion of benefits of technological innovation and adoption will be realised by the firm itself than is the case for many direct forms of regulation. Moreover, since market-based instruments are not usually "prescriptive", they are more likely than many types of direct regulation to ensure that the direction of technological change is cost-minimising with respect to the avoidance of damages (see Jaffe *et al.*, 2002). This usual taxonomy is sometimes complemented by review of measures designed to address related (but distinct) market failures, *i.e.* information-based measures, technical assistance, etc.

However, there can be as much variation within policy types, as between them. Two market-based instruments (*i.e.* a tax on carbon emissions relative to environmentally-motivated product tax differentiation) may be as different from each other as each is in relation to some forms of direct regulation. Therefore, the stark juxtaposition between market-based instruments and direct forms of regulation is somewhat misleading. It is more helpful to think in terms of vectors of characteristics of different instruments, and what effect each of these characteristics has on innovation. Relevant vectors would include at least the following: stringency; predictability; flexibility; depth; and incidence.

Unfortunately, the empirical literature does not generally examine the specific role of these different policy attributes on environmental innovation. This paper focuses on the issue of innovation and technology transfer in the areas of air pollution abatement, wastewater effluent treatment, and solid waste management. Drawing upon the *EPO Worldwide Patent Statistical (PATSTAT) Database* of patent applications from over 80 national and regional intellectual property offices the individual effects of three of these factors (stringency, predictability and flexibility) is examined empirically. Evidence is found that both predictability and flexibility have distinct effects on innovation above and beyond the effect of policy stringency.

It is important to recognise that patents cannot be used to develop a measure of all innovations. First, they are designed only to protect technological inventions. Other IPR regimes exist to protect innovations in other fields – for example, copyrights for literature, trademarks for words or graphic devices which distinguish a product and the registration of designs, and where protection is focussed on the appearance of a product (Adams, 2006). In addition, less formal ways (than intellectual property rights) to protect technological inventions also exist – notably industrial secrecy, or purposefully complex technical specifications (Frietsch and Schmoch, 2006). Surveys of inventors indicate that the rate at which new innovations are patented varies across industries (Cohen *et al.*, 2000 and Blind *et al.*, 2006). A further critique of patent data relates to the fact that not everything that is patented is eventually commercialised and adopted. There are, however, significant fees attached to the examination of a patent application (and to renewal fees, once the patent has been granted). So it is safe to assume that, at least in the expectations of the applicant or patent holder, the prospects for commercialisation and adoption are good. Nonetheless, the economic value of patents varies (Popp, 2005). For meaningful empirical analyses, it is therefore important to control statistically for differences in the propensity to patent, the scope of the claims, the value of the patent and other factors which vary across countries, time and technology fields. In the studies which follow we control for such factors to the extent possible.

The reminder of this paper is structured as follows: Chapter 2 discusses characteristics of environmental policy regimes that are amenable to encouraging innovation of environmental technologies. The relevant literature is reviewed and the hypotheses are presented; Chapter 3 presents the data and describes the trends in innovative activity related to selected areas of pollution abatement and control technologies; Chapter 4 then provides empirical evidence on the role of various determinants (including general characteristics of countries' environmental policy regimes) in encouraging innovation; Chapter 5 concludes with a discussion of the policy implications.

Environmental policy design characteristics as determinants of innovation

Assessing the determinants of "environmental" innovation (as reflected in patenting activity) requires an understanding of the determinants of innovation more generally. Indeed, aside from environmental policy, there are, of course, other important determinants of innovation for environmentally preferable technologies. Factors such as general scientific capacity, market conditions, openness to trade, etc. will also have an important effect on innovation in general, and (see Jaumotte and Pain 2005 for some recent evidence). Such factors are also likely to influence the specific field of environmental technologies.

Moreover, not all inventions are patented, and this may vary across time and countries. For instance the characteristics of intellectual property rights (IPR) regimes are likely to have a significant effect on the propensity to seek protection through the IPR regime rather than by some other means (*e.g.* industrial secrecy). The propensity of inventors from a particular country to patent is likely to change over time, both because different strategies may be adopted to capture the rents from innovation (*e.g.* Cohen *et al.*, 2000) and because legal conditions may change through time (*e.g.* Ginarte and Park, 1997).

However, relative to other fields of innovation, it is evident that in the case of environmental technologies the regulatory framework plays a particularly important role. As noted above, 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, performance standards) in order to induce innovation. However, the stark juxtaposition between market-based instruments and direct forms of regulation is somewhat misleading. It is more helpful to think in terms of vectors of characteristics of different instruments, and what effect each of these characteristics has on innovation. Relevant vectors would include at least the following:

- *Stringency* – *i.e.* how ambitious is the environmental policy target, relative to the "baseline" emissions trajectory?
- *Predictability* – *i.e.* what effect does the policy measure have on investor uncertainty; is the signal consistent, foreseeable, and credible?
- *Flexibility* – *i.e.* does it let the innovator identify the best way to meet the objective (whatever that objective may be)?
- *Depth* – *i.e.* are there incentives to innovate throughout the range of potential objectives (down to zero emissions)?; and,
- *Incidence* – *i.e.* does the policy target directly the externality, or is the point of incidence a "proxy" for the pollutant?

There is no precise mapping from instrument type to each of these vectors. For instance, different environment-related taxes may have very different attributes. A tax on CO_2 is flexible, targeted, deep, and often predictable. However, a differentiated tax for "environmentally friendly products" is not very flexible, targeted or deep. Indeed, depending upon how the tax rate is determined, such a measure may actually have more similarity with technology-based standards than with an emissions tax.

More generally, a performance standard with a similar point of incidence (*i.e.* on the pollutant itself) and degree of flexibility may have more similarities with a tax than with a technology-based standard. While it does not provide the same "depth" of incentive – *i.e.* there is no incentive to go beyond the standard[1] – in other respects it is likely to have similar innovation impacts as an emissions tax.

The key point is that correlation between instrument types and policy design attributes is imperfect. Any incentives for innovation arise out of the underlying policy attributes and not the broad policy type *per se*. As such, it is important to assess incentives for innovation in terms of the underlying policy attributes rather than by broad instrument type.

Environmental policy stringency

The effect of **stringency** on innovation is a correlate to the Hicksian notion that a change in the relative prices of factors of production will motivate firms to invent new production methods in order to economise the use of a factor which has become relatively expensive. Originally developed in the context of labour economics, this idea came to be known as the "induced innovation hypothesis". Applied to the environmental policy framework, it implies that if governments could affect relative input prices, or otherwise change the opportunity costs associated with the use of environmental resources, firms' incentives to seek improvements in production technology which save on these inputs would be increased. Since markets often fail to put a price on environmental resources, the opportunity costs of many environmental assets is to a large extent formed by government regulation.

By imposing a price (whether explicitly or implicitly) on the costs of pollution emissions, or by otherwise changing the opportunity costs associated with environmental assets, environmental policy is likely to induce innovation – because firms seek to meet the policy objectives at least cost. Of course, different policy measures may be more or less likely to induce innovation. Irrespective of the nature of the instrument applied, some innovation is likely to be induced. However, as argued previously, policy stringency is only one aspect of the public policy regime which affects the rate of innovation. Other potentially important aspects are discussed next.

While theoretical work has shown that stringent environmental regulation may provide incentives for technological improvements, empirical evidence on the effect of stringency of environmental policy on innovative behaviour remains limited (for recent reviews of the empirical literature on this theme see Popp *et al.*, 2009; Vollebergh, 2007; Jaffe *et al.*, 2002). The major reason is that the effect is unobservable to a researcher; hence, its measurement is complicated. As a consequence, cross-country (or cross-sectoral) data on regulatory stringency are rarely available, or are not commensurable. Moreover, public policies typically target specific environmental impacts (pollutants) using a specific policy instrument.

A number of imperfect proxies have been used in the literature. This includes reported data on pollution abatement and control expenditure measured at the macroeconomic (*e.g.* Lanjouw and Mody, 1996) or sectoral level (*e.g.* Brunnermeier and Cohen, 2003), the frequency of inspection visits (*e.g.* Jaffe and Palmer, 1997), parameterisation of policy types (*e.g.* Fischer and Newell, 2008), or various derived measures based on the point of policy implementation (*e.g.* Johnstone and Labonne, 2006). In general the results are consistent with the hypothesis that stringent environmental policy will induce environment-saving innovation.

Environmental policy predictability

Policy **predictability** can reduce uncertainty for investors. This is important since it is well-known that economic uncertainty can be a significant "brake" on investment (see Pindyck, 2007; Dixit and Pindyck, 1994). However, this may be particularly true of investments in R&D, which are by nature risky and with uncertain outcomes. This is compounded by the fact that such investments are irreversible; should market conditions change, "sunk costs" cannot be recovered in the market. Both characteristics (uncertainty and irreversibility) thus give rise to a commercial risk associated with innovative activities.

Investment in R&D is therefore often sub-optimal. For instance, in a panel data study of nine OECD countries covering the period 1981-92, Goel and Ram (2001) find a much sharper adverse effect of uncertainty on R&D investments than on non-R&D (and aggregate) investments.

In the case of "environmental" innovations, this market uncertainty can be compounded by environmental policy uncertainty. This may arise due to concerns over the "predictability" of the policy framework, as well as of the signals provided by the policy itself. In such cases, uncertain signals and "irreversible" investments give rise to great option values, implying strong incentives to postpone investments.[2] Recent work at the IEA (2007) has examined this issue in the context of climate policy uncertainty.

As such, it might be supposed that governments which do not provide clear signals about policy intentions over the duration of firms' planning horizons will retard investment in innovation. In particular, if the future trajectory of the costs associated with policies is uncertain, individual firms may choose to wait before undertaking investments which seek to identify means of reducing this cost (*i.e.* before investing in environmental R&D). Since expectations concerning the path of future environmental policy can be a key determinant of perceived uncertainty over the firm's planning horizon, policy "predictability" can play an important role in inducing environmental innovation, and one which is distinct from that played by policy "stringency".

However, the effect of policy uncertainty on innovation with respect to environmental technologies has not been examined empirically. (For a recent paper which looks at the role of policy uncertainty on abatement investment decisions, rather than innovation *per se*, see Löfgren *et al.*, 2008.) However, there is significant anecdotal evidence in the area of renewable power development to support the hypothesis that policy predictability has played at least as important a role as policy stringency (see Söderholm *et al.*, 2007; Wiser and Pickle, 1998; Barradale, 2008). For instance, Barradale (2008) argues that in the case of the United States, uncertainty concerning the annual renewal of the federal production tax credit (PTC), discouraged investment in renewable energy. This finding is supported by anecdotal evidence presented in Wiser and Pickle (1998) concerning both wind and solar power. In a comparison of wind power development in Denmark, Germany and Sweden, Söderholm *et al.* (2005) argue that the relatively slow pace of development in Sweden is due to instability in the policy framework, more than the actual level of support, with a number of different subsidy programmes implemented successively for short periods of time.

The effects of frequent policy changes on long-term investments can, therefore, be considerable. Since the planning horizon for investments in innovation is particularly long, such investments are likely to be significantly affected by policy instability. A history of abrupt policy changes can discourage investment, and this is likely to be exacerbated by the perception that such instability is likely to continue. Interestingly, Barradale (2008) provides evidence that perceived uncertainty is correlated with instrument choice. Investors in the sector believed that renewable energy portfolio standards were more likely to stay in effect long enough to influence long-term investment decisions than depreciation rules, tax credits, feed-in tariffs or production subsidies. Table 1.1 gives a possible classification of different policy instrument types according to the uncertainty of the signals they typically provide.

Table 1.1. **Policy instrument types and policy predictability**

Instrument type	Predictability of signals provided
Taxes	Predictable price signals – assuming that taxes are set at a level which investors see as being sustainable and credible.
Subsidies	Relatively predictable price signals – but credibility may be more of a concern (public finance).
Permits	Unpredictable price signals – but (assuming no expropriation) equivalent to commercial risk for investors.
Performance-based standards	Essentially analogous to permits – but greater bureaucratic discretion can introduce uncertainty.
Technology-based standards	Predictability at a point in time – but problem of "ratcheting" (*e.g.* new source bias).

Environmental policy flexibility

The role of the **flexibility** of environmental policy measures on innovation has also not been examined closely. In this paper we assess whether more flexible policies (of equal stringency) induce more innovation than prescriptive policies. 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.

The most prominent example of a flexible environmental policy is the US Clean Air Act Amendments (CAAA) of 1990 which sought to reduce SO_2 emissions by implementing a tradable permit system in place of direct regulations. The programme was designed to encourage the electricity industry to minimise the cost of reducing emissions. The industry is allocated a fixed number of total allowances, and the firms are required to surrender one allowance for each tonne of sulphur dioxide emitted by their plants. Firms may transfer allowances among facilities or to other firms, or bank them for use in future years.

Prior to the CAAA, plants were required to use the best available technology for pollution control, which was a scrubber. As a result, while there were incentives for innovation that would lower the cost of installing and operating scrubbers, there would be little incentives for innovation to improve the efficiency of the scrubbers (that is, ability to actually remove pollutants) (see Bellas, 1998). Moreover, the most significant benefits of the trading system was that it gave firms the freedom to search for all possible technologies to reduce SO_2 emissions (see Burtraw, 2000).

As an alternative example, consider the NO_X charge in Sweden. The introduction of a rather stringent tax on NO_X emissions, supported by close monitoring, created a strong incentive for polluting firms to search for abatement options. Most significantly, the tax induced abatement over a wide range of responses, including fuel switching, modifications to combustion engineering, installation of specific abatement equipment such as catalytic converters and selective non-catalytic reduction, as well as fine-tuning combustion and other processes to minimise emissions (for more detail on the Swedish NO_X charge; see Millock and Sterner, 2004).

Both of these examples relate to market-based instruments: tradable permits; and, environmentally-related charges. However, it is important not to conflate market-based instruments with policy flexibility and direct regulations with inflexibility. Some market-based instruments can be prescriptive (*e.g.* differentiated value-added taxes based upon technical criteria of the product) and some direct forms of regulation can be flexible (*e.g.* performance standards in which the point of incidence is the pollutant itself). In such cases

the direct regulation may well provide greater space for potential technologies than a market-based instrument, thus inducing more innovation.

Environmental policy depth

The "depth" of a policy refers to the range of environmental outcomes for which incentives for further environmental improvements are provided. In general, a policy which is continuous in nature is "deep", while one which is discrete will be "shallow". A policy is "deep" if there are opportunity costs associated with emitting pollutants across the entire feasible range of emissions (*i.e.* down to zero emissions). A tax on emissions would be one such example. Such a policy has the advantage that it can provide incentives for innovation above and beyond that which seems feasible – *i.e.* upside surprises may occur. Conversely, a performance standard related to emissions of the same pollutant only provides incentives for innovation to the level of the standard. Innovators have no incentive to develop and market technologies which exceed the standard unless they feel that it will induce a "ratcheting" of the standard by policymakers (see Milliman and Prince, 1989 for a general discussion).

"Depth", is therefore, distinct from stringency. A measure can be stringent and shallow, or lax and deep; and, depth is by no means correlated with policy instrument type. A tax on carbon content of fuels is "deep", while a tax on vehicle characteristics is generally "shallow". Similarly, an eco-label can be "shallow" (*i.e.* indicating whether the product passes some established level of energy efficiency performance) or "deep" (*i.e.* giving the estimated level of performance itself). However, both technology-based standards and performance standards are, by definition, "shallow" in nature. Table 1.2 gives a possible classification of policy instrument types according to the depth of incentives they provide.

Table 1.2. **Policy instrument types and depth**

Instrument type	Depth of incentives provided
Taxes, tradable permits	Generally "deep" incentives, but not necessarily so (*i.e.* product taxes based on discrete characteristics).
Information-based measures (*e.g.*"continuous" labelling)	Potentially "deep" incentives if the label reports actual estimated performance.
Subsidies	Potentially "deep" incentives in cases where the allocation of funds targets performance.
Performance-based standards, technology-based standards	By definition, "shallow" incentives.

Environmental policy incidence

While the sole objective of environmental policy should be to internalise the market externality directly, for reasons of administrative cost, it can be difficult to target the externality directly. Indeed, the vast majority of policies target a proxy for the externality, rather than the externality itself. One of the few policy measures which can be said to have direct incidence on the externality is a CO_2 tax, permit or performance standard. Using this as an example, incidence can be said to be increasingly direct as one progresses along the following:

- Energy-using durable $\Rightarrow$ Energy efficiency performance $\Rightarrow$ Fossil fuel use $\Rightarrow$ CO_2 emissions.

Of course in some cases, the indirect nature of incidence may be intentional – *i.e.* to meet multiple policy objectives. However, if the policy only targets the externality indirectly, this can have important implications for the direction of innovation. The policy measure will provide incentives for technological innovation which "saves" on the proxy

for the bad, rather than the bad itself. Alternatively, it will encourage the use of an input which is thought to be less environmentally damaging than some other input which generates the externality.

This will certainly result in important environmental benefits. However, since the correlation between the "proxy" and the "externality" is imperfect, the trajectory of innovation will be sub-optimal. More significantly, once the proxy is targeted, the apparent correlation between the proxy and the externality may break down. The relationship between the technological trajectory inducted by the policy which targets a proxy and the optimal technological trajectory with respect to the externality will become increasingly distant (see Johnstone, 2007 for a discussion).

Indicator of innovation in general environmental technologies

In order to test these hypotheses data on the extent of innovation across time and countries is required. This section describes trends across countries and over time for selected general environmental technologies (including air pollution control, water pollution control, and solid waste management) using patent data. The data were extracted from the *PATSTAT Database* (EPO, 2008) using a search algorithm developed at the OECD and based on a selection of IPC classes (see list presented in Annex B and *www.oecd.org/environment/innovation*).[3]

Indicators of innovation were constructed based on counts of patent applications (claimed priorities, worldwide) in the selected areas of environmental technology, classified by inventor country (country of residence of the inventor) and priority date (the earliest application date within a given patent family). In order to ensure that only high-value patents are included only applications in which protection has been sought in at least two offices (*i.e.* "claimed priorities") are included (see Guellec and van Pottelsberghe, 2000 and Harhoff *et al.*, 2003 for empirical evidence supporting this approach). A panel of patent counts for a cross-section of all countries and over a time period of 1975-2007 was obtained. Search strategies were developed for different areas, including:

- Air pollution abatement from stationary sources.
- Wastewater effluent treatment.
- Solid waste management (landfill disposal, recycling, incineration and some aspects of prevention).

Data on the first three categories are presented in Figure 1.1 relative to the rate of patent activity overall. The data suggest a recent stagnation in the rate of innovation in these areas. In particular, innovations related to solid waste management reached a peak in 1993 and have declined since. For water pollution control technologies, the peak occurred in the late 1990s. Only air pollution control innovations have been increasing rapidly until very recently, keeping pace with the growth in patenting overall (shown on the right-hand axis).

The domain of air pollution abatement and control includes technologies that limit emissions of local air pollutants from stationary sources (*e.g.* SO_X, NO_X, PM). Figure 1.2 gives patent counts for selected countries with the highest levels of innovation in air pollution abatement, including Germany, Japan, the US, France and the United Kingdom. While these countries are consistently important in environmental technologies examined, other significant innovators in air pollution control have included Sweden, Italy, Austria, and very recently also Korea (Figure 1.3).

Figure 1.1. **General "environmental" technologies by environmental medium**

Number of patent applications – claimed priorities, worldwide

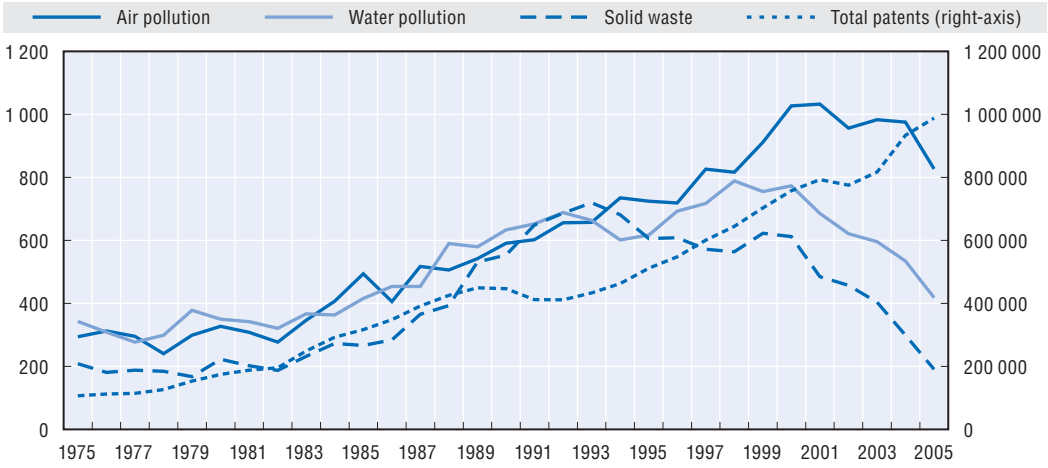


Figure 1.2. **Air pollution abatement and control technologies**

Number of patent applications – claimed priorities, worldwide; 3-year moving average

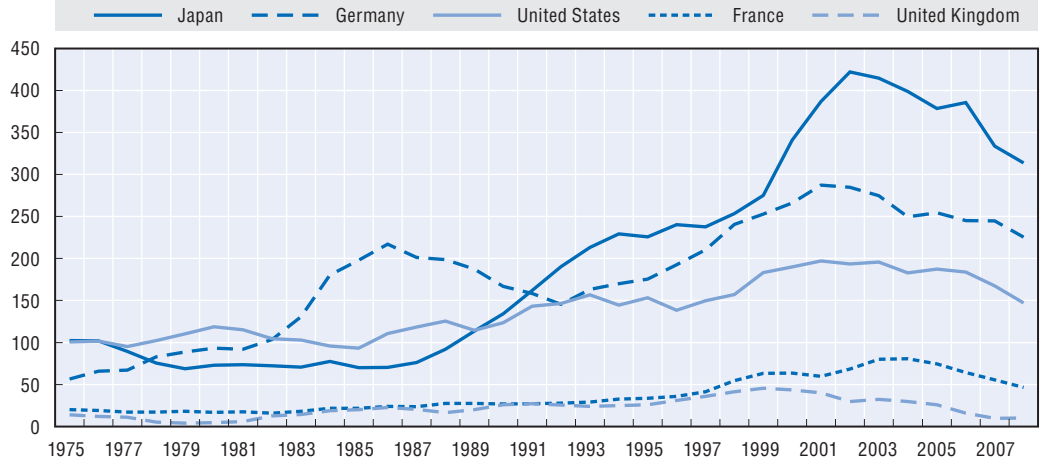
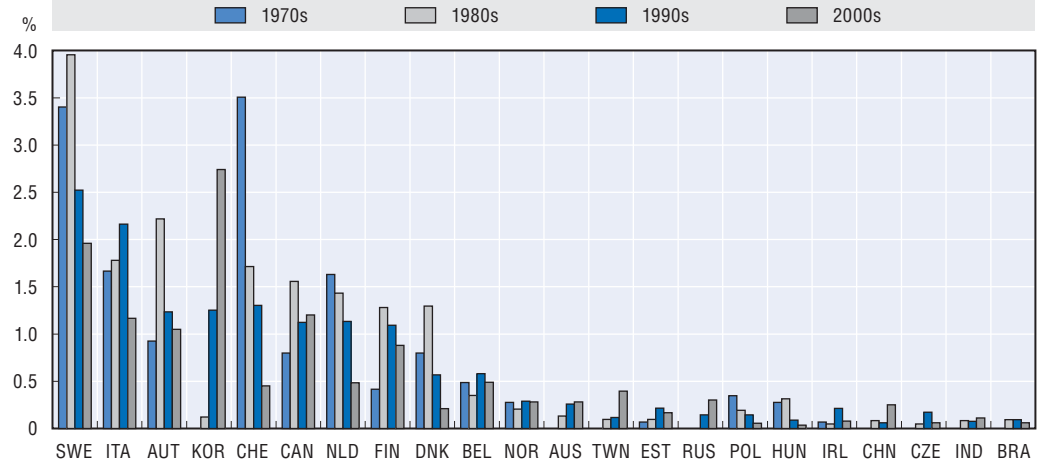


Figure 1.3. **Air pollution abatement and control technologies**

Share of world patenting by inventor country



The water pollution abatement and control technologies identified here include all wastewater treatment techniques – primary (mechanical), secondary (biological) and tertiary (chemical) treatment technologies. Figure 1.4 gives patent counts for the five major inventor countries, suggesting that Germany and the US have historically been the major innovators, with Japan taking the lead more recently. Other significant innovators in this field have included Canada, the Netherlands, Sweden, and more recently Korea, Australia and Spain (Figure 1.5). The rate of growth of this type of innovation in Korea and especially in China in recent years has been startling, increasing four-fold in the period 1999-2004. This is in marked contrast to developments elsewhere, with patent counts for most of the large innovating countries actually decreasing in recent years.

Figure 1.4. **Water pollution abatement and control technologies**

Number of patent applications – claimed priorities, worldwide; 3-year moving average

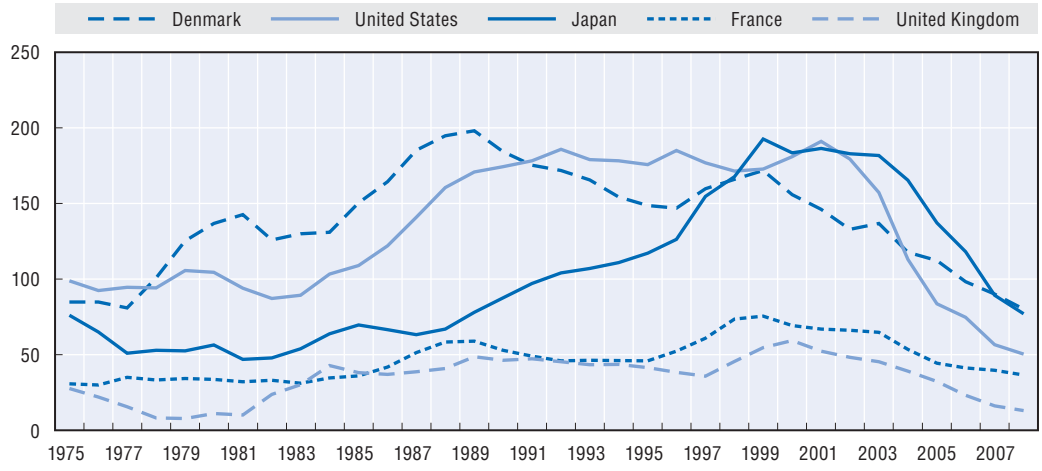
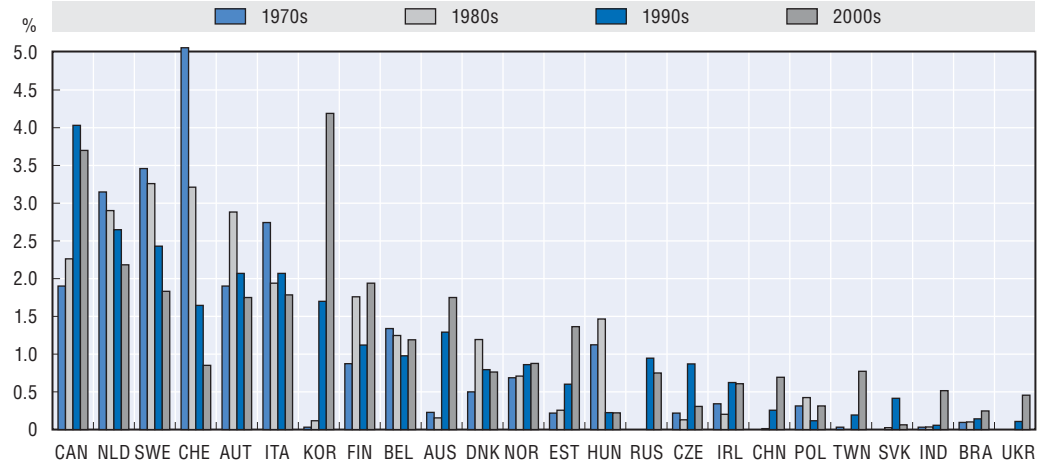


Figure 1.5. **Water pollution abatement and control technologies**

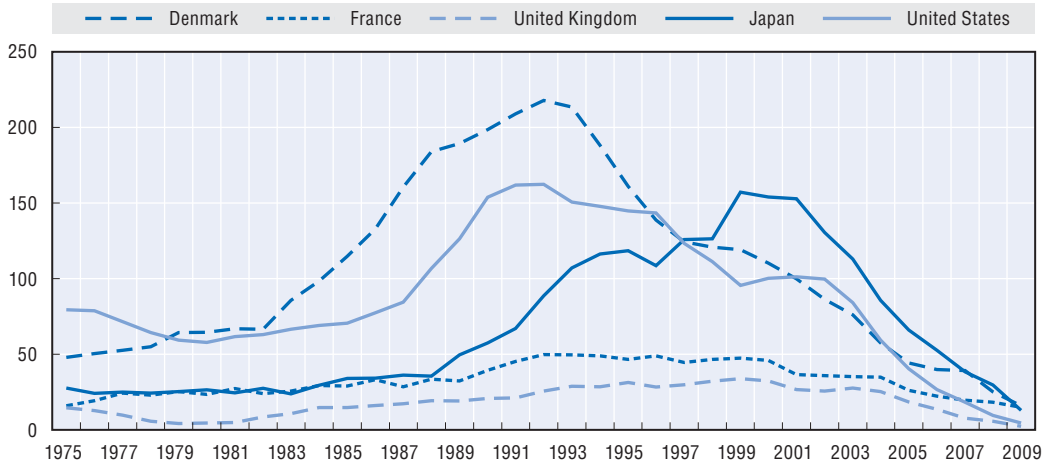
Share of world patenting by inventor country



The domain of solid waste management included technologies that relate to waste disposal and landfilling, as well as incineration, energy recovery, material recycling and some aspects of waste prevention (see Chapter 4). As can be seen in Figure 1.6, there has been a marked decrease in patent activity in this area since a peak in the early 1990s, with

Figure 1.6. **Solid waste management technologies**

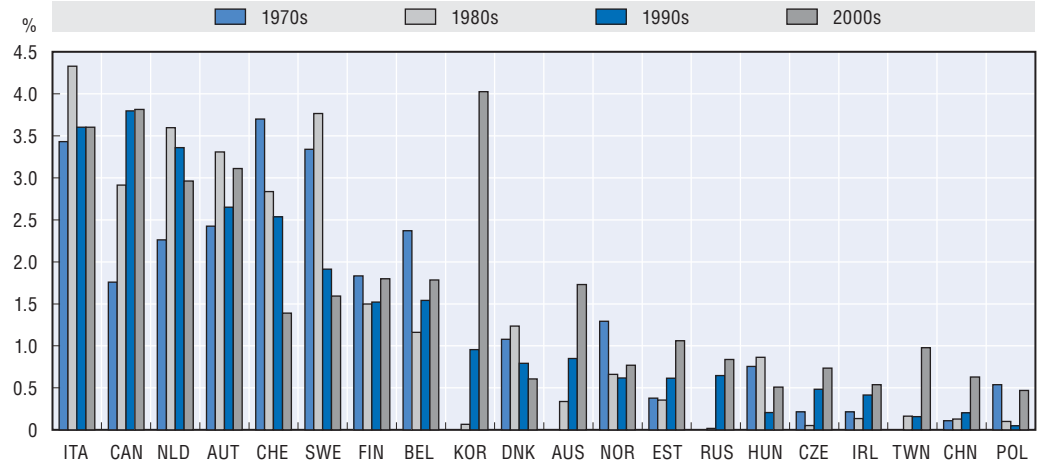
Number of patent applications – claimed priorities, worldwide; 3-year moving average



German inventors dominating the field throughout the 1980s and 1990s. Among the medium-sized inventor countries (Figure 1.7), Italy and Canada have sustained a relatively strong performance. Fast growth rates in the sector have recently been recorded by inventors in Korea, Chinese Taipei, China and Poland.

Figure 1.7. **Solid waste management technologies**

Share of world patenting by inventor country

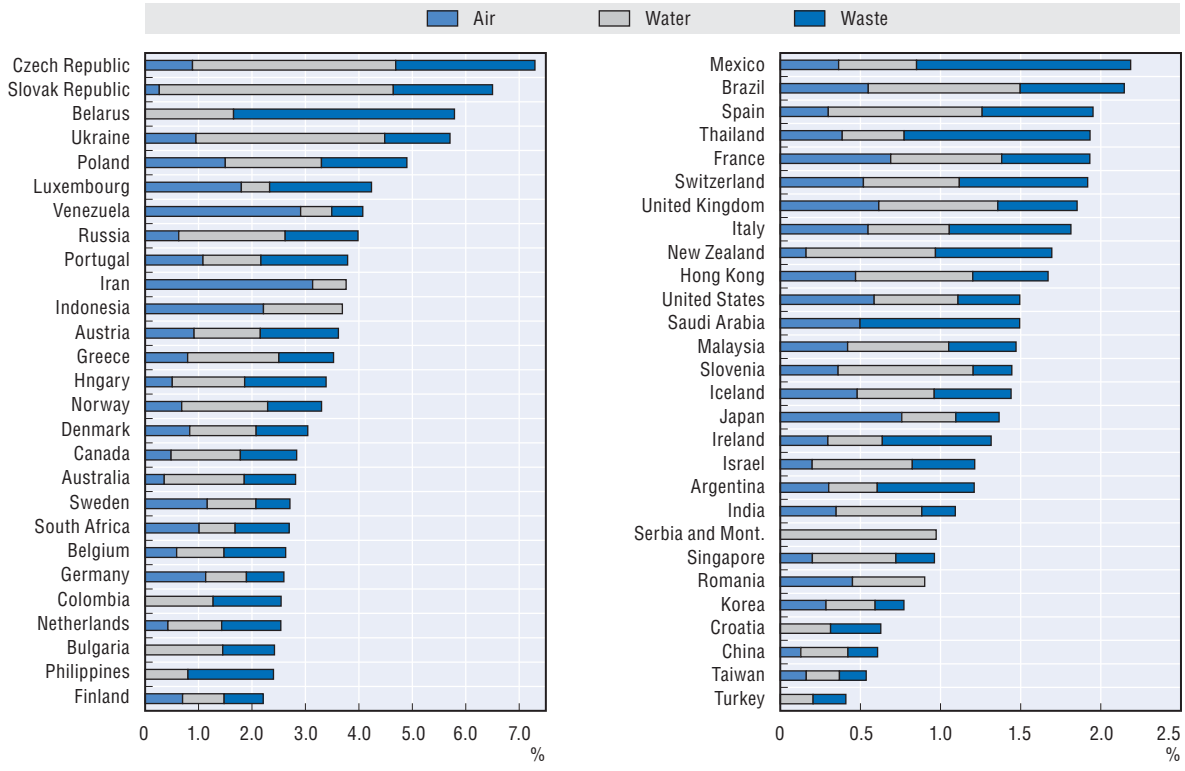


The observed decline in the rate of innovation with respect to solid waste management may be due in part to the difficulty associated with defining search strategies for some aspects of energy recovery, material recycling and waste prevention, which may result in a downward bias in the figures. This is likely to be particularly important in recent years as countries have focussed more of their efforts in these areas.

It is also interesting to examine the role of innovations in general environmental technologies in terms of their relative importance in countries' patenting activity overall (specialisation in AWW technologies). Figures 1.9 and 1.10 provide information on how "specialised" countries have been in general "environmental" technologies over the

Figure 1.8. **Proportion of patenting in general "environmental" technologies in patenting overall**

Per cent share of air + water + waste in total patenting, 1990-2005



period 1990-2007. Several factors could play a role here. On the one hand, these figures may reflect a degree of "catch-up" – with many countries focusing efforts on areas which have been somewhat neglected in the past (this could explain the high rank of some Central and Eastern European countries). On the other hand, they may also be a function of the weight of relatively more dynamic sectors in a country's innovation portfolio (this could explain the low rank of some fast-growing Asian economies).

Table 1.3 provides some preliminary information on the main "assignees" (*i.e.* owners of patents) in the three areas. This table illustrates that invention in air pollution control is relatively more concentrated than in the remaining two sectors, where the most important innovating firms are responsible for less than 1% of patenting. The dominant role of firms from a single country is less evident here. In addition, firms from multiple industrial sectors are represented, including the manufacturing, chemicals, water supply, and engineering sectors.[4]

Table 1.3. **Patent applicants**

Per cent share of sector total, based on counts of claimed priorities worldwide, 1986-2005

m	m	m	m	m	m
Air		Water		Waste	
Applicant name	Share (%)	Applicant name	Share (%)	Applicant name	Share (%)
Toyota Motor Corp.	4.031	Sanyo Electric	0.679	NIPPON KOKAN KK	0.610
Bosch GMBH Robert	2.381	Nalco Chemical	0.667	BAYER AG	0.511
Nissan Motor	1.676	Kurita Water Ind.	0.605	SIEMENS AG	0.440
Emitec Emissions	1.463	Bayer AG	0.473	MATSUSHITA ELECTRIC	0.411

Table 1.3. **Patent applicants** *(cont.)*

Per cent share of sector total, based on counts of claimed priorities worldwide, 1986-2005

m	m	m	m	m	m
Air		Water		Waste	
Applicant name	Share (%)	Applicant name	Share (%)	Applicant name	Share (%)
NGK Insulators Ltd.	1.356	Ebara Corp.	0.433	BASF AG	0.404
Denso Corp.	1.345	BASF AG	0.394	Metallgesellschaft	0.383
Mitsubishi Heavy Ind.	1.319	Degremont	0.376	Hitachi Ltd.	0.376
Volkswagen AG	1.142	Betz Laborator	0.354	Sanyo Electric Co.	0.376
Daimler Chrysler	1.100	Omnium Traiteme	0.348	Westinghouse Elect.	0.340
Siemens AG	0.988	Hitachi Ltd.	0.348	Plastic Omnium Cie	0.305
Metallgesellschaft	0.662	Degussa	0.342	Canon KK	0.298
Sanshin Kogyo KK	0.657	Hoechst AG	0.319	Mitsubishi Heavy Ind.	0.298
Hitachi Ltd.	0.609	Sharp KK	0.308	Kobe Steel Ltd.	0.270
Ford Global Tech.	0.577	Ahlmann ACO	0.279	Ebara Corp.	0.262
Mitsubishi Motors	0.571	Rhône Poulenc	0.274	Zoeller Kipper	0.248
Eberspaecher J.	0.545	Organo KK	0.262	Voest Alpine Ind. ANL	0.248
Ford Global Tech.	0.529	Henkel KGAA	0.262	Toyota Motor Corp.	0.241
Mazda Motor	0.518	Fraunhofer GES	0.257	Sony Corp.	0.234
General Motors Corp.	0.502	Konishiroku	0.251	Voith Paper Patent	0.227
Mann and Hummel	0.502	Eastman Kodak Co.	0.245	Solvay	0.213
Peugeot Citroën	0.497	Passavant Werke	0.228	Henkel KGAA	0.213
BMW AG	0.486	Mitsubishi Electr.	0.211	Hitachi Shipbuilding	0.199
Inst. Français Petro	0.475	Linde AG	0.200	Fraunhofer Ges For	0.199
Donaldson Co. Inc.	0.470	Zenon Environm.	0.200	Geesink BV	0.184
Flaekt AB	0.459	Comm Ener Atom	0.194	Inst. Français Petro	0.184
Daimler Benz AG	0.448	Evac Int. OY	0.183	Commiss. En. Atom.	0.184
Ford Motor Co.	0.443	Permelec Elect.	0.183	Du Pont	0.184
Yamaha Motor Co.	0.438	Samsung Elect.	0.177	Kao Corp.	0.177
Isuzu Motors Ltd.	0.432	Nippon Catalytic	0.171	Martin Umwelt Ener.	0.170
Nippon Denso Co.	0.422	US Filter Corp.	0.171	Gen Electric	0.163
Mitsubishi Electric	0.406	Betzdearborn Inc.	0.165	Hoechst AG	0.163
Renault	0.400	Buckman Labor	0.160	Nippon Electric Co.	0.163

Note: This data is only preliminary. The data on applicant names have not been fully harmonised, neither have mergers and acquisitions been taken into account.

Empirical evidence on the effect of environmental policy characteristics on innovation

The key point developed is that correlation between instrument types and policy design attributes is imperfect. Any incentives for innovation arise out of the underlying policy attributes and not the broad policy type *per se*. As such, it is important to assess incentives for innovation in terms of the underlying policy attributes rather than by broad instrument type. Because of this imperfect correlation, it is necessary to disentangle the distinct effect of each of these attributes empirically.

Fortunately, data obtained from the *World Economic Forum*'s "Executive Opinion Survey", previously asked respondents a number of questions related to environmental policy design. The survey was implemented by the WEF's partner institutes in over 100 countries, which include departments of economics at leading universities and research departments of business associations. The means of survey implementation varied by country and included postal, telephone, internet and face-to-face survey. In most years, there were responses from between 8 000 and 10 000 firms (see WEF, 2008 for a

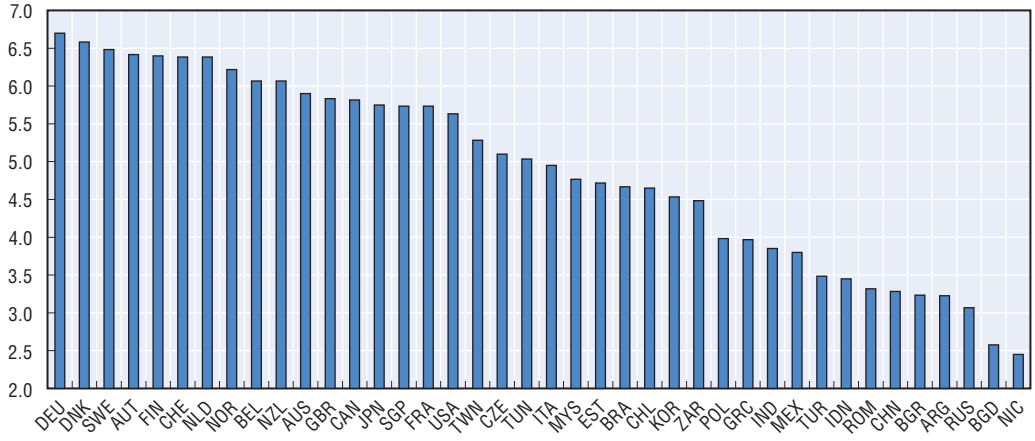
description of the sampling strategy.) However, due to data constraints, only the first three attributes (stringency, flexibility and predictability) can be assessed empirically in this paper.

Drawing upon the *PATSTAT Database* of patent applications, we argue that the different types of environmental policy regimes have an important and distinct role in encouraging innovation. The principal hypotheses to be examined are:

- H_1: Policy stringency has an effect on invention.
- H_2: Policy predictability has an effect on invention above and beyond that of stringency.
- H_3: Policy flexibility has an effect on invention above and beyond that of stringency.

Figure 1.9. **Stringency of environmental policy regimes in selected countries**

Mean value of the index over 2001-07

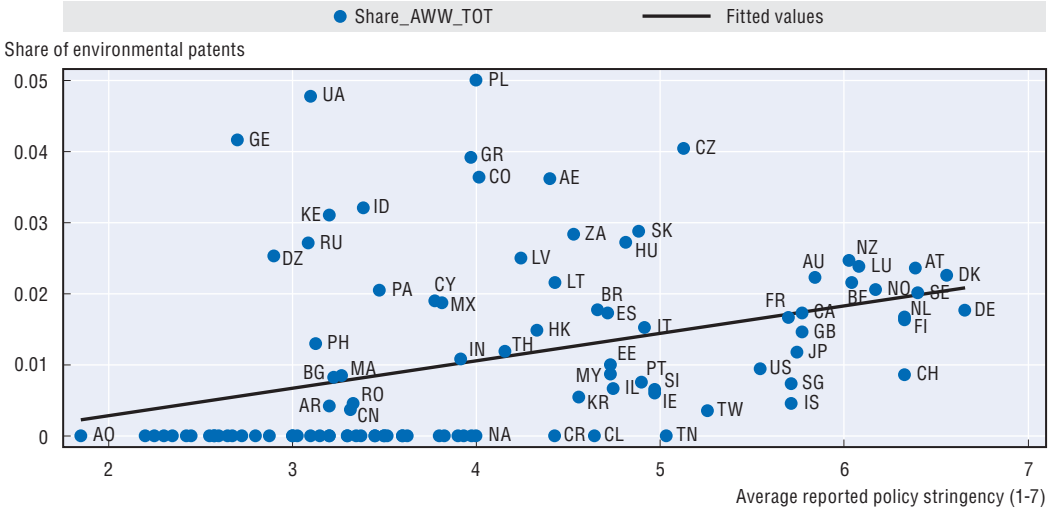


Survey question: Environmental policies in your country are: 1 = lax compared with that of most of other countries, 7 = among the world's most stringent.

Source: WEF (2008).

Figure 1.10. **Stringency of environmental policy regimes and innovation in environmental technologies**

Mean value over 2001-07



An empirical model is developed and to test these hypotheses by drawing upon the WEF survey data on policy attributes and the *EPO PATSTAT Database* of patent documents. The following reduced-form equation is specified and estimated for stringency, predictability, and flexibility as policy design attributes:

$$AWWPAT_{i,\,t} = f\,(ENVPOLICY_{i,\,t},\ TOTPAT_{i,t})$$

where *i* indexes country and *t* indexes year. The dependent variable is measured by the number of patent applications in selected areas of environmental technology which was described above. However, due to the nature of the questions posed, only inventions which relate to air and water pollution abatement and solid waste management are included. Nonetheless, general lessons learned are likely to be applicable to other fields (*i.e.* climate change mitigation). ENVPOLICY accounts for the different attributes of countries' environmental policy regimes (stringency, predictability, flexibility), and the construction of these variables is discussed below.

Aside from environmental policy, there are, of course, other important determinants of patenting activity for environmentally preferable technologies. This includes the propensity to invent technologies, in general, and the propensity to obtain any investor protection through existing intellectual property rights (IPR) regimes. Factors such as general scientific capacity, market conditions, openness to trade, etc. will also have an important effect on patenting activity, in general, and thus also in the specific field of environmental technologies. The propensity of inventors from a particular country to patent is likely to change over time, both because different strategies may be adopted to capture the rents from innovation (*e.g.* Cohen *et al.*, 2000) and because legal conditions may change through time (*e.g.* Ginarte and Park, 1997). In addition, it is important to control statistically for differences in the propensity to patent across countries.

As noted above, it is important to control statistically for differences in the propensity to innovate and patent across countries. In order to capture the effect of such factors (which are not specific to environmental technologies), we include the variable TOTPAT reflecting the total number of patent applications (claimed priorities) filed across the whole spectrum of technological fields (not only environmental). This variable thus serves both as a "scale" and as a "trend" variable in that it controls for differences in the effects of the size of a country's research capacity on innovation as well as changes in general propensity to patent over time and across countries. All the residual variation is captured by the error term ($\varepsilon_{i,\,t}$). A negative binomial model is used to estimate the model.

Environmental policy stringency

Given the heterogeneity of environmental policy regimes both across countries, and within countries across sectors and impacts as well as through time, it is difficult to construct a general index of the stringency of environmental policy regimes. However, in the WEF survey, respondents (usually CEOs) were requested to indicate the "stringency" of a country's overall environmental regulation. More specifically, they were requested to assess the degree of stringency on a Likert scale, with 1 = lax compared with that of most other countries, 7 = among the world's most stringent. Mean responses for 40 selected countries from our sample are provided in Figure 1.9.

Figure 1.10 shows a scatter plot of the stringency of environmental policy regimes (mean responses for the period 2001-07 for 102 OECD and non-OECD countries for which the WEF data is available) and of innovations which relate to environmental technologies

(the share of "environmental" patents over total patents, shown as mean values for the same time period). The plot suggests a positive linear relationship (Pearson correlation coefficient is 0.37).

Table 1.4 reports the results from the estimation of the reduced-form model of environmental innovation presented above on the WEF index of policy stringency for 77 countries over the period 2001-07. Hardly surprisingly, the estimate of STRING is always positive and significant no matter whether we include year fixed effects or not. This result confirms previous evidence (*e.g.* Lanjouw and Mody, 1996 and Brunnermeier and Cohen, 2003).

Table 1.4. **Policy stringency and environmental patents (2001-07)**

Dependent variable: AWWPAT	(1)	(2)
Stringency of Env Policy (STRING)	0.791***	0.850***
	(0.071)	(0.069)
Total Patents (TOTPAT)	0.204***	0.191***
	(0.026)	(0.023)
Intercept	–2.580***	–2.411***
	(0.334)	(0.432)
Year fixed effects	No	Yes
N	440	440
Log Pseudolikelohood	–1 104.36	–1 083.09
(Prob > Chi2)	0.000	0.000

Standard errors in parentheses: * p < 0.05, ** p < 0.01, *** p < 0.001.

Next, we estimate the model using a two-stage procedure of the form AWWPAT = *f*(ENVPOLICY,TOTPAT), where total patenting activity is first estimated as TOTPAT = *g* (economic size, scientific capacity, rule of law, openness, etc.). In Table 1.5 we present the results from the first-stage regression of total patents (TOTPAT) on lagged gross domestic product ($GDP_{(-1)}$) and an index of the strength of property rights protection ($IPR_{(-1)}$), gross domestic expenditure on R&D (GERD) as a percentage of GDP, and net international trade value. The equation is estimated as an unconditional negative binomial fixed effects model. The results are in line with previous work on general innovative

Table 1.5. **Determinants of total patents (2001-07)**

Dependent variable: TOTPAT	
GDP	0.711***
	(0.066)
Gross domestic expenditures on R&D	0.681***
	(0.139)
IPR protection	1.614***
	(0.186)
Net international trade	0.076***
	(0.011)
Intercept	–2.161**
	(0.683)
N	191
Log Pseudolikelihood	–1 452.89
(Prob > Chi2)	0.000

Standard errors in parentheses: * p < 0.05, ** p < 0.01, *** p < 0.001.

activity, including that undertaken in the Economics Department of the OECD (see Jaumotte and Pain, 2005).

From the estimation above we calculate the fitted values of total patents (PREDPAT) and use them as an explanatory variable, instead of actual TOTPAT, in the second-stage of the regression on AWWPAT. In Table 1.6 we compare the results with the predicted values of total patents (columns 1 and 3) and the TOTPAT variable (columns 2 and 4) as regressors. 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 and thus justify the use of the reduced-form model in the subsequent econometric analyses.

Table 1.6. **Second-stage regression of environmental innovation on stringency**

Dependent variable: AWWPAT	Predicted total patents (1)	Observed total patents (2)	Predicted total patents (3)	Observed total patents (4)
Stringency of Env Policy (STRING)	0.803***	0.506***	0.815***	0.529***
	(0.102)	(0.087)	(0.097)	(0.083)
Total Patents (TOTPAT)		0.134***		0.128***
		(0.015)		(0.014)
Predicted Total Patents (PREDPAT)	0.067***		0.071***	
	(0.011)		(0.010)	
Intercept	–1.564**	–0.465	–1.275*	–0.271
	(0.544)	(0.460)	(0.565)	(0.479)
Year fixed effects	No	No	Yes	Yes
N	191	191	191	191
Log Pseudolikelihood	–754.68	–714.21	–733.00	–699.94
(Prob > Chi2)	0.000	0.000	0.000	0.000

Standard errors in parentheses: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

By imposing a price (whether explicitly or implicitly) on the costs of pollution emissions, or by otherwise changing the opportunity costs associated with environmental assets, environmental policy is likely to induce innovation – because firms seek to meet the policy objectives at least cost. Of course, different policy measures may be more or less likely to induce innovation. Irrespective of the nature of the instrument applied, some innovation is likely to be induced. However, as argued previously, policy stringency is only one aspect of the public policy regime which affects the rate of innovation. Other potentially important aspects are discussed next.

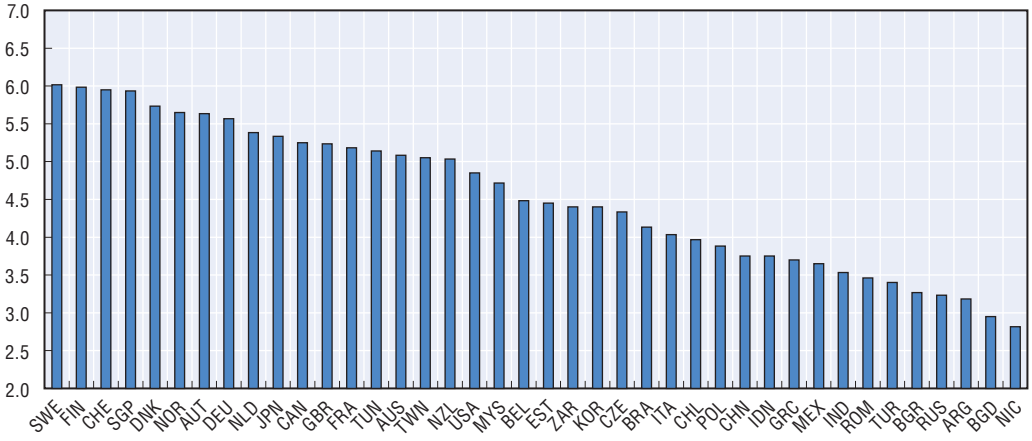
Environmental policy predictability

To test the second principal hypothesis (concerning the relationship between policy predictability and environmental innovation), we need an appropriate measure of policy predictability. Given the heterogeneity of environmental policy regimes – both across countries, and within countries across sectors and impacts (as well as through time) – it is difficult to construct a general index of the "predictability" of environmental policy regimes. However, for 2001-06, the WEF survey also asked respondents about their perceptions of the "stability and clarity" of the environmental policy regime in different

countries. Respondents were requested to indicate on a Likert scale whether environmental regulations were "confusing and frequently changing" (1) or "transparent and stable" (7). We use these measures as an indicator of policy predictability. They were invited to provide responses for all countries in which their firm was present. Mean responses for selected countries are provided in Figure 1.11. The Nordic and Alpine countries would appear to have the most "stable" regimes, with some G7 countries (*e.g.* Italy) recording rather low scores.

Figure 1.11. **Stability and transparency of environmental policy regimes**

Mean value of the index over 2001-06



Survey question: Environmental policies in your country are: 1 = confusing and frequently changing, 7 = transparent and stable.

Source: WEF (2008).

Figure 1.12 presents a scatter plot of the relationship between the index of the stability of environmental policy regimes (mean responses for the period 2001-06 for 102 OECD and non-OECD countries for which the WEF data is available) and of innovations which relate to environmental technologies (the share of "environmental" patents over total patents, shown as mean values for the same time period). The correlation is 0.30.

As noted above, there are a number of factors (other than policy stability) which affect an individual country's innovative activity with respect to the environment. Firstly and most significantly, as has been reported, policy stringency is likely to play a role. However, the two measures of environmental policy (stability and stringency) are highly correlated (> 0.80) which will lead to multicollinearity if we consider them jointly in the regression. To deal with this potential problem we use factor analysis to construct a variable which is a linear combination of the two correlated environmental policy measures plus an error term.[5] In the empirical analysis *FACTOR* accounts for the joint impact of uncertainty of the policy conditions and stringency of environmental regulations on innovative activity with respect to environmental technologies. It will be possible to extract the individual effect of policy stability by comparing the coefficient estimates of *FACTOR* with that of *STRING*. Descriptive statistics for the estimation sample of 77 countries over the period 2001-06 are provided in Table 1.7.

Table 1.8 reports the empirical results. Models (1a) and (1b) consider the effect of environmental policy stability over the whole sample in a pooled estimation, while Models

Figure 1.12. **Stability and clarity of environmental policy regimes and innovation of environmental technologies**

Mean value over 2001-06

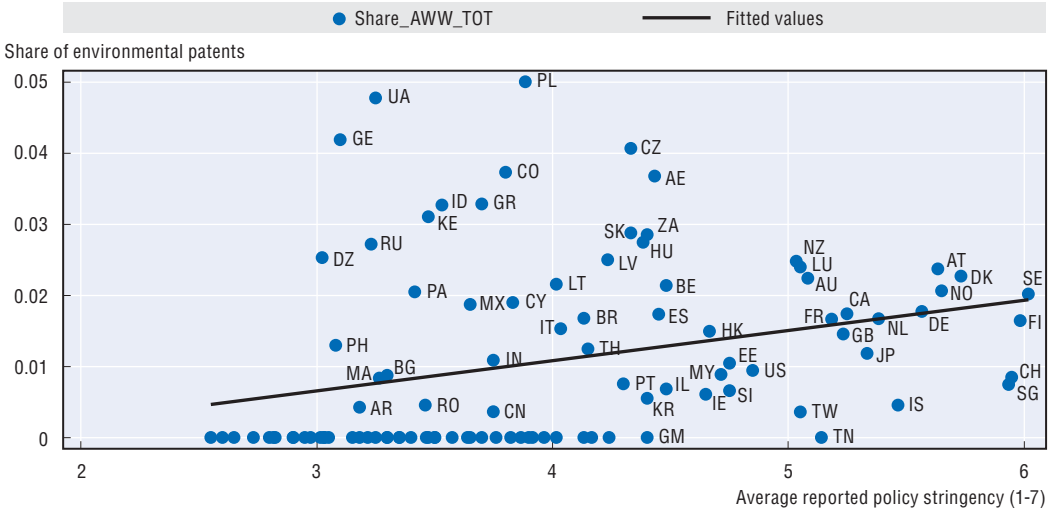


Table 1.7. **Descriptive figure title statistics (2001-06)**

Variable	Unit	Obs.	Mean	Std. dev.	Min.	Max.
AWWPAT	Count	386	26.423	86.191	0	622
STRING	Index	386	4.554	1.254	1.200	6.800
STAB	Index	386	4.320	0.939	1.600	6.700
FACTOR	Normalised	386	0.000	0.955	–2.720	1.995
TOTPAT	Count	386	2 111.30	6 863.44	0	49 263

Table 1.8. **Regression results: Policy stability and innovation (2001-06)**

Dependent variable: AWWPAT	(1a)	(1b)	(2a)	(2b)
Stringency of Env Policy (STRING)	0.814***		0.838***	
	(0.075)		(0.072)	
Factor of Env Policy (FACTOR)		1.061***		1.089***
		(0.104)		(0.097)
Total Patents (TOTPAT)	0.181***	0.182***	0.185***	0.184***
	(0.030)	(0.029)	(0.029)	(0.028)
Intercept	–2.528***	1.202***	–2.328***	1.560***
	(0.394)	(0.107)	(0.450)	(0.230)
Year fixed effects	No	No	Yes	Yes
N	386	386	386	386
Log Pseudolikelohood	–1 027.52	–1 031.70	–1 019.50	–1 023.57
(Prob > Chi2)	0.000	0.000	0.000	0.000

Robust standard errors in parentheses: * p < 0.05, ** p < 0.01, *** p < 0.001.

(2a) and (2b) include year fixed effects. The estimate of FACTOR is positive and highly significant in all specifications estimated. The coefficient on the STRING variable is also positive and significant. Most importantly, the FACTOR coefficient is always larger than the

measure of policy stringency. These results indicate that policy stability has a positive and statistically significant impact on inventive activity in "environmental" technologies (air, water, waste) that is distinct from, and additional to, the effect of stringency. The coefficient on the TOTPAT variable is positive and highly significant suggesting that patenting activity in the selected "environmental" technologies is also explained by variation across countries and over time in patenting activity overall.

Related work has examined the relative effects of the levels and volatility in the levels of public R&D expenditures on patented inventions in "environmental" technologies (Kalamova *et al*., 2011). The measure includes both direct government expenditures for R&D undertaken in government and state university laboratories, as well as the provision of support (grants, tax credits, etc.) for R&D undertaken by the private sector and other organisations. This measure should reflect at least two aspects of uncertainty. Firstly, since some form of public fiscal support is usually necessary in order for privately-undertaken R&D projects in environmental technologies to be feasible at all this will reflect variation in the cost of the investment. Secondly, since public R&D in a specific field can be considered as a "signal" of more public policy objectives, volatility in such expenditures can be used as a measure of commitment. It is found that a 10% increase in the level of R&D expenditures will cause between 2.6% and 3.9% increase in environmental patent activity. Conversely a 10% increase in the volatility of government support for R&D will decrease innovation by 1.2% to 2.8%.

To conclude, these results indicate that policy stability has a positive and statistically significant impact on inventive activity in "environmental" technologies (air, water, waste) that is distinct from the effect of stringency. This empirical evidence supports the hypothesis that environmental policy uncertainty can result in less innovation in environmental technologies. The more "unstable" a policy regime, the less innovation takes place. This implies that governments have strong incentives to behave in a predictable manner if they wish to induce innovations which achieve environmental objectives at lower cost. Frequently changing policy conditions come at a cost, and to the extent that these arise out of reasons which are unrelated to changing market or ecological conditions, such instability should be avoided.

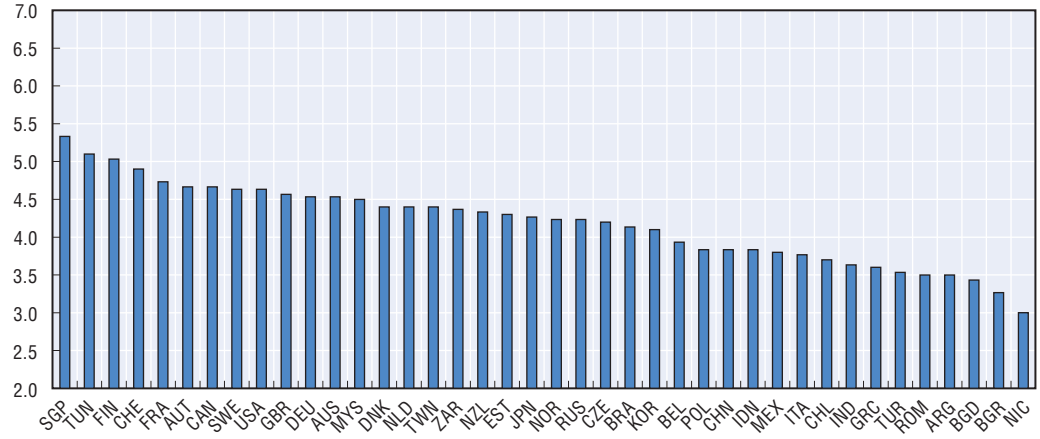
However, it must be recognised that in some cases policy instability can arise from the acquisition of information. Damages may be higher or lower than initially foreseen, encouraging the use of more or less stringent policies (see Baker and Adu-Bonnah, 2008 for a discussion in the context of climate change). Similarly, abatement costs may be higher or lower than initially foreseen (see Burtraw and Palmer, 2004 for a review). This uncertainty can persist for some time, with new information sometimes running counter to previous findings. In such cases, there is a trade-off between changing environmental objectives to reflect the new information and keeping incentives constant in order to reduce uncertainty. Further theoretical and empirical work is needed to assess this trade-off.

Environmental policy flexibility

In order to test our third principal hypothesis (about the relationship between policy flexibility and environmental innovation) we use the flexibility index from the WEF survey over the period 2001-03. In particular, respondents were requested to assess the degree of flexibility on a Likert scale, with 1 = offer no options for achieving compliance, 7 = are flexible and offer many options for achieving compliance. Mean responses for some of the countries included in the sample discussed here are provided in Figure 1.13.

Figure 1.13. **Flexibility of environmental policy regimes**

Mean value of the index over 2001-03



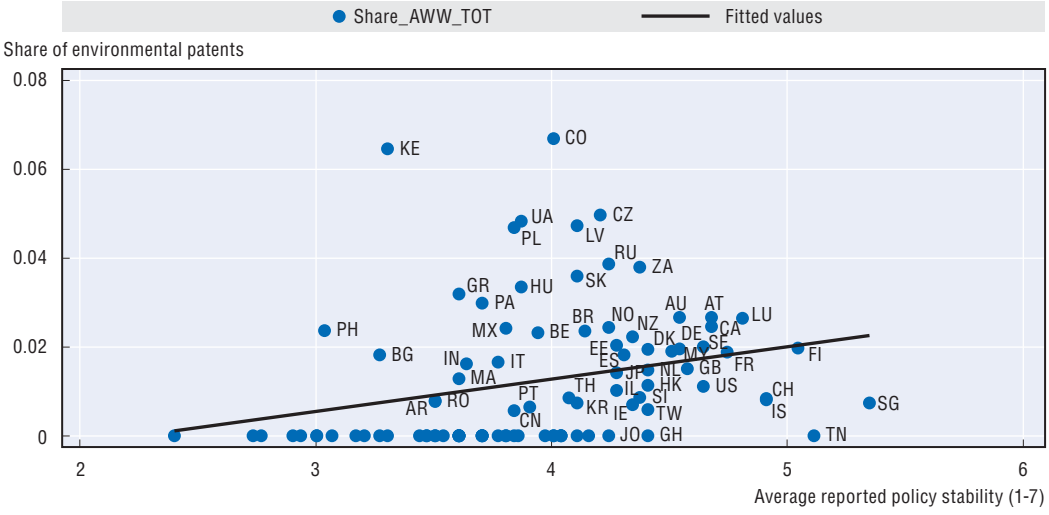
Survey question: Environmental policies in your country are: with 1 = offer no options for achieving compliance, 7 = are flexible and offer many options for achieving compliance.

Source: WEF (2008).

Figure 1.14 shows a scatter plot of the relationship between the index of flexibility of environmental policy regimes (mean responses for the period 2001-03 for 95 OECD and non-OECD countries for which the WEF data is available) and of innovations which relate to environmental technologies (the share of "environmental" patents over total patents, shown as mean values for the same time period). The data suggest a positive relationship (correlation is 0.27).

Figure 1.14. **Flexibility of environmental policy regimes and innovation of environmental technologies**

Mean value over 2001-03



As discussed above, there are a number of other factors that may affect an individual country's innovative activity with respect to the environment. Most importantly – evidence presented above indicates that policy stringency plays a role. However, as with the case of

policy stability since the two measures characterising environmental policy (flexibility and stringency) are highly correlated (0.80), considering them jointly in a regression may lead to multicollinearity. We tackle the potential problem in a similar way to the previous subsection by applying the method of factor analysis. In the empirical analysis *FACTOR* will account for the joint impact of flexibility of the policy conditions and stringency of environmental regulations on innovative activity with respect to environmental technologies. It will be possible to identify the individual effect of policy flexibility by comparing the coefficient estimates of *FACTOR* with the one of *STRING*. Descriptive statistics for the estimation sample of 73 countries over the period 2001-03 are provided in Table 1.9.

Table 1.9. **Descriptive statistics (2001-03)**

Variable	Unit	Obs.	Mean	Std.	Min.	Max.
AWWPAT	Count	204	29.438	94.218	0	622
FLEX	Index	204	4.016	0.608	1.700	5.400
STRING	Index	204	4.388	1.314	1.200	6.700
FACTOR	Normalised	204	0.000	0.871	–2.895	1.804
TOTPAT	Count	204	1 991.419	6 542.097	0	41 904

Table 1.10 reports the empirical results. Models (1a) and (1b) consider the effect of environmental policy regime over the whole sample in a pooled estimation, while Models (2a) and (2b) include year fixed effects. In order to pick up the distinct effect of environmental policy flexibility on innovation we compare the coefficients of FACTOR and STRING. The estimate of FACTOR is positive and highly significant in all model specifications estimated. The coefficient of the STRING variable is also positive and significant. Most importantly, the coefficient of FACTOR is always larger than that of STRING policy stringency. These results clearly indicate that policy flexibility has a positive and statistically significant impact on inventive activity in environmental technologies (air, water, waste) that is distinct from, and additional to, the effect of policy stringency. The coefficient of the TOTPAT variable is positive and highly significant suggesting that patenting activity in the selected environmental technologies is also explained by variation in total patenting activity across countries and over time.

To conclude, empirical evidence has been presented which supports the hypothesis that increased flexibility of environmental policy can result in greater innovation in environmental technologies. For a given level of policy stringency, the more "inflexible" a policy regime, the less innovation takes place. This implies that rather than prescribing certain abatement strategies (such as technology-based standards), governments should give firms stronger incentives to look for the optimal technological means to meet a given environmental objective. This is important because if firms are allowed to search across a wider "space" to identify the means of complying with regulations, the objectives of environmental policy will be met at lower cost. Moreover, such issues are of relevance in other policy spheres. For instance, both Gann *et al.* (1998) and Oster and Quigley (1977) discuss the case of effect of building codes and standards on technological innovation.

Table 1.10. **Regression results: policy flexibility and innovation**

Dependent variable: AWWPAT_it	(1a)	(1b)	(2a)	(2b)
Policy Stringency (STRING_it)	0.891***		0.891***	
	(0.102)		(0.101)	
Factor of Policy (FACTOR_it)		1.506***		1.534***
		(0.150)		(0.152)
Total Patents (TOTPAT_it)	0.163***	0.169***	0.163***	0.164***
	(0.039)	(0.042)	(0.039)	(0.038)
Intercept	–2.626***	1.255***	–2.529***	1.435***
	(0.543)	(0.138)	(0.582)	(0.211)
Year fixed effects	No	No	Yes	Yes
N	204	204	204	204
Log Pseudolikelihood	–557.05	–556.41	–556.83	–552.83
(Prob > Chi2)	0.000	0.000	0.000	0.000

Robust standard errors in parentheses: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

Concluding remarks

In this chapter, the potential impacts of environmental policy design on innovation were discussed. Previous empirical work examined the role of market-based instruments *versus* direct regulation in their potential to induce innovation. However, juxtaposing the incentives associated with market-based instruments with direct regulations in broad terms may be misleading since there is no necessary mapping from instrument type to each of the characteristics listed above. The key point is that correlation between policy instrument types and policy design attributes is imperfect. Any incentives for innovation arise out of the underlying policy characteristics. As such, it is important to assess incentives for innovation in terms of their specific characteristics rather than by broad instrument type. Because of this imperfect correlation, it is necessary to disentangle the innovation effect of each of these characteristics.

This chapter draws upon a worldwide database of patent applications and introduces an indicator of innovation in technologies related to air pollution abatement, wastewater treatment and solid waste management. On the basis of the data presented, the rate of innovation in these areas is no greater than the rate of innovation more generally. This data is used to examine the effects of three of the most important characteristics (stringency, predictability and flexibility). The empirical evidence presented provides some support for the hypotheses developed.

On the one hand, it has been found that policy stringency plays a significant role in inducing innovation. More specifically, based on evidence from a broad cross-section of countries over the period 2000-07 it is found that policy stringency has a positive impact on the likelihood of developing innovative means of air and water pollution abatement and solid waste management. A more "stringent" policy will provide greater incentives for polluters to search for ways to avoid the costs imposed by the policy. All "environmental" policies – whether taxes, subsidies, regulations, information – attach a price to polluting. By increasing the "price" of polluting, it is hardly surprising to find that the more stringent the policy the greater the effect on innovations which have the effect of reducing emissions.

However, this is not to say that different policy measures of equal stringency will not have different effects on the rate and direction of innovation. Policy stringency is only one aspect of the public policy regime which affects the rate of innovation, and it is important to examine some of the other characteristics of policy regimes as well. Evidence presented indicates that a stable and "predictable" policy regime is likely to induce more innovation than one where more uncertainty is associated with a country's environmental policy.

Why does this arise? Signals that are difficult to predict give investors strong incentives to postpone investments, including the risky investments which lead to innovation. There is an advantage to "waiting" until the policy dust settles. As such, by adding to the risk which investors face in the market, an unpredictable policy regime can serve as a brake on innovation, both in terms of technology invention and adoption. This implies that governments have an interest to behave in a predictable manner if they wish to induce innovations which achieve environmental objectives at lower cost. Frequently changing policy conditions come at a cost, and such instability should be avoided.

However, it must be recognised that in some cases policy instability can arise from the acquisition of information. Damages may be higher or lower than initially foreseen, encouraging the use of more or less stringent policies. Similarly, abatement costs may be higher or lower than initially foreseen. In such cases, there is a trade-off between changing environmental objectives to reflect the new information and keeping incentives constant in order to reduce uncertainty.

Finally, the third aspect of policy design that is examined empirically in this paper is policy flexibility, which can be characterised as technology-neutrality. The results presented here indicate that, for a given level of policy stringency, the more inflexible a policy regime, the less innovation takes place. In other words, the more flexible policy regime will induce more innovation than a regime which is prescriptive in nature. This implies that rather than prescribing certain abatement strategies (such as technology-based standards), wherever possible governments should give firms stronger incentives to look for the optimal technological means to meet a given environmental objective.

Since both governments and firms cannot foresee future trajectories of technological change, it is important to give innovators the incentive to search across a wider "space" to identify potential means of complying with regulations. Flexibility "unleashes" the search for new innovations, some of which may be only marginal (but environmentally significant) improvements on existing technologies. Therefore, by encouraging potential innovators to devote resources to identify the best way of achieving a given environmental objective, policy flexibility provides incentives for innovation above and beyond those provided by policy stringency. Of course, administrative and monitoring costs may prevent the use of flexible instruments in some cases.

Notes

1. Unless it is assumed that the standard itself will change as a consequence. See Milliman and Prince (1989).
2. In the environmental context, irreversibilities are partly a function of the nature of investments, *i.e.* end-of-pipe abatement *versus* change-in-production processes.
3. The selection of classifications benefited from searches developed by Lanjouw and Mody (1996) and Schmoch (2003). Assistance of Julie Poirier and Marion Hemar (ENSAE, Paris) in developing the search strategy is equally acknowledged.

4. The presence of a large number of motor vehicle firms as assignees for air pollution abatement patents indicates that further work needs to be done to distinguish between technologies for stationary and mobile sources.
5. The newly created variable (*FACTOR*) is normally distributed with a mean of 0 and variance of 1 and contains equal shares of the stringency and stability indexes.

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Chapter 2

Environmental Policy, Multilateral Environmental Agreements and International Markets for Innovation

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Flexibility of the national policy framework and international policy co-ordination are two key factors that affect international transfer of environmental technologies. In this chapter, empirical evidence is provided that indicates that the degree of flexibility of national environmental policy regimes has a positive effect on technology transfer. Flexibility ensures that markets are not fragmented across different countries as would be the case with prescriptive regimes. In the second case, we also examine whether adherence to a series of international agreements on reducing SO_X and NO_X emissions has induced the transfer of technologies between signatory countries. Supporting descriptive and econometric evidence to this end is provided.

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Introduction

International technology transfer (ITT) can provide significant economic benefits, giving countries access to inventions which improve macroeconomic performance (see Keller, 2002; Coe and Helpman, 1995). Based on an extensive review of empirical studies Keller (2002) argues that foreign sources of technology account for 90% of domestic productivity growth. As a consequence, it is important to ensure that appropriate framework conditions are in place in order to encourage the international diffusion of technologies.

While this is true of OECD economies, it is particularly true of non-OECD economies (see *e.g.* Savvides and Zachariadis, 2005; Schiff and Wang, 2008) since the majority of R&D is still undertaken by OECD countries. Helping less-developed economies get on the "first rung of the innovation ladder" is, of course, an important development policy objective of OECD economies. Indeed, Article 66 of the TRIPS Agreement "requires developed countries' governments to provide incentives for their companies to transfer technology to least-developed countries". The extent to which this obligation is implemented in an explicit manner is, however, unclear (see Maskus, 2004). However, it is interesting to note that in a study of regulation of coal-fired electricity generating plants, Lovely and Popp (2008) find that international economic integration eases access to environmentally friendly technologies and leads to earlier adoption of regulation in developing countries.

There is another important motivation for encouraging the international transfer of technologies in which some of benefits arising from these transfers are transnational in nature. Specifically, for technologies whose impacts have international "public good" characteristics, the source country can indirectly benefit from the transfer in various non-market forms. For example, policies that are designed to address issues of *public health* which cross national borders (*i.e.* infectious diseases such as SARS) generate clear benefits in encouraging the transfer of technologies which mitigate these adverse impacts. Indeed, it might be argued such potential "win-wins" were part of the motivation for the WTO "Medicines Decision" (see Abott, 2005).

The case is even stronger with respect to (at least some) *environmental* concerns. For the technology source country, the welfare implications of the transfer of technologies to recipient countries which mitigate trans-frontier (*e.g.* regional pollutants such as sulphur dioxide) or global "public bads" (*e.g.* greenhouse gas emissions such as carbon dioxide) are very different than the transfer of technologies in which such impacts are absent. More specifically, in the case of global public "bads", all countries (including the source country) benefit from increased greenhouse gas mitigation, irrespective of its location.

It is precisely for this reason, of course, that a number of Multilateral Environmental Agreements (MEAs) have included elements which encourage ITT. Examples include the Multilateral Fund for Implementation of the Montreal Protocol as well as Annex III-Article 5 of the United Nations Convention on the Law of the Sea. The effectiveness of

these different measures varies, with the Multilateral Fund standing out as being a particular success story.

In the context of climate change, a Special Climate Change Fund was initially created under the Marrakech Accords. At COP 16 in Cancun richer countries promised to provide USD 100 billion by 2020 for a "Green Climate Fund" to help developing countries finance investment in clean energy technology. In addition, a Technology Executive Committee was established to analyse "needs and policies for transfer to developing countries of technology for clean energy and adaptation to climate change". Recent work on the Clean Development Mechanism also supports the hypothesis that the CDM can be an important source of both "embodied" and "disembodied" technology transfer (see Dechezleprêtre *et al.*, 2008; Seres *et al.*, 2010; Haščič and Johnstone, 2011).

However, the domestic policy framework can also play a role in encouraging ITT for environmental inventions. Unlike many other areas, "demand" for environmental inventions is largely driven by the public policy framework (for evidence see Lanjouw and Mody, 1996; Brunnermeier and Cohen, 2003; Johnstone *et al.*, 2010). As a consequence, the relative degree of stringency and other design characteristics related to domestic environmental policy can have implications for the international diffusion of technologies. Conversely, incompatible domestic policy frameworks may create barriers for international transfer.

Drawing on a database of patent applications from a wide cross section of countries, this paper provides evidence for the positive effect of "flexibility" of the domestic environmental policy regime on the propensity for the inventions induced to be diffused widely in the world economy. In addition, the role that multilateral environmental agreements (MEAs) can play in encouraging technology transfer is examined. In order to undertake these analyses, a measure of international technology transfer is developed for environmental technologies. This measure is then used to examine the role of both the domestic policy framework and MEA's in encouraging transfer. The results of the empirical analyses confirm the positive role of policy flexibility and international co-operation on technology transfer.

International transfer of environmental technologies

Overall, our understanding of patterns of technology transfer remains limited. Through the use of citation data, a small number of papers (Peri, 2005; Co, 2002; Maurseth and Verspagen, 2002) have extended the insights obtained from gravity trade models to examine trade in knowledge. In one of the few papers to model the international diffusion of technologies (and not ideas and knowledge), Eaton and Kortum (1996) modelled the probability that a claim for a patented invention originating in a particular country would be filed in another country. Amongst the determinants they included geographic distance between the countries and the level of trade between the countries, as well as the level of human capital in the "adopting" country. They find that diffusion falls rapidly with geographic distance.

Technology transfer can be either embodied or disembodied, and take place through the market or by non-market means. A possible taxonomy might take the following form (see Maskus, 2004; Hoekman and Javorcik, 2006):

- Market:
  - Trade in goods and services.

- Foreign direct investment.
- Licensing.
- Joint ventures.
- Cross-border movement of personnel.

- Non-market:
  - Imitation and reverse engineering.
  - Employee turnover.
  - Published information (journals, test data, patent applications).

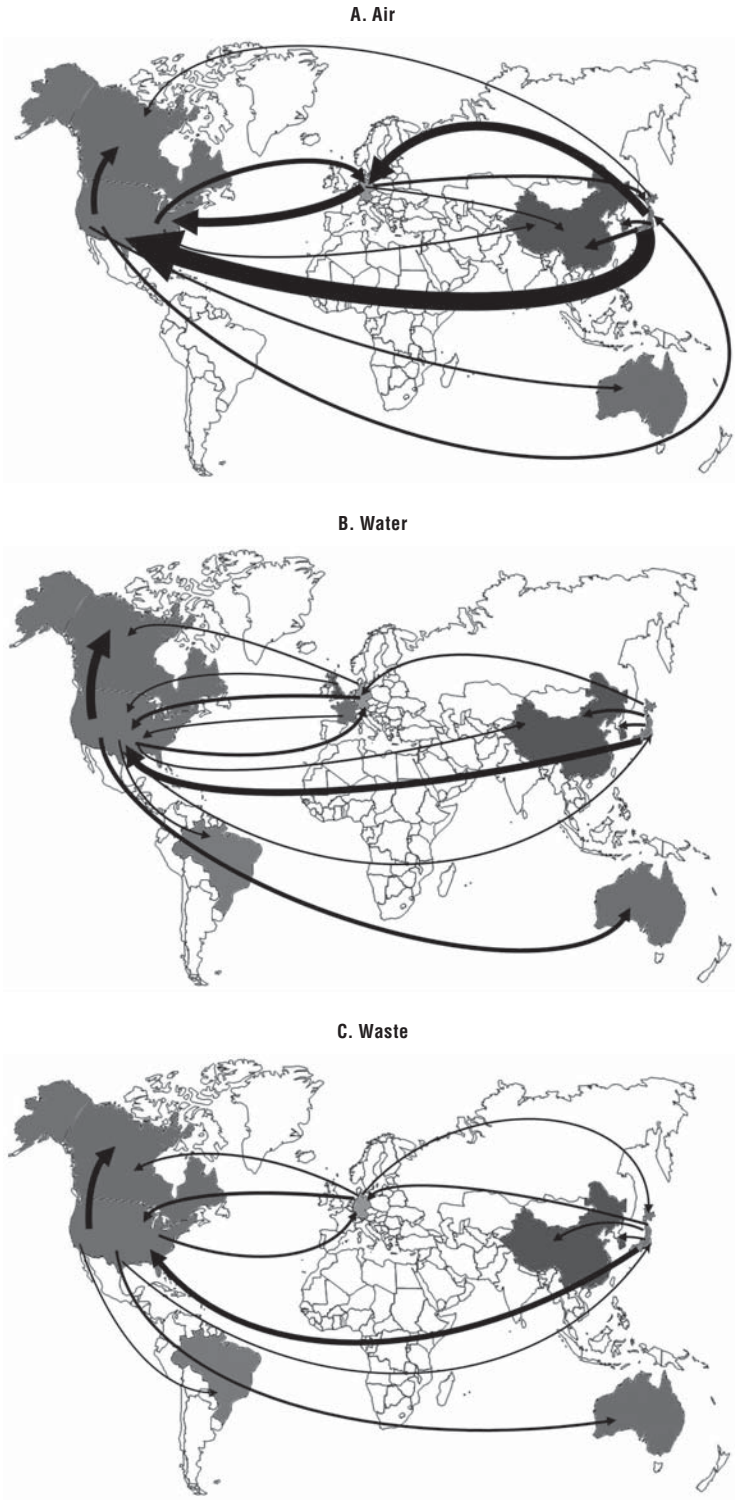
The empirical evidence strongly supports the finding that the bulk of technology transfer takes place via trade, foreign direct investment and licensing (Maskus, 2004). Precisely which channel is most important depends in part on the characteristics of the "recipient country" (domestic research capacity, strength of intellectual property rights regimes, etc.) and nature of the technology being "transferred" (*i.e.* potential for imitation and reverse engineering). The use of patent data to measure international technology transfer arises from the fact that there will be a partial "trace" of all three of these channels of transfer in patent applications. If there is any potential for reverse engineering, then exporters, investors, and licensors have an incentive to protect their intellectual property when it goes overseas.

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 a single invention may be sought in a number of countries. While the vast majority of inventions are only patented in one country (often that of the inventor, particularly for large countries), some are patented in multiple 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, a patent only gives the patentee 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, and duplicate patent applications would not be a good proxy variable for transfer.

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; Berger (2005) and Van Pottelsberghe and François (2006) also provide more recent data for European Patent Office applications). Moreover, if enforcement is weak, the publication of the patent in a local language can increase vulnerability to imitation (see Eaton and Kortum, 1996, 1999). Independently, inventors are unlikely to apply for patent protection in a second country unless they are relatively certain of the potential market for the technology that the patent covers (see the Annex A to this volume for methodological discussion and empirical evidence on the reliability of such a measure).

In this paper, indicators of transfer were developed for technologies that relate to air pollution abatement, water and wastewater treatment, and solid waste management. The patent classes are the same as those used in the previous chapter, and are listed in Annex B. (For more information see *www.oecd.org/environment/innovation/indicator*.) The data was extracted from the *EPO Worldwide Patent Statistical (PATSTAT) Database*, and measures of transfer were developed, with priority office defined as the "source" country and duplicate office as the "host" country. Figure 2.1 presents the most important bilateral

Figure 2.1. **International transfer of selected environmental technologies (1975-06)**



Note: This map is for illustrative purposes and is without prejudice to the status of or sovereignty over any territory covered by this map.

transfer relationships for air pollution abatement, water and wastewater treatment, and solid waste management, based on patent applications filed from 1975 to 2006.

However, the extent of transfer of "environmental" technologies is partly a consequence of close economic relations more generally. In Table 2.1 the data is normalised by total rates of transfer, and the most "environment-intensive" flows are presented. For example, almost 19% of all technologies transferred from Japan to Poland relate to "environmental" technologies.

Table 2.1. **Most AWW-intensive bilateral transfer relations (2001-03)**

Source	Recipient	AWW transfer	Total transfer	Share (%)
JP	PL	36	191	18.85
NL	BE	7	61	11.48
CZ	SK	8	76	10.53
AT	MX	8	90	8.89
CN	HK	10	122	8.20
AT	PL	9	114	7.89
NO	MX	5	64	7.81
FI	MX	11	142	7.75
PL	AU	15	212	7.08
CZ	AU	6	85	7.06
RU	UA	8	115	6.96
FI	NO	18	259	6.95
JP	ZA	17	246	6.91
FI	PL	9	132	6.82
KR	SG	4	60	6.67
GR	AU	6	92	6.52
CA	NZ	4	62	6.45
UA	RU	19	299	6.35
GB	IE	6	97	6.19
AU	NZ	46	761	6.04
CA	KR	5	83	6.02
AT	BR	11	183	6.01

Note: Number of duplicate patent filings in AWW-relevant fields as a share of overall transfer, 2001 to 2003. "Environmental" technologies covered include: Air + Water + Waste, or AWW. Only bilateral relations with total transfers greater than fifty applications were included.

The role that domestic policy factors and multilateral environmental agreements play in encouraging inventors to protect their inventions in multiple countries is the subject of the following two sections.

Environmental regulation and fragmentation of innovation markets

While the empirical evidence on the effects of environmental policy on trade in goods and services remains limited and ambiguous (see Levinson and Taylor, 2008 for new results and a methodological discussion of the reasons why positive evidence in this area remains limited), there is reason to expect that differences in environmental policy regimes would have an effect on international trade and foreign direct investment patterns. Indeed some environmentalists have argued that the stringency of environmental policies should be harmonised in order to avoid such effects, but this is unlikely to be welfare-improving.

Environmental policies may differ across countries due to both supply (*i.e.* ecological conditions) and demand (*i.e.* preferences for environmental quality) conditions, and these factors should be reflected in domestic policy regimes if it is to bring about welfare improvements. While there are some arguments for policy harmonisation in certain cases

(*e.g.* imperfect enforcement, trans-frontier pollution), economists are more concerned with the potential for domestic environmental policy to be used as a barrier to trade in order to protect domestic industries (see Ederington and Minier, 2003 for an empirical study) (see Greaker and Eggert, 2008 for a discussion of the GMO case).

Unfortunately, much of the relevant literature in this area has focused on the effects of differences in the stringency of environmental policy, and not on the effects of differences in policy design. In addition to their effects on the *rate* of innovation, different policy measures (of equal stringency) are likely to generate different *types* of innovation. As such, if different countries introduce different types of policy measures, there is likely to be national specialisation in different types of technological innovation to meet similar environmental objectives. This fragmentation of environment-related innovation along national lines can result in increased costs in meeting given environmental objectives. While the effects of policy design on the international diffusion of innovations has not been addressed in the literature, in other areas there is evidence of the costs associated with differentiated regulatory systems for pharmaceutical (Vogel, 1998) and food (Thilmany and Barrett, 1997) markets. In the environmental domain there have been a number of studies on the effect of differentiated gasoline content regulations in the United States on gasoline price levels and variability (see Morriss and Stewart, 2006; Chakravorty and Nauges, 2005; Chakravorty *et al.*, 2008).

In addition to the price effects of policy heterogeneity, the potential innovation effects of this regulatory heterogeneity may be considerable. Since investment in R&D is risky, any measures that constrain the potential market for innovations generated are likely to present a significant disincentive. Moreover it can be costly to gather the information required in order to determine what types of innovations are likely to be permitted under a wide variety of policy regimes. However, no empirical evidence on the innovation impacts of policy design is available.

The specific effect of the "flexibility" of domestic environmental policy has not been addressed in the literature. Since flexible environmental policies – whether they are environment-related taxes, tradable permit systems, or even non-prescriptive performance standards – allow for the use of a wide variety of technological measures, the international market opportunities for the technologies thus arising are likely to be wider. It might be imagined that such effects could further be realised through the implementation of identical technology-based standards. Indeed this is similar to the arguments put forth by Sykes (1995) and others.[1] However, this assumes a level of co-ordination that is unlikely to be realised in practice for environmental technologies, although de Coninck *et al.* (2008) provide some examples of international technology-oriented agreements related to climate change.

Alternatively, in circumstances where a dominant country regulates first, the policy may induce innovations that affect the policy decisions of subsequent regulators, encouraging them to adopt similar regulations. The example of California motor vehicle emissions controls might represent such a case (see Vogel, 1995. However, an empirical study by Fredriksson and Millimet, 2002 finds limited evidence of the "California effect" in state-level environmental policy-making). While this may result in an unfragmented market, it does so at the cost of imposing regulations of equal stringency across countries with different ecological conditions and heterogeneous demand for environmental quality. There is no reason to expect that the optimal path of innovation will be induced.

Conversely, the use of flexible instruments allows for both broad markets for innovation as well as differentiated levels of stringency. In effect, with flexible policy instruments the level of stringency determines the size of different national markets, without bringing about market fragmentation.

Data construction

Exploiting the transfer data discussed above, it is possible to examine the role that policy design plays in allowing countries to exploit international technological opportunities. However, given the heterogeneity of environmental policy regimes both across countries, and within countries across sectors and impacts (as well as through time), it is difficult to construct a general index of the "flexibility" of environmental policy regimes. Fortunately, in the period 2001 to 2003, the World Economic Forum's *Executive Opinion Survey* asked respondents a number of questions related to environmental policy design.

The survey is implemented by the WEF's partner institutes in over 100 countries, which include departments of economics in leading universities and research departments of business associations. The means of survey implementation varies by country and includes postal, telephone, Internet, and face-to-face survey. In most years there are responses from between 8 000 and 10 000 firms (see Sala-i-Martin *et al.*, 2008 for a description of the sampling strategy). Specifically, respondents (usually CEOs) were requested to indicate the extent to which they had the freedom to choose different options in order to achieve compliance with environmental regulations. Respondents were requested to assess the degree of flexibility on a Likert scale, with 1 = offer no options for achieving compliance, 7 = are flexible and offer many options for achieving compliance (HSTFLEX and SRCFLEX).

For a given level of flexibility, the stringency of environmental policy will determine the size of markets for innovation. So it may be necessary to control for differences in the stringency of environmental policy across countries and over time. For this purpose an index of perceived stringency of a country's overall environmental regulation is used (Sala-i-Martin *et al.*, 2008). The degree of stringency has been assessed on a Likert scale, with 1 = lax compared with that of most other countries, 7 = among the world's most stringent (HSTSTRNG and SRCSTRNG).

As found in more general studies of technology transfer, domestic absorptive capacity is an important factor. In practice, while the number of scientific personnel or expenditures on R&D in the relevant fields could be used as measures of domestic scientific capacity, the lack of data for many non-OECD countries (even at the macroeconomic level) prohibits the use of such a measure. Therefore, we use patent data to measure absorptive capacity of the recipient country. A count of patented inventions by domestic (*i.e.* recipient country's) inventors is included for this purpose (ABSCAP).

Technologies may only be transferred if they have been developed in the first place. To capture the stock of inventions in a given source country that are potentially available for transfer elsewhere, a variable (AWWSTOCK) is constructed that reflects the number of patent applications by domestic inventors filed in the current year or the three previous years. This time span is appropriate given the limitations on international patenting imposed by international patent treaties.[2] Thus the mode of the distribution of transfer lags is between 1 and 2 years, as expected. It must also be noted that, as in the case above,

the entire stock of inventions in PATSTAT is considered when constructing the variable, including inventions for which no claims for protection have been sought in countries other than that of the priority office. The sign of this variable is expected to be positive.

Finally, differences in the general propensity to transfer patents between countries and over time are captured through the use of a variable that reflects overall duplicate patent applications filed across the whole spectrum of technological areas (TOTALTT). This variable should capture all of the more general economic factors that are likely to influence transfer (common language, geographic distance, commercial relations, strength of intellectual property rights, etc.) but that are not specific to "environmental" innovation. The sign is expected to be positive. In other words, while TOTALTT controls for any factors that determine the *rate* of transfer, the remaining explanatory variables measure the role of factors that "bend" the *direction* of this transfer towards more environmental ends. Table 2.2 gives the basic descriptive statistics for the sample used in the model presented below.

Table 2.2. **Descriptive statistics for the panel dataset**

Variable	Observed	Mean	Standard deviation	Minimum	Maximum
$AWWTT_{ijt}$	21 822	0.57	8.27	0	498
$SRCFLEX_{it}$	21 822	3.94	0.62	1.7	5.4
$HSTFLEX_{jt}$	21 822	3.94	0.62	1.7	5.4
$SRCSTRNG_{it}$	21 822	4.12	1.31	1.2	6.7
$HSTSTRNG_{jt}$	21 822	4.12	1.31	1.2	6.7
$AWWSTOCK_{it}$	21 822	421.25	1 273.64	0	7 790
$ABSCAP_{jt}$	21 822	109.32	329.02	0	2 024
$TOTALTT_{ijt}$	21 822	42.74	768.19	0	49 584

The empirical model

Our aim is to analyse the relationship between the nature of policy regimes and technology transfer. To do so, we construct a gravity model that allows us to examine all potential bilateral relations between source and recipient countries. The hypothesis is that, other things being equal, more "flexible" environmental policy regimes are likely to generate innovations with broad potential acceptance in overseas markets. Figure 2.2 provides a scatter plot of the relationship between the index of the flexibility of environmental policy regimes and the log of "exports" (outflows) of environmental technologies (measured by duplicate patent applications), suggesting a positive relationship with the correlation coefficient = 0.45 (at < 0.001% significance level).

Moreover countries with more flexible policy regimes are more likely to be able to benefit from inventions developed elsewhere. As such, Figure 2.3 presents the same information but from the viewpoint of the recipient country. The relationship between the flexibility index and "imports" (inflows) of environmental technologies is positive, with the correlation coefficient = 0.26 (at < 0.001% significance level).

Based on the discussion above, the following model is specified:

$$AWWTT_{ijt} = f\,(SRCFLEX_{it},\ HSTFLEX_{jt},\ SRCSTRNG_{it},\ HSTSTRNG_{jt},\ AWWSTOCK_{it},\ ABSCAP_{jt},\ TOTALTT_{ijt},\ \gamma_i,\ \delta_j,\ \omega_t) + \varepsilon_{ijt}$$

where i represents the source country, j the recipient country,[3] and t = 1998, ..., 2006 indexes over time.[4]

Figure 2.2. **Relationship between the flexibility of environmental policy regimes and source country patent applications**

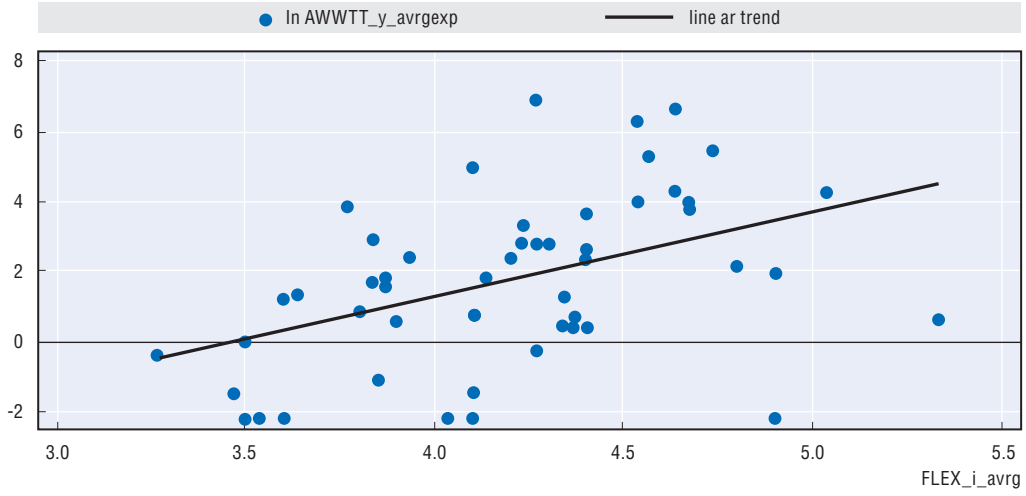
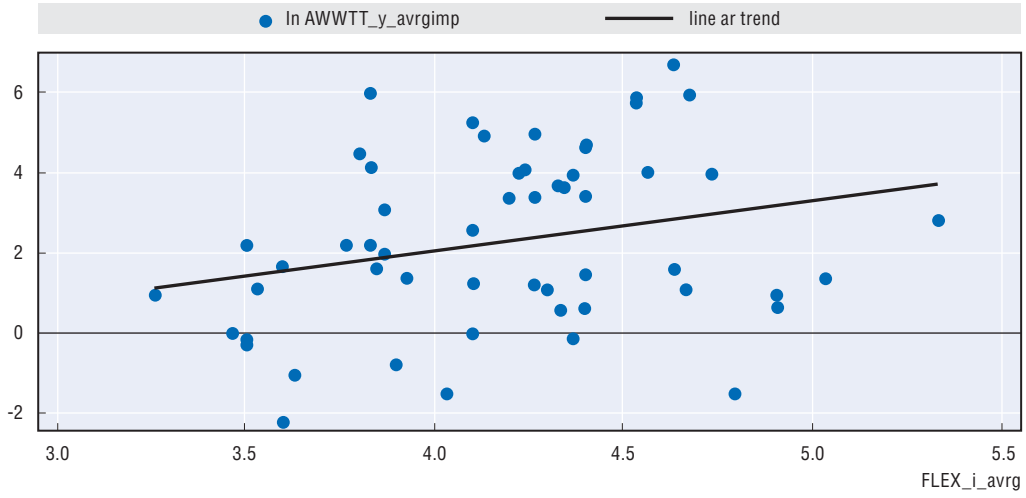


Figure 2.3. **Relationship between the flexibility of environmental policy regimes and patent applications in recipient country**



Our dependent variable is a measure of the number of patents in the source country *i* (the "priority" office) for which protection has also been sought in recipient country *j* (the "duplicate" office) in year *t* (the year of duplication). On the right-hand side of the equation, $SRCFLEX_{it}$ and $HSTFLEX_{jt}$ reflect the degree of flexibility of the source and recipient country's environmental policy regimes, respectively. It is expected that the sign of these variables is positive. Similarly $SRCSTRNG_{it}$ and $HSTSTRNG_{jt}$ reflect the degree of stringency of the source and recipient countries' environmental policy regimes.

$AWWSTOCK_{it}$ is the available stock of inventions in environment-related technologies measured as the sum of patent applications invented in the source country during the current and the previous three years. The sign is expected to be positive. $ABSCAP_{jt}$ is the total number of patent applications for environment-related technologies invented in the recipient country and the expected sign is positive, since increased absorptive capacity

should increase transfers. Last, $TOTALTT_{ijt}$ is the total number of patents that is transferred from the source country to the recipient country, and sign is expected to be positive. Fixed effects γ_i, δ_j, ω_t are included to control for any omitted time- and country-specific heterogeneity. All the residual variation is captured by the error term (ε_{ijt}). Given the count nature of the dependent variable, the equation is estimated as a negative binomial model using maximum likelihood (for further details on negative binomial models, see Cameron and Trivedi, 1998).

Results and discussion

Several alternative model specifications are estimated (Table 2.3). This includes models where the flexibility index varies over time, placing a constraint on the length of the panel, 2001-03 (Models 1 and 2). Alternatively, the mean value of the index is used instead allowing for a longer panel, 1998-2006 (Models 3 and 5). However, this is shorter when the stringency variables are included as the data is only available for the 2001-06 period (Models 4 and 6). Finally, in the last two models only observations with non-zero overall transfer were included (TOTALTT > 0). Thus, the sample size varies between 90 900 and 4 946 observations.

Table 2.3. **Estimated coefficients of the AWW technology transfer model**

Dependent variable: $AWWTT_{ijt}$	Using $FLEX_{jt}$ (time-variant)		Using $FLEX_{j_avg}$ (mean values of the flexibility index)			
	Full sample		Full sample		Sub-sample, if TOTALTT > 0	
	t = 2001-03		1998-2006	2001-06	1998-2006	2001-06
	(1)	(2)	(3)	(4)	(5)	(6)
$SRCFLEX_{it}$	1.5741***	0.4906**	2.2157***	0.6880***	1.2422***	0.5282*
	(0.1299)	(0.1630)	(0.1449)	(0.2009)	(0.1527)	(0.2153)
$HSTFLEX_{jt}$	1.2925***	0.9103***	1.5577***	1.2511***	0.6237***	0.8400***
	(0.1145)	(0.1575)	(0.1141)	(0.2359)	(0.1416)	(0.2504)
$SRCSTRNG_{it}$		0.7329***		0.7127***		0.3482***
		(0.1038)		(0.1070)		(0.0785)
$HSTSTRNG_{jt}$		0.2513**		0.2118		–0.0294
		(0.0894)		(0.1201)		(0.0876)
$AWWSTOCK_{it}$	3.51E-04***	3.13E-04***	4.06E-04***	3.65E-04***	2.27E-04***	2.00E-04***
	(4.56E-05)	(4.62E-05)	(4.45E-05)	(4.41E-05)	(4.03E-05)	(4.15E-05)
$ABSCAP_{jt}$	1.16E-03***	1.18E-03***	1.28E-03***	1.29E-03***	5.40E-04***	4.88E-04***
	(1.23E-04)	(1.26E-04)	(1.05E-04)	(1.10E-04)	(1.05E-04)	(1.08E-04)
$TOTALTT_{ijt}$	3.43E-03***	2.43E-03**	3.44E-03***	2.01E-03**	9.09E-04**	7.80E-04**
	(1.03E-03)	(8.31E-04)	(1.08E-03)	(7.43E-04)	(3.17E-04)	(2.78E-04)
Year fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
N of obs.	21 822	21 822	90 900	37 200	8 866	4 946
N of country-pairs	10 100	10 100	10 100	10 100	1 832	1 526
Log Pseudolikelohood	–5 644.45	–5 494.47	–15 452.13	–7 784.96	–11 683.28	–6 208.74
Wald chi2	1 453.27	1 422.79	2 377.15	1 713.34	764.86	565.94
(Prob > Chi2)	0.000	0.000	0.000	0.000	0.000	0.000

Robust standard errors adjusted for country-pair clusters are in parentheses: * p < 0.05, ** p < 0.01, *** p < 0.001.

The empirical results confirm all of our principal hypotheses. Starting with the control variables, the results suggest that the stock of inventions that are potentially available for transfer in the source country, as well as the absorptive capacity of the recipient country,

are both important determinants of transfers of "environmental" technologies. Moreover such transfer is positively (and significantly) correlated with the volume of technology transfer overall. These results hold for all the alternative models estimated.

When it comes to characterisation of the differences in policy regimes between the source and recipient countries, the results suggest that countries with more flexible policy measures are more likely to be able to "export" their inventions to markets abroad as well as benefit from inventions already developed elsewhere. The estimated coefficients are positive and statistically significant in all models estimated. Moreover controlling for differences in policy stringency (or not) does not affect the qualitative nature of this finding.

We note that the models reported here include year fixed effects. Convergence problems prevented us from including also country fixed effects. However, country-specific heterogeneity is already controlled for by a number of regressors in the model that vary across individual countries.

Table 2.4 presents the elasticities for the models estimated. Overall, the elasticity of transfer of environmental technologies with respect to the four policy variables is much higher than with respect to the other control variables. An interesting result is that, controlling for the effect of stringency (Models 2, 4, 6), the estimated elasticity of transfer with respect to policy flexibility is always higher for host-country than that for source-country. There is some evidence that the converse is true for policy stringency. These results indicate that while stringent and flexible policies are important in both source and recipient countries, on the margin there is a difference in their relative importance. Specifically, our results suggest that if increasing ITT in environmental technologies is the objective then it is relatively more important that stringent policies be implemented in countries that tend to generate innovations (source countries) rather than in countries that tend to rely on imports of such innovations (recipient countries). On the other hand, having flexible (technology-neutral) policies is relatively more important for technology importers than for technology producers.

Table 2.4. **Estimated elasticities**

	(1)	(2)	(3)	(4)	(5)	(6)
$SRCFLEX_{it}$	6.1963***	1.9312**	8.6296***	2.7290***	5.3670***	2.2809*
$HSTFLEX_{jt}$	5.0876***	3.5835***	6.0669***	4.9628***	2.6486***	3.5929***
$SRCSTRNG_{it}$		3.0232***		3.0316***		1.8258***
$HSTSTRNG_{jt}$		1.0366**		0.9011		–0.1476
$AWWSTOCK_{it}$	0.1478***	0.1318***	0.1445***	0.1707***	0.2948***	0.2933***
$ABSCAP_{jt}$	0.1272***	0.1292***	0.1223***	0.1600***	0.1742***	0.1901***
$TOTALTT_{ijt}$	0.1464***	0.1039**	0.0886***	0.0825**	0.2402**	0.2405**

Note: Conditional elasticities evaluated at sample means.

In summary, there appears to be a strong relationship between CEO's perception of the flexibility of environmental policy regimes in different countries and the spatial scope of diffusion of inventions that are patented in these countries. These results provide further support for the use of "flexible" instruments (including market-based instruments) in environmental policy.

Multilateral environmental agreements and technology transfer

While the characteristics of the domestic policy framework appear to have an influence on the propensity for technology transfer (Chapter 3), the international policy framework can also play a role. In particular, and has been noted above (Chapter 1), a number of multilateral environmental agreements encourage sharing of knowledge and technologies. In this section we use a sub-set of the technologies used in the previous section to assess the role of multilateral environmental agreements in encouraging the transfer of abatement equipment that reduces pollutants contributing to acid rain.[5]

Among the most notable effects of acid rain[6] are its negative impacts on surface waters, soil and forest cover. It arises from airborne emissions of sulphur dioxide (SO_2) and nitrogen oxides (NO_X). Acid rain has been a political issue for over three decades. Moreover, it has often resulted in international political tensions due to the trans-frontier pattern of its deposition. While considerable reductions of these emissions have been achieved in recent years (Annex 2.A1 provides data on emissions from OECD member countries), emissions remain considerable. Most OECD countries have policies in place with an objective to further reduce emissions. Indeed, a proposed tradable permit scheme in the European Union is under discussion (ENTEC-UK, 2010).

The countries that imposed the most binding regulations initially were concerned that acid rain diffused across international borders. Those countries that lay downwind from important sources, and the Scandinavians in particular, began to envision a multilateral approach. This soon led to the Convention on Long Range Transboundary Air Pollution (LRTAP), signed in 1979, and endorsed by the United Nations Economic Commission for Europe. Initially there were 32 signatories in 1979 including major emitters of SO_X and NO_X such as the United States, Germany and the United Kingdom. The Convention has now been signed by 51 countries.

A range of technologies have been introduced in an effort to reduce emissions. In this paper, we focus on a subset of such technologies, and are particularly interested in the transfer of the technologies between countries. For local pollutants the adoption of abatement innovations at the national level is primarily beneficial for the country itself. However, since SO_X and NO_X pollution can sometimes travel hundreds of kilometres, often originating from a foreign source, there are potential environmental benefits (and not just economic benefits) from the transfer of technologies between countries. This has lead to the consideration of how to encourage the diffusion of new abatement technologies abroad.

To this end, the signatories to the Protocols arising out of the LRTAP Convention have identified technology transfer as a particular objective to encourage cost-effective reductions in environmental damages. The aim of this paper is to assess empirically whether the Protocols have had an impact on such technology transfer. To do so, we estimate a model to empirically test the hypothesis that the Protocols have had a positive impact on technology transfers between the signatories.

Before proceeding to a discussion of the model estimated, we first discuss the characteristics of the acid rain problem, and how it can be addressed. Following this, we present the data used and the model estimated. Finally, we discuss the empirical results and the implications of the findings.

The environmental, technological and policy background

Emission sources, environmental impacts and abatement technologies

Acid rain designates both wet and dry depositions from the atmosphere and containing an unusual amount of nitric and sulphuric acids. These acids come from the mixing of compounds released by combustion reactions and precipitation: sulphur dioxide (SO_2), nitrogen oxides (NO_X) and volatile organic compounds (VOCs). While natural sources, such as volcanoes, are also sources of these compounds, the most important sources are anthropogenic emissions from the combustion of fossil fuels. For example, electricity-generating plants were responsible for as much as 70% of all SO_X and 20% of all NO_X emissions in 2007 in the United States. In Germany, these proportions were 43% of SO_X and 20% of NO_X emissions, and in Japan, 25% and 15% respectively (OECD Environmental Data Compendium). (See Annex 2.A1 for data on SO_X and NO_X emissions for other OECD countries.) Industrial combustion of fossil fuels and the transportation sector also contribute significant shares. Importantly, airborne emissions of these compounds are easily transported for hundreds of kilometres by wind.

In addition to acid rain formation, the most visible impacts of acid rain include the presence of an abnormally high amount of nitrogen and sulphur in lakes and rivers with detrimental effects on the fish populations and aquatic biodiversity in those freshwater sources more generally. Sulphuric and nitric acids fall with precipitation, acidifying rivers, lakes and other surface waters, decreasing the pH of these aquatic environments by 1 or 2 points (usually the pH of these waters is around 6 or 7; some particularly affected lakes, such as the Little Echo Pond in the US, has a pH of 4.2) (INRA, 2009; USEPA, 2010). Acid rain also has a detrimental effect on soils in forested areas. The acid depositions kill the fertile compounds of forest soils resulting in *Waldsterben* or forest death (Dupuy, 2003).

While acid rain does not directly harm human health, the precursor pollutants to acid rain (SO_X and NO_X compounds) do have important human health effects (*e.g.* respiratory diseases). Lastly, the deposition of these acidic compounds can corrode monuments, statues, buildings or even cars. In the automobile industry for instance, acid rain is characterised as "environmental fallout", in reference to the damage done to the paint and structure of cars by dry acid deposition (USEPA, 2010).

SO_X and NO_X are primarily emitted when fossil fuel is burned to produce energy. This occurs in electricity generating plants and in transportation when fossil fuels are combusted. So the key point in reducing emissions is to know how to control the combustion process, or how to increase its energy and environmental efficiency. Three approaches can be considered:

- Changing inputs at the pre-combustion process.
- Modifying the combustion itself (integrated approach).
- Approaching the problem after combustion (flue gas treatment).

Reducing emissions of sulphur and nitrogen particles can be achieved through the modification of the composition of the combustion input. First, the fuel can be changed for a cleaner one (for instance change from high-sulphur coal to low-sulphur coal). Second, the input can be cleaned (desulphurised). Another method is to reduce the emissions of the targeted compounds by modifying the combustion process itself. For instance, this can be achieved by using the waste heat of engines or gas turbines in power generation, by injecting lime stone (SO_X) or making the combustion occur in a fluidised bed of fuel or

other particles. In the case of NO_X, the use of low-NO_X burners and flue gas recirculation can be effective means as well. Lastly, the end-of-pipe approach involves reducing emissions after combustion takes place. Catalytic or non-catalytic purification or flue gas desulphurisation are among the most efficient tools available today.

This paper focuses on the post-combustion abatement technologies (see Annex B for a list of patent classes used in the analysis reported in this section). Since the late 1960s when awareness of the acid rain problem grew, the development of these various abatement technologies has been a response to domestic policy measures. But, as noted above, one particularity of the targeted compounds (SO_X and NO_X) is that they can be carried by the wind thousands of kilometres away from where they were emitted. Emissions not only have an impact on a local scale, they are a transboundary problem.

International co-operation and the Protocols

As noted above, in the late 1960s Scandinavian countries were the first to recognise the magnitude of damages from acid rain. Leading scientists hypothesised that the pollution was due not only to local emissions, but also transboundary pollutant compounds carried over from neighbouring countries. While the Scandinavian countries began to pursue significant abatement of emissions, the rest of Europe did not immediately recognise that they too were being affected by acid rain, and did not initially introduce regulations to reduce emissions.

However, this soon changed and the Convention on Long Range Transboundary Air Pollution (LRTAP) was signed in November 1979 and implemented through the United Nations Economic Commission for Europe (see *www.unece.org/env/lrtap*). It has since been signed by 51 countries (32 countries in 1979 including major emitters of SO_X and NO_X as the United States, Germany and the United Kingdom). The Convention was more an official acknowledgment from the signatories that ecological damage from air pollution was significant and that transboundary air compounds were partly responsible.

At the time of signature, there were no real constraints on the signatories, and as such the countries had no real disadvantage in signing the Convention. Most of the countries that ultimately became signatories had already developed domestic policies, but of varying stringency. Indeed, in the years immediately following, the Convention did not appear to induce different behaviour among the signatories (Levy, 1995). However, the Convention initiated a process through which further agreements became feasible, and above all it has become a stable international agreement on transboundary pollution.

This political will to try to address the acid rain problem on a multilateral scale has resulted in four Protocols from 1985 to the latest one in 1999.[7] While the Protocols have a common approach on emissions reduction, they were nevertheless slightly different from each other:

- 1985: *the Helsinki Protocol* calling for a 30 per cent reduction of SO_X emissions by 1993 based on 1980 emission levels.
- 1988: *the Sofia Protocol* calling for stabilisation of NO_X emissions by 1994 based on 1987 emissions level.
- 1994: *the Oslo Protocol* calling for differentiated reductions in SO_X by country by 2000 (with some countries adopting scheduled reductions for 2005 and 2010).

- 1999: *the Gothenburg Protocol* giving a precise table of reduction goals in SO_X and NO_X for each signatory to be achieved by 2010.

The first Protocol (Helsinki) followed the decision of the German government to join the Scandinavians on reducing SO_2 emissions in the 1982 Stockholm conference on Acidification of the Environment (Levy, 1995). It was a first cautious step, establishing the emissions reduction system that would be used in future. However, the common 30% reduction (base year: 1980) was not binding enough, with some countries even complying with the commitment at the time of signature (at least 8 out of the 19 countries who signed in Helsinki were already in compliance with their commitments). The Protocol could be considered an agreement on the minimum commitment that should be achieved in the following decade. According to Levy (1995) it is the "Least-Common-Denominator Protocol". The following Protocols gave rise to more concrete co-operation.

The Sofia Protocol which followed only affected NO_X. It bound the countries to freeze NO_X emissions at their level in 1987 by 1995. The exchange of technologies was mentioned in one article of the Protocol, the first time since the signing of the Convention in 1979. The Protocol was, therefore, not only concerned with setting mutually agreed emission reduction plans, but co-operation in the means of meeting these commitments was encouraged. In principle, signing the Protocols was intended to increase mitigation capacity in each country by encouraging technology transfers and information sharing.

The Oslo Protocol, which only concerned SO_X emissions, included clauses concerning the exchange of technology and information on the level of acidification, as well as documentation on the characteristics of control technologies. A major change relative to Helsinki was the differentiation of emissions commitments, and negotiations started on the percentage reductions to be achieved by 2000. Some countries added deadlines for 2005 and 2010. The Protocol's overall aim was to reduce the level of depositions in most of Europe by 60% (Wettestad, 2001).

The latest of the Protocols – Gothenburg (signed in 1999) – introduced a major modification because, in addition to SO_X and NO_X, it also targets emissions of volatile organic compounds (VOCs) and particulate matter (PM). In this sense, the Gothenburg Protocol is the fulfilment of the LRTAP Convention which targeted all transboundary compounds. It was also more ambitious with respect to reduction targets and more countries took part in the Protocol, with 31 signatories by May 2000. It also appended Guidance Documents on the characteristics and performance of different control options (*www.unece.org/env/documents/2005/1999/eb/eb.air.1999.2.e.pdf*). Since the targets have to be reached by 2010, it can be assumed that there will be a new Protocol with further commitments for the years to come.

In conclusion, the Protocols added to the LRTAP Convention are quite diverse, with somewhat different aims. The first Protocol tried to assemble the countries and make a minimal commitment that was not particularly binding. The second introduced a new pollutant (NO_X) and put the exchange of technology and knowledge at the fore. The latest ones have included further precisions such as available technologies, emissions from mobile sources, differentiated commitments by countries and still more pollutants (VOCs and PM).

At the same time, a significant international collaborative research project was instituted. It arose out of previous OECD work in the early 1970s and has been continued under the name of the European Monitoring and Evaluation Programme (EMEP), which was

created to provide high-quality scientific information on emissions and the diffusion of transboundary emissions covered by the LRTAP. This contributed to the understanding of which countries were the main emitters and how emissions travelled to other countries. It was the predecessor of the RAINS model (Regional Air Pollution INformation and Simulation) which was more accurate and had greater coverage (for more details on the RAINS model see *e.g.* Alcamo *et al.*, 1990).

Motivations to co-operate

This scientific work showed how important it was that some specific countries joined the agreement. As such, it is important to assess the possible motivations of the signatories. The difficulty here is that we only observe the outcomes of the choice of whether or not to sign an agreement, and not the process that drove the country to do so. Clearly, a given country will only join an international agreement if it brings net benefits. Several factors can influence the cost/benefit calculus, including the cost of compliance, demand for environmental quality, and geographic location (Beron *et al.*, 2003).

An individual country's decision to sign a Protocol will be affected by relative demand for environmental quality and the susceptibility of local ecological conditions to damage from acidification. (See Annex 2.A2 for a list of the signatories and their dates of signature.) The more vulnerable a country is to damage from acidification and the greater the demand for preservation of environmental quality, the greater the likelihood that the country will join an international agreement. In some countries, especially the UK and Germany, public awareness of the acid rain problem may have been influential in inducing the country to sign the Protocol (Levy, 1995).

Cost of compliance with the Protocol will also play a role. The cost of reducing SO_X and NO_X emissions arises through investment in abatement technologies, and with rising marginal abatement costs the country's ability to negotiate emission reduction commitments which are not excessively burdensome will affect whether they ultimately sign the Protocol. Any given commitment will be easier to meet with falling baseline emissions due to factors such as structural changes in the economy or fuel-switching in the electricity sector.

In one study (Mäler and de Zeeuw, 1998) it was found that a co-operative outcome was more likely if there are countries with high critical loads but low emissions who will reduce their emissions (but not by as much) and countries with low critical loads and high emissions who will have to reduce their emissions in any case. One can conclude that in this situation, it will be beneficial for all players to co-operate.

However, geographic location clearly plays a particularly important role. Local pollutants can be addressed efficiently with national policies, so an international agreement would only improve efficiency if two countries face the same type of pollution and want to share information or technology on how to address it. At the other pole are global pollutants such as ozone-depleting substances or CO_2 pollution. For this type of pollution, an international agreement is motivated by efficiency gains from addressing all sources of pollution, irrespective of location.

In the case of SO_X and NO_X, there is an asymmetry. As noted, the Scandinavians were the ones who pushed for the first Protocol. They were aware that reducing emissions on their own would not be sufficient to get emission levels below critical loads, which is the maximum level of acidification the environment is capable to absorb and eliminate itself

(Nilsson, 1986). Trans-frontier emissions from southern and continental Europe were sufficient to exceed critical loads on their own soil.

As such, the incentive for the Scandinavian countries to enter an international agreement was clear: to encourage "upwind" countries emitting pollutants to reduce emissions in order to reduce their downwind acidification levels. But what about the "upwind" countries, whose emissions do not exclusively fall within their borders, but diffuse to the neighbours? At first glance, they have no incentive to enter an international agreement which would commit them to reduce emissions, but bear the costs of doing so.

The best response is then to leave the agreement or to not sign it in the first place (Wagner, 2001). While free-riding would seem to be the best alternative for those countries that are situated upwind , in the end we witness a signature, suggesting that other factors play a role. From a game-theoretical framework, Mäler and de Zeeuw (1998) point out that a co-operative solution will occur if there are side payments, ensuring that countries jointly minimise their costs. Many such side payments may not be "visible" to the observer, or may manifest themselves in other "related" games. For instance, Wagner points out that mutual presence in other agreements can affect countries' decision to sign (Wagner, 2001).

However, other forms of "payment" may be reflected in the agreements themselves. For instance, if the environmental leaders are downwind, they may be able to influence compliance costs in other countries. The innovation undertaken by those downwind countries will result in a spillover that lowers the marginal abatement costs in upwind neighbours, with increased abatement yielding benefits in the downwind countries. We could make the assumption that these side payments are realised by the technology transfers that occur from downwind countries to upwind countries.

The Protocols and technology transfer

Each Protocol has added a new dimension to the issue of technology transfer and knowledge diffusion in the combat against acid rain. In Annex 2.A3 we summarise what each Protocol said on the issue of technology transfer and knowledge sharing, but an overview is provided here.

The first Protocol did not explicitly mention technology transfer. However, the Sofia Protocol included a technology transfer clause that has been in the Protocols ever since. The Oslo Protocol added a clause regarding the sharing of research and development efforts in abatement technologies. It stated that any innovation discovered in one of the signatory shall be transferred to the other signatories. While in principle this information diffusion clause is strong, the mechanics of implementation of the clause are not elaborated. More recently, the Gothenburg Protocol reiterated all the previous clauses.

According to the Protocols, the signatories shall co-operate in some projects, but also share information on abatement technologies and promote exchange of technology and information. For instance, the detailed Guidance Documents that are provided may result in important knowledge spillovers among signatories (*www.unece.org/env/documents/2005/1999/eb/eb.air.1999.2.e.pdf*). However while the Protocols clearly advocate the promotion of technology transfer as a means of reducing pollution, they do not evoke any incentive on how the promotion of these transfers should happen.[8] Moreover, all documentation is unrestricted, with benefits accrued to all countries, whether they are parties to the Protocol or not.

In order to test empirically whether technology transfer had an effect on motivations to sign the Protocols, we compared the ratio between transfers of SO_X abatement technologies and total technology transfers from a downwind country to an upwind country with the same ratio but from the upwind country to the downwind country (see Annex D for the list of classes used in the patent extraction). We expected that the first ratio would be higher than the second if the down-wind country transferred technology as an incentive to get the upwind country into an agreement of emissions reduction.

Table 2.5 summarises this ratio for various pairs of countries. The first row displays the ratio from the downwind country to the upwind country, and the second the inverse ratio. The figures represent "the percentage of the total transfers that occurred between the two countries that actually concerned SO_X/NO_X abatement technologies". Of the eight country-pairs, seven present a transfer ratio that is higher in the case of a downwind to an upwind transfer for SO_X-specific abatement technologies. In the case of NO_X-specific abatement technologies only four of eight do so.[9] The same is true for the third category of technologies designed for simultaneous SO_X and NO_X abatement.

Table 2.5. **Relative importance of transfers of SO_X/NO_X abatement technologies**

Assumed wind direction	Source of ITT	Recipient of ITT	SO_X (%)	NO_X (%)	Simultaneous SO_X and NO_X (%)
←	CA	US	0.0649	0.0295	0.0118
→	US	CA	0.0628	0.0409	0.0142
←	SE	GB	0.0561	0.0000	0.0000
→	GB	SE	0.0000	0.0000	0.0000
←	FI	GB	0.5544	0.0693	0.0693
→	GB	FI	0.0187	0.0374	0.0000
←	DE	GB	0.0916	0.0438	0.0319
→	GB	DE	0.0179	0.0339	0.0000
←	DK	GB	0.1911	0.1911	0.1911
→	GB	DK	0.0168	0.0251	0.0000
←	SE	DE	0.1421	0.0398	0.0114
→	DE	SE	0.1176	0.1372	0.0588
←	FI	DE	0.1252	0.0385	0.0096
→	DE	FI	0.1279	0.1279	0.0295
←	DK	DE	0.2484	0.1988	0.0497
→	DE	DK	0.2060	0.1797	0.0337

While this data is of interest, the primary purpose of this paper is not to determine the motivation of a given country to sign a given Protocol, but rather the more general question of whether the Protocols have lead to more technology transfer between the signatories and if these political agreements have a real impact on the number of technologies actually transferred from one country to another.

Presentation of the data and the model

Our measures of technology transfer in SO_X/NO_X abatement technologies cover the period from 1980 to 2008. For many pairs of countries and individual years there is no evidence of transfer whatsoever. However, in other cases the flows represent non-negligible proportions of total transfer. Tables 2.6 and 2.7. list the top ten country-pairs with the highest amount of patents transferred in SO_X and NO_X abatement technologies.

Table 2.6. **Major source and recipient countries in SO_X abatement technologies**

Number of duplicate patent applications, 1980-2008

Source country	Recipient country										Total
	US	JP	CA	DE	AU	ES	DK	AT	PL	KR	
US		148	191	117	105	51	22	43	36	28	**741**
DE	138	118	67		46	49	55	69	23	9	**574**
JP	153		36	102	12	42	57	11	36	41	**490**
FR	36	35	18	38	11	30	13	11	6	9	**207**
SE	20	30	16	25	32	9	19	12	16	1	**180**
FI	23	11	22	13	22	11	7	3	14	1	**127**
NL	7	10	9	13	9	9	9	12	5	1	**84**
GB	9	14	12	10	12	5	2	2	2		**68**
AT	11	7	5	17	4	2	4		3		**53**
DK	11	11	5	10	5	4		2	3	2	**53**
Total	**408**	**384**	**381**	**345**	**258**	**212**	**188**	**165**	**144**	**92**	**2 577**

Note: Source country = office of priority application, recipient country = office of duplicate application. Applications from/to regional or international patent offices are not included. The two-letter codes represent the following patent offices: Austria (AT), Australia (AU), Canada (CA), Germany (DE), Denmark (DK), Spain (ES), Finland (FI), France (FR), Great Britain (GB), Japan (JP), Korea (KR), the Netherlands (NL), Norway (NO), Poland (PL), Sweden (SE), the United States of America (US).
Source: EPO (2010), "Global Patent Data Coverage", January.

Table 2.7. **Major source and recipient countries in NO_X abatement technologies**

Number of duplicate patent applications, 1980-2008

Source country	Recipient country										Total
	US	JP	DE	CA	AU	AT	ES	KR	DK	NO	
DE	204	164		59	56	70	61	15	48	35	**712**
US		162	98	124	126	45	29	45	16	18	**663**
JP	191		115	39	15	20	8	40	11	9	**448**
FR	42	32	28	22	14	19	19	7	8	9	**200**
GB	27	24	19	7	18	13	9	5	3	3	**128**
SE	12	12	7	6	7	3	4	1	4	4	**60**
NL	11	6	7	5	8	6	5	2	3	5	**58**
FI	8	6	4	9	7	3	3	1		2	**43**
AT	9	3	8	4	1		1	1	3		**30**
DK	4	3	8	3	2	1	3	1		1	**26**
Total	**507**	**412**	**294**	**278**	**254**	**180**	**142**	**118**	**96**	**86**	**2 367**

Note: Source country = office of priority application, recipient country = office of duplicate application. Applications from/to regional or international patent offices are not included. The two-letter codes represent the following patent offices: Austria (AT), Australia (AU), Canada (CA), Germany (DE), Denmark (DK), Spain (ES), Finland (FI), France (FR), Great Britain (GB), Japan (JP), Korea (KR), the Netherlands (NL), Norway (NO), Poland (PL), Sweden (SE), the United States of America (US).
Source: EPO (2010), "Global Patent Data Coverage", January.

In order to assess in a preliminary manner whether joint signature of the Protocols affected the rate of transfer of abatement technologies a binary variable was created indicating whether a particular country had signed a Protocol by a given year. This can be compared with the rate of transfer for abatement technologies relative to all technologies. As can be seen in Table 2.8 the rate of transfer for both SO_X and NO_X abatement technologies is greater between signatories than between other pairs. Specifically, the ratio is higher when both countries are signatories (bottom-right cell of the tables) than when neither are signatories (top-left), and when one has signed but not the other.

Table 2.8. **Technology transfer and protocol signature**

% of total transfer – by country pair and year

		Recipient country	
		0	1
SO_X transfers			
Source country	0	0.0256	0.0168
	1	0.0349	0.0376
NO_X transfers			
Source country	0	0.0156	0.0082
	1	0.0252	0.0440

However, many factors are likely at play in determining the pattern and extent of transfer of abatement technologies. As such, we will now construct an econometric model and try to estimate the effect of the signature of the Protocols on transfers of abatement technologies.

It is important to control statistically for differences in the general propensity to transfer inventions between pairs of countries. In order to capture the effect of such factors (which are not specific to environmental technologies), we include the variable $TOTTALTT_{ijt}$ reflecting the total number of duplicate patent applications across the whole spectrum of technological fields, between 1980 and 2008, for all countries concerned by our study. To re-iterate, the $TOTALTT_{ijt}$ variable thus controls for the general *rate* of transfer, while the remaining explanatory variables capture the factors that may "bend" the *direction* of transfer towards more environmental ends. Similarly as our dependent variable, $TOTALTT_{ijt}$ varies across all three vectors (time, source, recipient).

Our primary variable of interest is a variable reflecting joint signature of the Protocols by source and recipient countries ($SIGN_SOX_{ijt}$ and $SIGN_NOX_{ijt}$). This varies across country pairs and years. It takes the value "1" if both source (*i*) and recipient (*j*) countries have signed the Protocol in question in year t, and "0" otherwise. For example the Helsinki joint dummy equals 1 if *i* and *j* are signatories of the Helsinki Protocol in year *t* ($1985 \leq t \leq 1993$). We aggregate the Protocols' joint dummies in order to get a measure that considers the series of Protocols as though they were a single agreement with different amendments. The SO_X joint dummy contains the signature's status for Helsinki, Oslo and Gothenburg; while the NO_X joint dummy concerns the Sofia and the Gothenburg Protocols.

We also introduce other variables that are likely to have an effect on the technology transfer in order to isolate the effect of joint Protocol signature between pairs of countries. On the basis of previous work (see *e.g.* Haščič and Johnstone, 2011) a number of factors have been identified that can have a significant influence on the amount of transfer.

Policy stringency is clearly an important determinant of demand for environmental technologies in the recipient country. As a measure of policy stringency we created a variable which is the count of all patents filed in the previous four years in the office of the country receiving the technology transfer ($ENVPOL_{jt}$). If a country introduces commitments on emissions for any pollutants, then the industries will need to implement abatement techniques and technologies. It creates a demand for the adoption of abatement technologies, whether invented at home or abroad.[10] We assume that a more stringent policy will be reflected in the number of patents filed in this particular office. We expect its estimated sign to be positive.

$SRCPAT_{it}$ is the count of all patent applications in which the source country in question is the office of the "priority" application. The variable is constructed as the sum of the counts for the years *t*, *t*–1, *t*–2 and *t*–3 to reflect the fact that patentees have as long as 30 months after the priority date in which they are able to seek protection in other countries.[11] This variable allows us to control for the stock of available abatement technologies that could potentially be transferred from the source country. We expect this variable to have a positive coefficient.

The final variable ($ABSCAP_{jt}$) serves as a measure of the capacity of the recipient country to adapt foreign and new technologies. This capacity is measured as the % of skilled occupations on total workforce in the main industries concerned by SO_X/NO_X emissions abatement (manufacturing and electricity, gas and water supply). The occupations we focus on are described in the major groups 0/1 and 7/9 in the classification ISCO-1968 ("professional, technical and related workers" and "production and related workers, transport equipment operators and labourers") and the major group 3 in the classification ISCO-88 ("technicians and associate professionals"). Our variable is constructed as the percentage of people occupying these types of jobs regarding the total of active population in those industries. The data has been obtained from the *LABORSTA Database* of the International Labour Organisation (ILO). The descriptive statistics for each variable that will be used in the model are presented in Table 2.9.

Table 2.9. **Descriptive statistics of the variables of interest**

Variable	Unit	Obs.	Mean	Std. dev.	Min.	Max.
Full sample						
SOXTT	Count	14 419	0.1526	0.8259	0	21
NOXTT	Count	14 419	0.1378	0.8456	0	26
SIGN_SOX	Dummy	14 419	0.2150	0.4108	0	1
SIGN_NOX	Dummy	14 419	0.2352	0.4242	0	1
SRCPAT_SOX	Count	14 419	31.6494	97.4865	0	716
SRCPAT_NOX	Count	14 419	28.8916	88.9112	0	703
ENVPOL_SOX	Count	14 419	72.0012	146.2377	0	789
ENVPOL_NOX	Count	14 419	62.1170	124.7657	0	765
ABSCAP	Share	14 419	0.4906	0.3264	0	0.9342
TOTALTT	Count	14 419	267.4171	1 475.7060	1	4 4634
Sub-sample						
SOXTT	Count	9 335	0.2290	1.0110	0	21
NOXTT	Count	9 335	0.2069	1.0386	0	26
SIGN_SOX	Dummy	9 335	0.2969	0.4569	0	1
SIGN_NOX	Dummy	9 335	0.3275	0.4693	0	1
SRCPAT_SOX	Count	9 335	35.3775	104.3533	0	716
SRCPAT_NOX	Count	9 335	32.5987	96.0765	0	703
ENVPOL_SOX	Count	9 335	78.4829	151.1499	0	789
ENVPOL_NOX	Count	9 335	66.0847	127.8879	0	765
ABSCAP	Share	9 335	0.4952	0.3184	0	0.9087
TOTALTT	Count	9 335	397.4488	1 817.5380	1	4 4634

Note: The full sample is a panel of 29 years (1980-2008), 87 source countries and 65 recipient countries. The sub-sample includes only the 34 OECD member countries.

The model

In this paper a similar methodology is used to that which was applied in Eaton and Kortum (1996) for all technology fields. The following equations are specified for the purpose of our discussion above:

$$SOXTT_{ijt} = f(SIGN_SOX_{ijt}, SRCPAT_SOX_{it}, ENVPOL_SOX_{jt}, ABSCAP_{jt}, TOTALTT_{ijt}, \gamma_i, \delta_j, \omega_t) + \varepsilon_{ijt},$$

and

$$NOXTT_{ijt} = f(SIGN_NOX_{ijt}, SRCPAT_NOX_{it}, ENVPOL_NOX_{jt}, ABSCAP_{jt}, TOTALTT_{ijt}, \gamma_i, \delta_j, \omega_t) + \varepsilon_{ijt}$$

where *i* represents the source country, *j* the recipient (host) country, and *t* the year considered (1980-2008). The variables are those we just described and γ_i, δ_j, ω_t are the fixed effects to account for any omitted time- and country-specific (respectively host and source country) heterogeneity. ε_{ijt} captures the residual variation as an error term.

The dependent variable $SOXTT_{ijt}$ is the count of patent applications associated with a specified technology that are "transferred" from country *i* (priority office) to country *j* (duplicate office). So it is a count variable which can be estimated after transformations by the least squares. However, given the count structure of the data the estimates would be biased, and the coefficients difficult to interpret. Moreover, we also have a high proportion of zero outcomes.

One possible solution would be to estimate using the Poisson model, but the use of Poisson is dependent upon the strong assumption of equality between the mean and the variance (equidispersion), which is inappropriate when there is over-dispersion in the data. So in order to take into account such variability we will rather use a negative binomial model. The negative binomial model is attractive because it allows relaxing the strong equidispersion assumption.

The regression coefficients are estimated with a maximum likelihood method.[12] In the estimation sample we only include observations for which the pair of countries experienced a positive technology transfer in any technological field in that specific year, *i.e.* we restrict the estimation sample to cases when total transfer is non-zero (TOTALTT > 0). The reason for this is that, as explained above, we are interested in whether environmental policy characteristics bend the "direction" of transfer towards more environment-related technologies. This gives us a maximum sample size of 14 419 observations.

Results and discussion

First, we use the SO_X abatement technology transfer variable as a dependent variable, then we estimate with the NO_X abatement technology as the dependent variable. For each case the models are estimated with fixed effects absent (Model 1) and with both year and host country fixed effects included (Model 2). Including also the source country fixed effects poses significance problems for the signature dummy variable, which was predictable.

The estimation results for the SO_X model are displayed in Table 2.10. In both variants of the model, the estimation shows, as expected, that the explanatory variables which reflect general propensity to transfer technologies (TOTALTT), the potential supply of innovations (SRCPAT), the stringency of host country policy (ENVPOL), and the host country

Table 2.10. **Estimated coefficients of the SO_X model**

Dependent variable: $SOXTT_{ijt}$	Full sample		OECD countries	
	(1)	(2)	(3)	(4)
Protocols – joint signatories ($SIGN_{ijt}$)	1.0472***	1.1303***	0.7262***	0.8094***
	(0.1494)	(0.1349)	(0.1513)	(0.1415)
Level of innovation in source country ($SRCPAT_{it}$)	0.0047***	0.0052***	0.0044***	0.0046***
	(0.0005)	(0.0005)	(0.0005)	(0.0005)
Patenting in recipient country ($ENVPOL_{jt}$)	0.0018***	0.0032***	0.0016***	0.0034***
	(0.0004)	(0.0009)	(0.0004)	(0.0009)
Skilled workforce in recipient country ($ABSCAP_{jt}$)	2.4770***	0.5973	2.4529***	0.5156
	(0.2022)	(0.3645)	(0.2162)	(0.3681)
Overall technology transfer ($TOTALTT_{ijt}$)	6.14E-04***	4.51E-04***	4.66E-04***	3.69E-04***
	(1.57E-04)	(1.03E-04)	(1.02E-04)	(7.97E-05)
Intercept	–4.8448***	–8.6418***	–4.3253***	–3.2464***
	(0.1880)	(0.6203)	(0.2029)	(0.4802)
Dispersion parameter (alpha)	4.2693***	2.8765***	3.2954***	2.3567***
	(0.6791)	(0.5325)	(0.5352)	(0.4435)
Year fixed effects	–	Yes	–	Yes
Recipient country fixed effects	–	Yes	–	Yes
N of obs.	1 4419	1 4419	9 335	9 335
N of country-pairs	2 238	2 238	960	960
Log Pseudolikelihood	–4 113.88	–3 848.99	–3 691.26	–3 487.11
Wald chi2	293.79	17 999.49	250.53	4 636.34
(Prob > Chi2)	0.000	0.000	0.000	0.000

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Robust standard errors adjusted for country-pair clusters are in parentheses.

absorptive capacity (ABSCAP) have a positive and statistically significant effect on the number of environmental technologies transferred. The exception is our measure of absorptive capacity when both year and recipient-country fixed effects are included. This may be a consequence of the relative "inertia" of this variable through time for a given recipient country.

Our primary interest focuses on the joint signature dummy (SIGN_SOX). In all models, the estimated coefficient has a positive sign and is statistically highly significant. This suggests that when both source and recipient countries are signatories to the Protocols, the number of inventions that are transferred increases, holding all other effects fixed. For the sub-sample of OECD countries, the estimated impacts are lower, although still positive and significant. The reason may be that the impact of joint signature is greater for countries with less intensive economic ties, lower absorptive capacity, or lower stringency of their environmental policy. The relative magnitudes of these effects are compared and discussed below. For the moment, we conclude that the Protocols have a positive and statistically highly significant effect on technology transfer, which validates our main hypothesis.

In the case of the NO_X model (Table 2.11), the estimated coefficients are always positive and significant, with the exception of the measure of absorptive capacity which is insignificant when fixed effects are included (Models 6 and 8). The reasoning discussed above may apply here as well. The effect of domestic environmental policy stringency is not as strong as was the case in the SO_X models. Conversely, the absorptive capacity has a much greater effect in the model without fixed effects.

Table 2.11. **Estimated coefficients of the NO_X model**

Dependent variable: $NOXTT_{ijt}$	Full sample		OECD countries	
	(5)	(6)	(7)	(8)
Protocols – joint signatories ($SIGN_{ijt}$)	1.2093***	1.7901***	0.9876***	1.5680***
	(0.1274)	(0.1764)	(0.1310)	(0.1971)
Level of innovation in source country ($SRCPAT_{it}$)	0.0053***	0.0070***	0.0051***	0.0065***
	(0.0006)	(0.0006)	(0.0006)	(0.0007)
Patenting in recipient country ($ENVPOL_{jt}$)	0.0013**	0.0015*	0.0014**	0.0014*
	(0.0005)	(0.0007)	(0.0005)	(0.0007)
Skilled workforce in recipient country ($ABSCAP_{jt}$)	1.1820***	0.0643	1.2898***	0.0626
	(0.1813)	(0.3308)	(0.1958)	(0.3322)
Overall technology transfer ($TOTALTT_{ijt}$)	7.22E-04***	4.76E-04***	5.79E-04***	3.98E-04***
	(1.70E-04)	(1.18E-04)	(1.33E-04)	(9.87E-05)
Intercept	–4.4648***	–3.9653***	–4.0946***	–3.6753***
	(0.1567)	(1.2041)	(0.1764)	(0.4656)
Dispersion parameter (alpha)	4.6357***	2.9122***	3.8401***	2.4793***
	(0.7482)	(0.4638)	(0.6208)	(0.4069)
Year fixed effects	–	Yes	–	Yes
Recipient country fixed effects	–	Yes	–	Yes
N of obs.	1 4419	1 4419	9 335	9 335
N of country-pairs	2 238	2 238	960	960
Log Pseudolikelohood	–3511.82	–3 250.72	–3173	–2 963.53
Wald chi2	305.29	9 655	228.04	6 916.8
(Prob > Chi2)	0.000	0.000	0.000	0.000

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Robust standard errors adjusted for country-pair clusters are in parentheses.

The coefficient on the signature dummy (SIGN_NOX) is much higher than is the case with the SO_X models. Similarly as above, the corresponding estimates for the OECD sample are lower than for the full sample. The relatively greater importance of the Protocols in the case of NO_X might be explained by the fact that Sofia and Gothenburg emphasised transfer to a greater extent.

The explanatory variables used in our models include a dummy, a share, and nonnegative counts. As such it is difficult to compare the relative magnitudes of the estimated coefficients and interpret them in a meaningful manner. To do so, we conducted an in-sample simulation exercise and compare the impacts of three variables that are of primary interest – the Protocols, domestic absorptive capacity, and environmental policy demand. Specifically, we construct a scenario in which all countries (or rather, country-pairs) would become joint signatories to the Protocols. We express the "benefit" of such a policy scenario in terms of the change in the predicted values of technology transfer (TT) under the scenario compared to a baseline (observed sample values). Then we ask what changes in the other variables of interest would be necessary to obtain an equivalent outcome in terms of an increase in TT. Table 2.12 summarises the results.

Results for model 1 suggest that increasing the proportion of joint signatories from the observed 22% to 100% (an increase by 78 percentage points) is equivalent to an increase in these countries' ABSCAP by 59 percentage points.[13] A corresponding result for the sub-sample of OECD countries (Model 3) is an increase by 35 percentage points – a lower value being expected given the coefficient estimates presented above. At first, these results would seem to indicate that changes in recipient countries' ABSCAP are relatively more important than accession to the Protocols. However, results from Models 2 and 4 suggest

Table 2.12. **Importance of selected regressors in their effect on predicted technology transfer**

Policy scenario: All country-pairs become joint signatories

	SO_X models				NO_X models			
	Full sample		OECD countries		Full sample		OECD countries	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SIGN (in % points)								
Observed (%)	22	22	30	30	24	24	33	33
New joint signatories (%)	78	78	70	70	76	76	67	67
	(1.9 σ)	(1.9 σ)	(1.5 σ)	(1.5 σ)	(1.8 σ)	(1.8 σ)	(1.4 σ)	(1.4 σ)
Equivalent change in ABSCAP (in % points)[1]								
All country-pairs (%)	49	> 100	24	> 100	> 100	> 100	> 100	> 100
	(1.5 σ)	(> 3.1 σ)	(0.7 σ)	(> 3.1 σ)	(> 3.1 σ)	(> 3.1 σ)	(> 3.1 σ)	(> 3.1 σ)
New joint signatories (%)	59	> 100	35	> 100	> 100	> 100	> 100	> 100
	(1.8 σ)	(> 3.1 σ)	(1.1 σ)	(> 3.1 σ)	(> 3.1 σ)	(> 3.1 σ)	(> 3.1 σ)	(> 3.1 σ)
Equivalent change in ENVPOL (number of patents)[2]								
All country-pairs (%)	508	304	346	188	> 765	> 765	552	> 765
	(3.5 σ)	(2.1 σ)	(2.3 σ)	(1.2 σ)	(> 6.1 σ)	(> 6.1 σ)	(4.3 σ)	(> 6.1 σ)
New joint signatories (%)	595	354	452	242	> 765	> 765	727	> 765
	(4.1 σ)	(2.4 σ)	(3.0 σ)	(1.6 σ)	(> 6.1 σ)	(> 6.1 σ)	(5.7 σ)	(> 6.1 σ)

Note: Changes expressed with respect to a baseline which was calculated using observed sample values. Values expressed as multiples of the sample standard deviation (σ) are in parentheses.

1. % point increase bounded to 100.
2. Increase bounded to sample maximum.

that even an increase to 100% would not suffice to achieve equivalence with Protocols. As such this result runs counter the previous one, although the ABSCAP estimate in Models 2 and 4 is insignificant.

How does this compare with environmental policy demand (ENVPOL)? For Model 1, an increase by 595 patented SO_X-related inventions (about 4.1 standard deviations) would be necessary in order to achieve an increase in SO_X technology transfer equivalent to Protocol accession. This is a much greater increase than the one in ABSCAP (1.8 standard deviations) or in joint signatories (1.9 standard deviations), indicating that acceding to the Protocols may be a good alternative for countries where improvements in domestic environmental policies are not forthcoming. As one would expect, such improvements are more likely to occur within the sample of OECD countries – and this is confirmed by our results – the increase in terms of standard deviations is about identical between ENVPOL and SIGN (1.6 and 1.5 respectively, Model 4).

Results for the NO_X models are less revealing, as most of the predicted effects would require a change that is greater that the sample (or theoretical) maximum. In summary, to obtain an effect that is equivalent to the scenario change in joint signature (1.4-1.8 standard deviations), out-of-sample values of ABSCAP and ENVPOL would be required This indicates that Protocol accession was a meaningful strategy to encourage transfer of NO_X abatement technologies.

In summary, whether it concerns SO_X or NO_X, we can say that for a given country-pair a joint signature increases the probability that there will be transfer of abatement technologies between these particular countries, when all other factors are held constant.

Conclusions

Technology transfer is key to realising environmental objectives at least cost. Moreover, the benefits of such transfer are greatest when impacts are trans-frontier in nature. The propensity for international diffusion of environmental technologies is a function of both domestic policy frameworks and international environmental co-operation. Drawing on a rich database of patent applications, we presented results on the effects of environmental policy design and multilateral environmental agreements on the international transfer of environmental technologies.

More specifically, on the one hand we have argued that "differentiated" and "prescriptive" technology-based regulations can result in fragmented technology markets, with the potential market for the innovations induced split across different policy jurisdictions. International policy co-ordination would reduce the potential for such fragmentation. For global public goods (*e.g.* mitigation of climate change) such co-ordination is evident. The European Union's Emissions Trading Scheme is the most significant example. However, even for greenhouse gas emissions within Europe, this is the exception and not the rule. For many sources there a myriad of differentiated and prescriptive policy measures.

The problem is, of course, more important in the case of local and regional pollutants. Indeed the imposition of uniform standards across countries with different ecological and economic conditions would not likely improve welfare. However, this does not mean that the benefits associated with globalised markets for innovation cannot be realised. "Flexibility" of policy regimes (rather than relative stringency) ensures that markets are not fragmented. Given the risks associated with expenditures on research and development, and the economies of scale required to recover such expenditures, it is important that regulatory regimes not constrain the potential markets for any induced innovations.

This flexibility is primarily a consequence of the point of incidence of different policy measures. Any policy that focuses on the environmental "bad", rather than mandating a certain means of reducing its impact, will provide potential innovators with the flexibility to identify the optimal means of its mitigation. This can include performance standards as well as market-based instruments such as environmentally related taxes and tradable permits. The key is that the policy measure be "technology neutral" in the sense that innovators have the choice of technology to use to meet a given environmental objective (*e.g.* SO_2 emission levels, wastewater effluent quality).

From our results there appears to be a strong relationship between CEO's perception of the flexibility of environmental policy regimes in different countries and the spatial scope of diffusion of inventions that are first patented in these countries. These results provide further support for the use of "flexible" instruments (including well-designed market-based instruments and performance standards) in environmental policy. And while the focus of this chapter was on the specific case of environmental policy, the discussion is equally applicable to aspects of product and labour market regulation that have implications for technological innovation, such as product and workplace safety.

On the other hand, we examined the role of international co-operation in encouraging the transfer of abatement technologies which mitigate acid rain. Indeed, the trans-frontier nature of SO_X and NO_X emissions make an international agreement essential to try to avoid over-acidification of environments at reasonable cost. We have noted that there are some factors which determine the likelihood that such co-operation will take place: the

presence of leaders, the number or participants in the Protocols, etc. Moreover, we have seen that a specific type of game takes place for the acid rain issue. Because of natural and geographic conditions, in particular location of a country regarding the direction of wind, taking part in an international agreement can be costly relative to free riding. In such a case, the agreement will be unstable because all countries will not join.

We hypothesised that transfer of technology between signatories can be a way of encouraging adherence, providing an inducement for upwind countries to participate. Some empirical results provide descriptive evidence of the plausibility of such an assumption, but more formal analysis might be addressed in future work. In particular, we believe that a similar econometric model to ours, which directly reflects ecological conditions (wind direction), can help in testing this hypothesis. Moreover it would be interesting to broaden the spectrum of technologies considered. We only focus on post-combustion abatement technologies, which are however, the most commonly used.

However, the primary focus of this paper has been an assessment of whether the Protocols arising out of the LRTAP have encouraged the transfer of technologies between signatories. Indeed the major finding of this paper is that there is an effect on technology transfer for a country which joins the Protocols. We studied both SO_X and NO_X abatement technology transfer between countries which are joint signatories of the LRTAP Protocols and those who are not. In both cases, there is a positive effect on transfer between those pairs of countries who are joint signatories.

We can assume therefore that inducements related to technology transfer can play a positive role in encouraging the stability of international environmental agreements. However, it is revealing that the text of the Protocols says very little about the mechanics of such transfer, and the specific role that the Protocols can play in encouraging it. The simple sharing of information on available abatement technologies – *i.e.* through regular conferences and documentation – may be the factor which lies behind these results. Moreover, sharing of information on the choice and design of particular policies to encourage abatement may play a role as well.

However, it is possible that financial incentives could be provided. For instance, innovating countries that lie downwind from important sources could provide preferential access to protected inventions as an inducement for upwind sources. This would encourage the upwind countries to sign the Protocols and commit to emissions reductions. However, the owners of the IPRs in the downwind countries would likely demand compensation.

In general, it is heartening to find that international environmental agreements have encouraged the transfer of technologies that are essential to reduce pollution and to bring about environmental improvements. This is likely to become more important in future years. In particular, emerging economies, such as India and China which have fast-growing industries in the most polluting sectors are significant emitters of SO_X and NO_X. In some cases wind patterns plays an important role in diffusing emissions across border (China, Korea and Japan for example), and the need to induce increased abatement through technology transfer is particularly pressing in such cases.

Notes

1. Standardisation is, of course, important in the presence of network externalities (see Shy, 2001). However, this is of limited relevance to environmental concerns.
2. Lags associated with filing duplicate applications are, in part, determined by the Paris Convention (1883), stipulating that applications abroad must be filed within one year of the date when the initial application was filed (referred to as "priority date"). If the inventor does file abroad within one year, the inventor will have priority over any similar patent applications received in those countries since the priority date. In addition, under the Patent Co-operation Treaty (1970), the applicant may file an international application that allows further 18 months to make any duplicate filings in signatory countries.
3. There are 101 source and recipient countries in the sample. This includes the 34 OECD member countries as well as Brazil, Russia, India, Indonesia, China, South Africa and others.
4. That is, three years after and three years prior to the availability of data on the flexibility index.
5. A previous study (Dekker *et al*., 2009) has used difference in the factors which encourage applications of different types of patents (claimed priorities and duplicates) to assess the role of the Protocols in encouraging both the development and international diffusion of abatement technologies. The work reported on in this section focuses only on the latter issue, using a somewhat different methodology.
6. "Acid rain" designates either dry or wet acid deposition, with elevated levels of hydrogen ions (equivalent to low *pH*).
7. According to the preamble to the Protocols each country is "aware of the fact that the predominant sources of air pollution contributing to the acidification of the environment are the combustion of fossil fuels for energy production, and the main technological processes in various industrial sectors, as well as transport, which lead to emissions of sulphur dioxide, nitrogen oxides, and other pollutants" and considered "that high priority should be given to reducing sulphur emissions, which will have positive results environmentally, on the overall economic situation and on human health".
8. While there is indeed no explicit discussion of the possible mechanism of encouraging such transfers, the Protocols also include documents providing information on the policy options available. This includes a review of the various approaches governments may adopt in regulating SO_X/NO_X emissions. For some countries, this type of information sharing could thus serve as another channel for creating demand for transfer of abatement technologies.
9. This may be because post-combustion technologies are generally more suitable for SO_X abatement. Beyond certain abatement levels, integrated approaches may be needed to achieve further NO_X reductions.
10. As such, the count includes claimed priorities, singulars and duplicates.
11. A maximum of 12 months under the Paris Convention (1883) and additional 18 months under the Patent Co-operation Treaty (1970).
12. We used STATA's procedure nbreg to fit the models and the option technique (dfp) in order to use the Davidon-Fletcher-Powell iteration method. This allowed us to introduce fixed effects, which was not possible using the default Newton-Raphson technique.
13. For example, increasing the share of skilled workforce from 0 to 0.59, or from 0.20 to 0.79. The increase in the share is bounded at 1.

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ANNEX 2.A1

Emissions of SO_X and NO_X in OECD Countries

	SO_X emissions in 2007 (1 000 tonnes)	Change on 1990 (%)	NO_X emissions in 2007 (1 000 tonnes)	Change on 1990 (%)
Canada	1 905	–39	2 275	–5
United States	11 635	–44	15 317	–33
Japan	780	–23	1 943	–5
Australia	2 490	56	1 762	41
New Zealand	73	36	158	47
Austria	26	–66	219	14
Belgium	126	–66	259	–31
Czech Republic	217	–88	285	–62
Denmark	23	–87	167	–39
Finland	82	–67	183	–38
France	435	–67	1 344	–31
Germany	494	–91	1 294	–55
Greece	543	15	374	26
Hungary	84	–92	190	–20
Iceland	11.3	56	25.6	–6
Ireland	54	–70	117	–6
Italy	339	–81	1 147	–43
Luxembourg	1.3[1]	–93	13.7	–41
Netherlands	59	–69	280	–48
Norway	20	–62	193	–7
Poland	1 131	–65	885	–44
Portugal	185	–42	255	0
Slovak Republic	71	–87	83	–61
Spain	1 156	–47	1 499	20
Sweden	34	–68	167	–45
Switzerland	14	–67	80	–50
Turkey	1 612	6	1 200	85
United Kingdom	590	–84	1 481	–46

Note: Total emissions, including mobile and stationary sources.
1. Refers to 2006.
Source: OECD Environmental Data Compendium.

ANNEX 2.A2

Signatories of the LRTAP Convention and Selected Protocols

		LRTAP	Helsinki		Sofia		Oslo		Gothenburg	
		Ratif	Sign	Ratif	Sign	Ratif	Sign	Ratif	Sign	Ratif
Albania	AL	2005		×		×				
Armenia	AM	1997							×	
Austria	AT	1979	×	×	×	×	×	×	×	
Azerbaijan	AZ	2002								
Belarus	BY	1979	×	×	×	×	×	×		
Belgium	BE	1979	×	×	×	×	×	×	×	×
Bosnia and Herzegovina	BA	1992								
Bulgaria	BG	1979	×	×	×	×	×	×	×	×
Canada	CA	1979	×	×	×	×	×	×	×	
Croatia	HR	1992				×	×	×	×	×
Cyprus[1, 2]	CY	1991				×		×		×
Czech Republic	CZ	1993		×		×	×	×	×	×
Denmark	DK	1979	×	×	×	×	×	×	×	×
Estonia	EE	2000		×		×				
Finland	FI	1979	×	×	×	×	×	×	×	×
France	FR	1979	×	×	×	×	×	×	×	×
Georgia	GE	1999								
Germany	DE	1979	×	×	×	×	×	×	×	×
Greece	GR	1979			×	×	×	×	×	
Hungary	HU	1979	×	×	×	×	×	×	×	×
Iceland	IS	1979								
Ireland	IE	1979	×	×	×	×	×	×	×	
Italy	IT	1979			×	×	×	×	×	
Kazakhstan	KZ	2001								
Kyrgyzstan	KG	2000								
Latvia	LV	1994							×	×
Liechtenstein	LI	1979	×	×	×	×	×	×	×	
Lithuania	LT	1994		×		×		×		×
Luxembourg	LU	1979	×	×	×	×	×		×	×
Malta	MT	1997								
Monaco	MC	1999						×		
Montenegro	ME	2006								
Netherlands	NL	1979	×	×			×	×	×	×
Norway	NO	1979	×	×	×	×	×	×	×	×
Poland	PL	1979			×		×		×	
Portugal	PT	1979							×	×
Moldova	MD	1995							×	

		LRTAP	Helsinki		Sofia		Oslo		Gothenburg	
		Ratif	Sign	Ratif	Sign	Ratif	Sign	Ratif	Sign	Ratif
Romania	RO	1979							×	×
Russian Federation	RU	1979	×	×	×	×	×			
San Marino	SM	1979								
Serbia	RS	2001								
Slovak Republic	SK	1993	×	×		×	×	×	×	×
Slovenia	SI	1992				×	×	×	×	×
Spain	ES	1979			×	×	×	×	×	×
Sweden	SE	1979	×	×	×	×	×	×	×	×
Switzerland	CH	1979	×	×	×	×	×	×	×	×
The FYR of Macedonia	MK	1997		×	×	×		×		
Turkey	TR	1979								
Ukraine	UA	1979	×	×	×	×	×		×	×
United Kingdom	GB	1979			×	×	×	×	×	×
United States	US	1979			×	×			×	×

Note: Assistance of Andreas Ferrara in compiling the Protocol data is gratefully acknowledged.

1. 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 recognises 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".
2. 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.

ANNEX 2.A3

Excerpts from the Protocols Related to Technology Transfer

Helsinki (1985)	The Parties shall reduce their annual sulphur emissions or their transboundary fluxes by at least 30 per cent as soon as possible and at the latest by 1993, using 1980 levels as the basis for calculation of reductions.
Sofia (1988)	The Parties shall, as soon as possible, and as a first step, take effective measures to control and/or reduce their annual emissions of nitrogen oxides or their transboundary fluxes. The Parties shall, as a second step, commence negotiations on further steps to reduce annual emissions […] to this end, the Parties shall co-operate. The Parties shall,…,facilitate the exchange of technology to reduce emissions of nitrogen oxide, particularly through the promotion of: *a)* commercial exchange of available technology; *b)* direct industrial contacts and co-operation, including joint ventures; *c)* exchange of information and experience; and *d)* provision of technical assistance. The Parties shall create favorable conditions by facilitating contacts and co-operation among appropriate organisations.
Oslo (1994)	The Parties shall control and reduce their sulphur emissions in order to protect human health and environment from adverse effects,… and to ensure that depositions… do not exceed critical loads for sulphur given in Annex 1. The Parties shall make use of the most effective measures which includes measures to apply best available control technologies not entailing excessive costs. The Parties shall facilitate the exchange of technologies and techniques, to reduce sulphur emissions, particularly through the promotion of: *a)* commercial exchange of available technology; *b)* direct industrial contacts and co-operation, including joint ventures; *c)* exchange of information and experience; and *d)* provision of technical assistance. The Parties shall create favorable conditions by facilitating contacts and co-operation among appropriate organisations. An Implementation committee is (…) established to review the implementation of the Protocol. The Parties may call for action to bring about full compliance with the present Protocol, including measures to assist a Party's compliance,… and to further the objectives of the Protocol.

Gothenburg (1999)	The objective of the present Protocol is to control and reduce emissions,… and to ensure as far as possible, that in the long term and in a stepwise approach,… atmospheric depositions or concentrations do not exceed… Each Party shall,… create favorable conditions to facilitate the exchange of information, technologies and techniques, with the aim of reducing emissions of sulphur, nitrogen oxides, ammonia and volatile organic compounds by promoting *inter alia*: *a)* the development and updating of databases on best available techniques, including those that increase energy efficiency, low-emissions-burners and good environmental practice in agriculture; *b)* the exchange of information and experience in the development of less polluting transport; *c)* direct industrial contracts and co-operation, including joint ventures; and *d)* the provision of technical assistance. Each Party shall create favorable conditions for the facilitation of contacts and co-operation among appropriate organisations. The Parties shall encourage research, development, monitoring and co-operation related to : the improving of monitoring techniques and systems,… emission abatement technologies, and technologies and techniques to improve energy efficiency, energy conservation and the use of renewable energy.

Source: LRTAP Protocols (*www.unece.org/env/lrtap/status/lrtap_s.htm*).

Chapter 3

Innovation in Electric and Hybrid Vehicle Technologies: The Role of Prices, Standards and R&D

by
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Policy instruments are often introduced in combination, sometimes with different but related environmental objectives. In this chapter, the relative importance of fleet-level fuel-efficiency standards, after-tax fuel prices, and public support for R&D is examined using data on patenting activity in alternative-fuelled vehicles. It is found that relatively minor changes in a performance standard or automotive fuel prices would yield effects that are equivalent to a much greater proportional increase in public R&D budgets. However, there are significant differences between types of technologies – electric and hybrid vehicles. Our results suggest that appropriate sequencing of policy measures is important.

* The assistance of Guillaume Lafortune (Paris School of International Affairs) in the preparation of the graphs is gratefully acknowledged.

Introduction

Faced with continuing local and regional air quality problems, greenhouse-gas reduction objectives, and energy security issues, many OECD governments have put in place policies with the objective to stimulate the development of alternative fuel vehicle technologies. Often this is accompanied by measures that aid specifically the diffusion of such innovations. While rather recent, these policies form a continuation of previous efforts to improve vehicle fuel efficiency which, depending on changes in crude oil prices and restrictions on oil supply, have been more or less high on the agenda of policy makers. They also follow on from previous regulatory efforts which have sought to reduce local and regional air pollution emissions from mobile sources (*e.g.* lead, sulphur compounds, carbon monoxide, nitrogen oxides, volatile hydrocarbons, particulate matter). This report examines the effect of the various policy and market factors on technological innovation with respect to alternative fuel vehicle technologies.

Technology overview

Fuel efficiency of motor vehicles became a heightened concern for policymakers, manufacturers and consumers in the 1970s in the aftermath of the oil price shocks. While early efforts concentrated mostly on re-designing the conventional internal combustion engine (improved engine design), at a later stage these measures were complemented with efforts to improve other, non-engine, characteristics of a vehicle which affect fuel consumption (improved vehicle design). However, further fuel efficiency improvements were necessarily deemed to be increasingly incremental.

More recently, innovations of a more radical nature have made it possible to develop vehicles relying on entirely new types of propulsion, and hence fuel, with a range of hybrid vehicles combining elements of the conventional and alternative technologies. These developments can bring about increased fuel efficiency, and reduce both greenhouse gas emissions and local and regional air pollution emissions. Governments have adapted their policies to support the development (and adoption) of such alternative-fuelled vehicles. However, they also represent a new challenge for policy makers who need to be wary of the possible negative environmental impacts of production and consumption associated with new vehicle types.

Previous efforts to improve motor vehicle fuel efficiency

Technologies to improve characteristics of a conventional engine (improved engine design)

Prior to the 1970s vehicle fuel efficiency was primarily affected by changes to carburettor settings. Following the oil price shocks in 1973 and 1979, and the introduction of the US Corporate Average Fuel Economy (US CAFE) standards in 1978, engineering of gasoline cars switched from carburettors to electronically-controlled fuel injection which allowed greater refinement in fuel mixture control. However, the introduction of catalytic

converters led to an increase in fuel consumption due to: *a)* the switch from the common lean setting to a (less lean) setting for optimal catalytic reactivity; and *b)* the increase in exhaust backpressure due to the catalyst.

In the 1990s, concerns over global warming and the perception of a looming regulatory response may have contributed to designing further engineering refinements, including the introduction of direct injection in diesel engines which was previously only available for heavy-duty applications. Most fuel economy improvements of gasoline engines involved optimising engine efficiency, such as improvements in basic engine design through the use of low friction materials and optimised geometry of the combustion chamber, intake manifolds, and outlet canals (OECD, 2004).

In late 1990s and 2000s, improvements in diesel engines were achieved through introduction of electronically-controlled fuel injection, such as common rail and unit injectors that allow flexible injection timing and rate shaping, but also enable much higher pressures. In gasoline cars improvements were achieved through better partial-load efficiency of the engine, through introduction of variable valve actuation, direct injection, or integrated starter alternator enabling start-stop driving mode (OECD, 2004).

In sum, measures which are primarily designed to improve fuel efficiency are listed below (see Annex B of the volume for the patent search strategy):

- Air-to-fuel ratio devices.
- Electronic fuel injection and engine management systems (on-board diagnostics, sensors).
- Ignition timing, variable valve timing, variable compression ratio, combustion chamber geometry.
- Engine performance during cold start, accelerating, decelerating idling, and cruising.
- Combustion air and fuel conditioning.

Measures to address local air pollutant emissions (emissions control technologies)

When considering motor vehicle fuel efficiency it is important to also take account of measures aimed at reducing local air pollutant emissions, such as carbon monoxide (CO), nitrogen oxides (NO_X), volatile hydrocarbon compounds (HCs) and particulate matter (PM). These measures include post-combustion (after-treatment) devices, engine design measures, and changes in fuel characteristics. Measures which are primarily designed to reduce local air pollutant emissions are listed below (see Appendix A2 for further details and the corresponding patent search strategy):

- Positive crankcase ventilation.
- Air injection.
- Exhaust gas recirculation.
- Thermal reactor.
- Catalytic converters, HC adsorbers, NO_X adsorbers, de-NO_X systems, diesel oxidation catalysts.
- Particle filters.
- Fuel characteristics that improve combustion (oxygen-containing additives).

Some of these measures may interfere with efforts to improve engine fuel efficiency. In many cases efforts to increase fuel efficiency (and reduce CO_2 emissions) will reduce

emissions of local air pollutants such as CO, NO_X and HCs. However, in other cases measures introduced to meet one policy objective may have negative impacts on the achievement of another objective – for example, oxygen-containing additives in fuel may reduce emissions of local air pollutants but increase fuel consumption; similarly, installation of catalytic converters in gasoline cars may reduce emissions of local air pollutants but increase fuel consumption; on the other hand, introduction of direct injection in diesel engines improves fuel economy but can have negative impacts on emissions of NO_X and PM; and finally, installation of diesel particle filters may reduce PM but increase NO_X emissions. Therefore, policy makers have at times faced the need to consider the various engineering and environmental trade-offs in setting their policy objectives.

However, the primary focus of this report is on the AFV technologies, and trade-offs between local air pollutants emissions and fuel economy are of less interest in the case of AFV technologies. For these reasons, this report does not devote more space to this issue (see, for example, Haščič *et al.* (2010) for analysis of effects of environmental policies on emissions control innovations; Vollebergh (2010) provides additional discussion of conventional fuel efficiency measures and the trade-offs involved). Nevertheless, even in the AFV field some engineering-environment trade-offs will necessarily arise (see Section 2.2 for a brief discussion).

Technologies to improve vehicle characteristics (improved vehicle design)

It is expected that further reductions in fuel consumption of the conventional internal-combustion engine will be achieved through lowering vehicle weight, rolling resistance, and other factors (not related to engine design) with an important effect on vehicle fuel consumption. Clearly, improved vehicle design will increase fuel efficiency of any vehicle, including those using AFV technologies. To summarise, these measures typically address the following issues (see Appendix A3 for further details and the corresponding patent search strategy):

- Inertia during acceleration or deceleration.
- Friction of moving and rotating components.
- Air resistance (improved aerodynamic design).
- Rolling resistance.
- Energy requirements of operating electric components of a vehicle (lighting, air-conditioning and heating system, other auxiliary electric systems and accessories).
- Light-weighting of complementary equipment (passive safety, noise insulation).
- Fuel-saving driver-support devices or devices that improve driving style (speed control, eco-driving).
- Non-combustion emissions (vapour recovery systems, improved fuel tanks).

Alternative fuel vehicle technologies

A variety of fuels have been proposed as alternatives to conventional purely petroleum-based blends, including:

1. *Liquid hydrocarbon fuels* such as methanol, ethanol (bio-ethanol), bio-diesel, and their blends with conventional fuels (E85, M85) – using such fuels requires development of dual-fuel (flexible-fuel or flex-fuel) vehicles capable of running on conventional gasoline

(or diesel) as well as an alternative fuel, or a blend thereof. While each of these alternative fuels have their pros and cons, they typically require only minor technical modifications to the vehicle. Rather than being a technological problem, the major obstacle to their wide-spread use seems to be the lock-in of the fuel distribution system, price competitiveness relative to conventional (gasoline/diesel) fuels as well as safety (*e.g.* methanol) and environmental and health concerns.[1]

There a number of other alternative fuels that may imply using new types of propulsion. However, the primary obstacle to their wider use has been the lack of appropriate storage systems. These fuels include:

1. *Gaseous hydrocarbon fuels* such as compressed natural gas (or CNG, mostly methane) and liquefied petroleum gas (or LPG, mostly propane) – this requires development of on-board pressurised storage systems.
2. *Hydrogen* – requires development of on-board storage systems (*e.g.* pressure vessels, in metal hydrides, in active graphite, or in nanofibres of graphite) or reforming and conditioning systems for production of hydrogen from hydrocarbon fuels (if fuel other than hydrogen is used) (*e.g.* steam reforming, shift reaction, partial oxidation).
3. *Electric energy* – requires development of on-board storage systems, that is, secondary cells (rechargeable batteries) such as the lead-acid, lithium-ion, nickel-cadmium, or nickel-metal-hydride batteries.

The alternative propulsion systems that have been developed include: *a)* hydrocarbon- or hydrogen-fuelled internal combustion engine; *b)* electric engine; and *c)* hybrid systems. Table 3.1 gives a schematic representation of the various fuel and propulsion alternatives for vehicles.

Table 3.1. **Alternative systems of vehicle propulsion and fuel supply**

			Type of propulsion		
			Internal combustion engine	Hybrid system	Electric engine
Type of fuel	Liquid	Hydrocarbons	Conventional gasoline/ diesel vehicle	Hybrid electric vehicle	Fuel-cell electric vehicle
	Gaseous	Hydrocarbons	LNG/LPG vehicle		
		Hydrogen	Hydrogen vehicle		
	Grid electricity (external supply)		–	Plug-in hybrid vehicle	Pure electric vehicle

In an *internal combustion engine* the chemical energy of fuel (hydrocarbon blends or hydrogen) is transformed into mechanical energy through thermal expansion (fuel combustion). Alternative fuels with the potential to reduce CO_2 emissions include those with lower carbon content and higher hydrogen content than conventional gasoline or diesel (*e.g.* hydrogen, methanol, natural gas, or bio-diesel).

A *fuel-cell electric vehicle* combines a hydrogen-fuelled cell with an electric engine. The chemical energy of fuel is first converted into electric energy, and subsequently transformed into mechanical energy using an electric motor. A fuel cell is a device which transforms chemical energy of fuel (hydrogen) into electric energy without combustion (hence unlike internal combustion engines, fuel cells convert chemical energy into electrically energy directly) (OECD, 2004). A number of different fuel cell types have been developed (are under development), each with its characteristic electrode materials,

electrolytes and membranes.[2] Hydrocarbon-based fuels can, in principle be used as well in fuel cell vehicles, however these need to be first converted into hydrogen fuels, and thus require also on-board reforming and conditioning systems. Advantages of fuel cells include their high conversion efficiency and zero (if hydrogen used as fuel) or very low pollutant emissions (if carbonaceous fuels used) (OECD, 2004).

In the case of a *pure electric vehicle* (also called, battery electric vehicle) electric energy is drawn directly from a storage medium (a battery).[3] The advantages of a vehicle equipped with an electric engine include regeneration of deceleration energy (*e.g.* regenerative braking), automatic engine shutdown (start-stop mode), and optimisation of engine drive conditions, all of which yield improved fuel efficiency and significantly better performance in terms of exhaust emissions. Moreover, no CO_2 is emitted in the case of hydrogen cells. The disadvantages include heavier weight and more complex engineering due to the additional motor and battery, as well as higher manufacturing costs (OECD, 2004).

At present electric vehicles are rarely commercialised in their pure form and are typically manufactured by combining elements of the conventional and alternative propulsion systems, as hybrid vehicles. A *hybrid electric vehicle* is equipped with: *i)* a primary power source (*e.g.* a conventional hydrocarbon- or hydrogen-fuelled internal combustion engine, or alternatives such as fuel cells) in order to power the electric generator; *ii)* a power storage unit (*e.g.* battery, flywheel, or ultra-capacitor); and *iii)* a drive unit (*i.e.* an electric engine). Combination of two propulsion systems allows a hybrid vehicle to achieve greater fuel economy. This is due to improved conversion efficiency since as much as 41-66% of energy consumed is used for propulsion, at zero (with hydrogen used as fuel) or very low (with hydrocarbon fuels) exhaust emissions (OECD, 2004). Table 3.2 provides a break-down of the various sources of fuel efficiency improvements of AFVs compared to conventional technologies.[4]

Table 3.2. **Breakdown of energy utilisation (%) by vehicle type**

Energy consumption	Conventional mid-size gasoline vehicle		Hybrid electric vehicle		Fuel-cell electric vehicle		Pure electric vehicle	
	Urban	Highway	Urban	Highway	Urban	Highway	Urban	Highway
A. Drivetrain losses	**76**	**68**	**68**	**65**	**71**	**67**	**51**	**40**
Thermodynamic losses[1]	60	60	51	56	31	27	18	13
Engine losses[2]	12	3	11	3	28	29	6	4
Transmission losses	4	5	6	6	12	11	27	23
B. Used for components	**13**	**12**	**19**	**11**	**16**	**12**	**27**	**22**
Auxiliaries	2	1	3	1	3	1	4	2
Accessories	1	1	1	1	1	1	2	2
Air conditioning	10	10	15	11	12	10	21	18
C. Used for propulsion	**11**	**20**	**13**	**22**	**13**	**21**	**22**	**38**
Air resistance	2	11	2	12	3	11	4	21
Roll resistance	4	7	5	8	5	8	8	13
Kinetic losses/braking	5	2	6	2	5	2	10	4
Total (%)	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**
C/(A + C) =	0.13	0.23	0.16	0.25	0.15	0.24	0.30	0.49

1. Battery losses in the case of full electric vehicle; Reformer losses in the case of fuel cell electric vehicle.
2. Fuel cell losses in the case of fuel cell electric vehicles.

Source: Adapted from OECD (2004: pp. 121, 139, 148, 149).

Potential negative environmental implications of AFVs

The fuel efficiency benefits associated with more widespread adoption of AFVs will likely result in reduced in-use CO_2 emissions as well as reduced emissions of local air pollutants (*e.g.* CO, HC, NO_X, PM). However, depending upon the means by which the alternative fuels (electricity, hydrogen, or biofuels) are generated, there may be negative environmental consequences. For instance, spent nuclear waste can be a significant environmental concern.[5] In addition, the manufacture and disposal of batteries needs to be undertaken with care to avoid negative environmental impacts (see Maclean and Lave, 2003. The IEA Implementing Agreement on Hybrid and Electric Vehicles examines such issues *www.ieahev.org/hybrid.html*).

Invention in AFV technologies: Evidence from patent data

As a measure of innovation in AFV (and other) vehicle 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 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. 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.

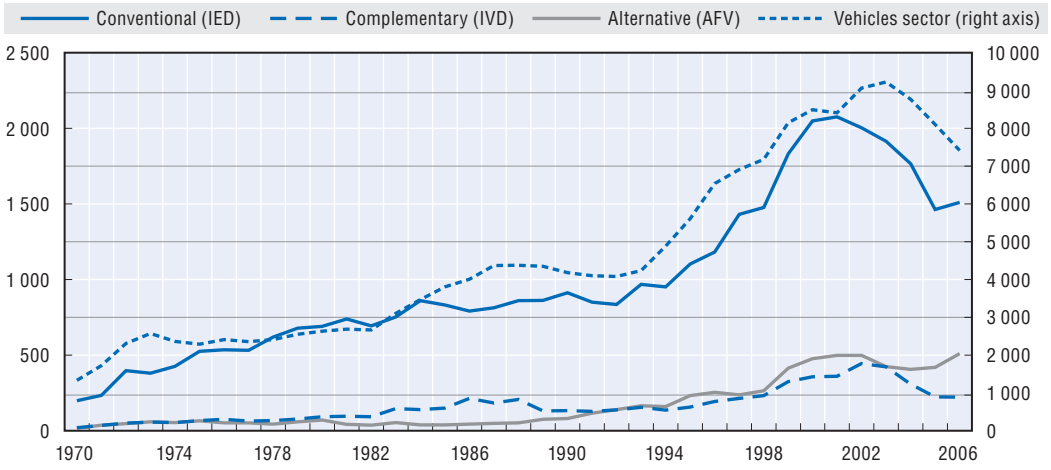
To identify the patents that are relevant for AFV and other technologies, we proceed as follows: First, we review the engineering and trade literature to identify relevant technologies. Subsequently, through a keyword search, we carefully review a number of patents abstracts in the selected technologies. As a result, we are able to identify International Patent Classification (IPC) codes used for filing patents of the selected technologies. Next, we use the individual IPC codes to examine a sample of patent documents in order to verify their "cleanliness". We only retain those IPC codes where conclude that they are not contaminated by many irrelevant patents (see Appendix A4 for a detailed description of the final patent search strategy). Finally, we use the selected IPC codes to extract patent data from the *PATSTAT Database* (EPO, 2009). This includes patents filed at more than 80 application authorities (including national patent offices but also regional patent offices such as the EPO) between the 1960 and 2007.

As the next step, we use the extracted patent data to construct a count of "claimed priorities" (CPs) which are defined as patent applications which have been filed at an additional office to the "priority" office. These patents represent the most valuable inventions in our sample because their patentee requested protection in more than one market. Previous research has shown that the number of additional patent applications (other than the priority application) is a good indicator of patent value (see Guellec and van Pottelsberghe, 2000; Harhoff *et al.*, 2003). The derivation of CPs based on an economic threshold criterion was advocated already by Faust (1990).

Figure 3.1 shows patenting in technologies that target fuel efficiency through *conventional* measures (improved engine design – IED), through *complementary* measures (improved vehicle design – IVD), such as improved air and rolling resistance, and through

Figure 3.1. **Patenting in alternative *versus* conventional fuel-efficiency technologies**

Number of patent applications (claimed priorities, worldwide)

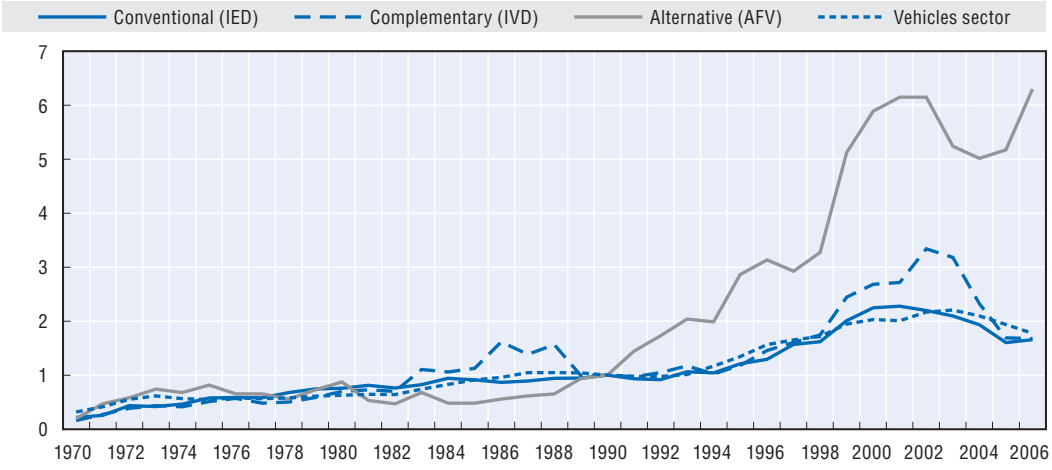


developing an *alternative* fuel vehicle (AFV). In addition, patenting for the entire motor *vehicle sector* is shown (displayed on the right axis). The data indicate that AFV patenting represents a relatively small portion (5-7%) of patenting in the vehicles sector. This is comparable with "complementary" (IVD) measures but is 3-4 times less than patenting in "conventional" (IED) technologies.

Despite the relatively small proportion, there has been a very strong growth in AFV patenting since the early 1990s. This is seen more clearly in Figure 3.2 where the data is indexed on a single year (1990). This contrasts with "conventional" technologies whose growth rate has more-or-less mirrored that in the sector overall. There was a stronger than average growth in "complementary" technologies in the 1980s, and then again during 1999-2004.

Figure 3.2. **Growth of patenting in alternative *versus* conventional fuel-efficiency technologies**

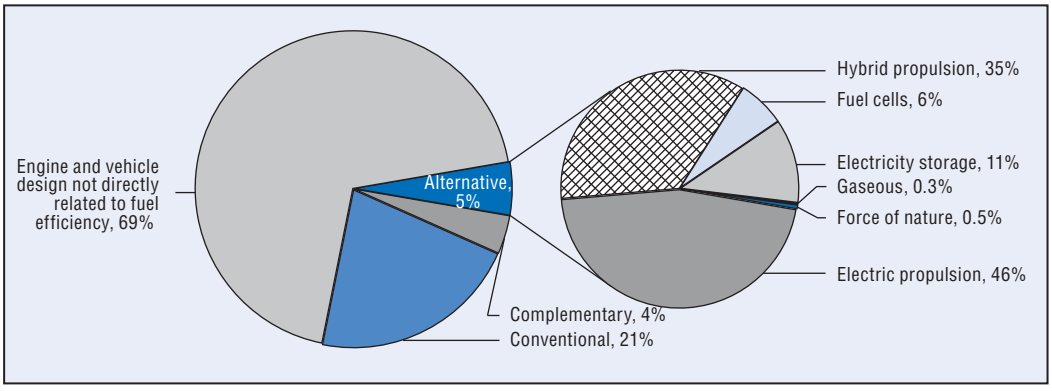
Number of patent applications (claimed priorities, worldwide), indexed on year 1990 = 1.0



At a more disaggregated level (Figure 3.3), most of AFV patenting can be categorised as relating to electric and hybrid propulsion, with patenting related to fuel cell applications and electricity storage being much less important. Finally, patenting in gaseous/hydrogen systems and propulsion via force of nature (solar/wind) is insignificant.

Figure 3.3. **Patenting in alternative fuel vehicle technologies**

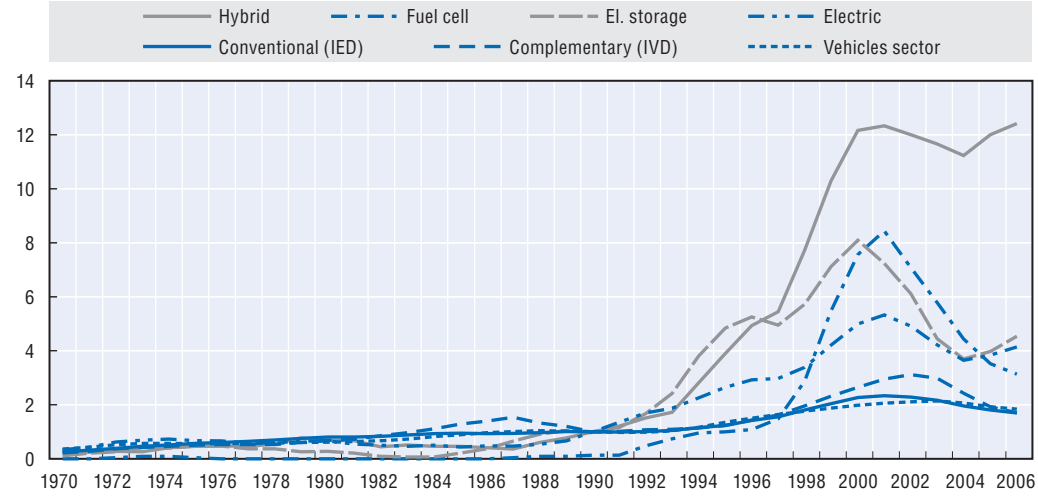
Number of patent applications (claimed priorities, worldwide)



In terms of growth rates (Figure 3.4), the fastest growth occurred in hybrid propulsion, especially between 1994 and 2000, with growth in storage, fuel cell applications, and electric propulsion being less pronounced.

Figure 3.4. **Growth of patenting in alternative fuel vehicle technologies**

Number of patent applications (claimed priorities, worldwide), 3-year moving average, indexed on year 1990



Note: Data for fuel-cell vehicle indexed on year 1995 because the base in 1990 is zero.

Next we examine the origin of AFV inventions by categorising patents by the country of residence of the inventor. Japan is by far the biggest inventor country in the field, followed by Germany and the United States (Figure 3.5).

The dominant position of Japanese inventors is also evident from the growth rates they achieved. Throughout the 1990s Japanese inventors recorded the fastest growth in

Figure 3.5. **Patenting in alternative fuel vehicle technologies, by inventor country**

Number of patent applications (claimed priorities, worldwide)

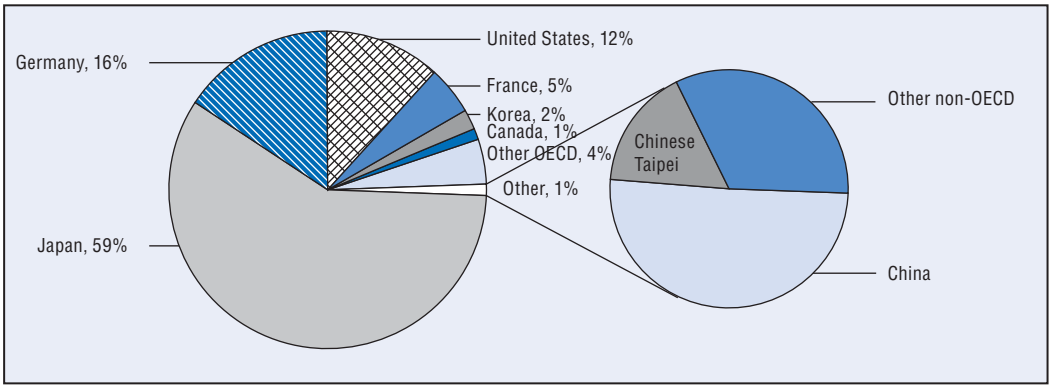
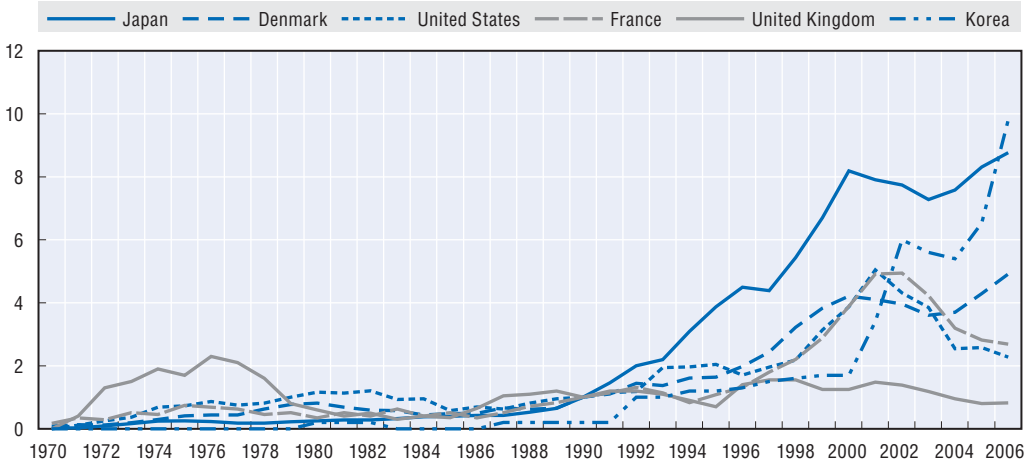


Figure 3.6. **Growth of patenting in alternative fuel vehicle technologies, by inventor country**

Number of patent applications (claimed priorities, worldwide), 3-year moving average, indexed on year 1990



Note: Data for Korea is indexed on year 1992 because the base in 1990 is zero.

patenting from among the major inventor countries. In the late 1990s, other countries started to challenge Japan's position, including Germany, France, and the US. Starting in 2001, Korean inventive activity showed unmatched growth rates.

Data for all inventor countries, disaggregated by technology (AFV, IED, IVD and the vehicles sector overall) are summarised in Table 3.3. Interestingly, countries such as China (CN) and Chinese Taipei (TW) have higher counts for "alternative" than for "conventional" technologies. Moreover, China has the highest share of alternative technologies on total sectoral patenting (Figure 3.7).

Within the AFV field, countries may specialise in specific technological areas (Figure 3.8). For example, in Korea and Canada most of their AFV patenting (> 90%) was in electric propulsion in 1990s, while both countries have become more "diversified" in the 2000s. To a lesser extent this is also true of the US, JP, DE, and FR. Conversely, Sweden had a rather diversified invention portfolio in the 1990s and became more specialised in the 2000s (in hybrid propulsion).

Table 3.3. **Inventing countries for alternative fuel vehicle technologies**

Number of patent applications (claimed priorities, worldwide), 1970-2006

	Alternative fuel vehicle (AFV) technologies							Conventional (IED)	Complementary (IVD)	Vehicles sector overall
	ELE	HYB	STO	FCL	GAS	NAT	Total			
JP	2 540	1 585	748	218	18	10	3 192	15 906	2 093	50 644
DE	648	436	131	97	6	7	990	10 137	1 557	42 970
US	628	271	139	51	8	18	844	4 181	939	23 844
FR	183	138	35	16	2	1	299	1 358	460	14 723
GB	103	42	16	2	2	2	134	1 046	238	5 913
IT	54	33	9	0	1	2	89	623	164	4 309
KR	60	27	25	6	3	3	86	208	53	2 227
CA	52	16	10	8	0	2	68	184	52	2 018
CH	44	21	6	3	0	0	52	158	28	1 361
SE	21	30	11	0	0	0	51	361	119	3 250
AT	25	8	4	1	0	0	32	398	26	1 392
NL	13	15	4	0	1	2	26	93	22	1 684
CN	12	5	4	0	0	2	21	16	7	271
TW	12	10	4	0	0	1	18	14	33	567
ES	8	10	3	0	0	1	17	58	22	990
FI	7	2	3	1	0	0	11	72	15	722
IL[1]	7	2	3	0	0	1	11	11	6	257
AU	6	2	0	1	0	0	7	97	17	546
CZ	3	6	0	1	0	0	7	13	4	148
BE	6	2	0	0	0	0	7	53	14	944
DK	2	3	1	0	0	0	5	67	5	407
BR	2	3	0	1	0	0	4	27	11	162
HU	2	1	1	1	0	0	3	15	8	200
IN	3	0	0	0	0	0	3	14	2	46
TR	2	1	0	0	0	0	2	18	0	22
PL	1	0	0	0	0	0	1	17	1	79
RU	0	0	0	0	0	1	1	17	11	128
LU	0	1	0	0	0	0	1	33	4	224

Note: Countries with at least 10 patents (CPs) in any of the major categories are included in the table.

1. The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

Figure 3.7. **Transition towards AFV technologies**

Ratio of AFV on total sectoral patenting, 1990-99 compared to 2000-07

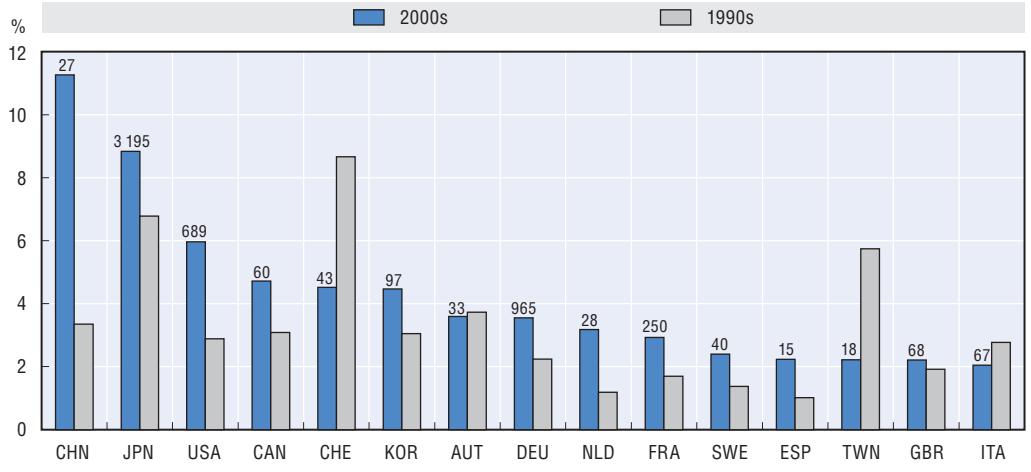
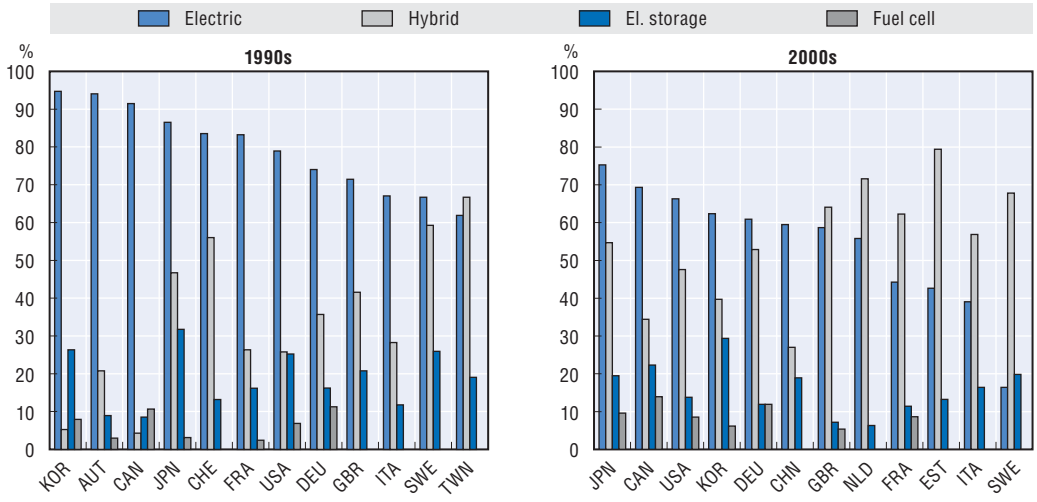


Figure 3.8. **Specialisation *versus* diversification**

Share within AFV Technologies



Note: Countries with at least 10 AFV patents (CPs) are included.

The car sector is a highly concentrated industry and of multi-national character, with research and development facilities frequently located in countries different from those of manufacturing facilities or those where they are legally domiciled. Therefore, rather than speaking of inventors, it may be useful to categorise the data by patentee (patent applicant or patent owner).

Table 3.4 gives lists the top forty patentees in each of the three fields examined. Three Japanese firms clearly dominate AFV patenting, followed by the US, Korean, and European patentees. Two main types of companies/groups can be distinguished – car manufacturers and equipment suppliers. Overall, 50% of inventions in AFV is due to 13 patentees (most of them car manufacturers). In the area of "complementary" vehicle design (IVD), there is less concentration, with 20 patentees (mostly equipment suppliers) responsible for 50% of patents. Conversely, in "conventional" (IED) there are only 10 patentees (mostly car manufacturers) responsible for half of the total count.

Table 3.4. **Top forty patentees for motor vehicle technologies: 1998-2007**

% share of patent applications within a field, based on claimed priorities, worldwide

Alternative (AFV)	%	Complementary (IVD)	%	Conventional (IED)	%
Toyota	12.05	Michelin	6.55	Bosch	18.96
Honda	7.40	Bosch	6.26	Siemens	5.92
Nissan	4.94	Continental	3.36	Toyota	5.54
Ford	3.79	Daimler/Chrysler	3.30	Denso	3.77
Hyundai	3.52	Toyota	2.90	Ford	3.40
Bosch	3.05	LUK	2.89	Hyundai	2.98
General Motors	2.98	Nissan	2.75	Honda	2.94
Renault	2.50	Siemens	2.62	Daimler/Chrysler	2.42
Daimler/Chrysler	2.28	Hyundai	2.11	Renault	2.29
Hitachi	1.98	ZF Group	1.82	Mitsubishi	2.17
Aisin	1.83	Denso	1.77	Nissan	2.13
ZF Group	1.74	Volkswagen	1.76	Delphi	2.11
Peugeot Citroën	1.61	BMW	1.73	Volkswagen	1.75
Siemens	1.25	Gertrag Ford	1.68	Hitachi	1.64

Table 3.4. **Top forty patentees for motor vehicle technologies: 1998-2007** *(cont.)*
% share of patent applications within a field, based on claimed priorities, worldwide

Alternative (AFV)	%	Complementary (IVD)	%	Conventional (IED)	%
Mitsubishi	1.09	Bridgestone/Firest.	1.65	Caterpillar	1.60
LUK	1.06	Honda	1.58	General Motors	1.35
Denso	1.02	Renault	1.46	Continental	1.24
Volkswagen	0.97	Goodyear	1.38	Peugeot Citroën	1.20
BMW	0.90	Eaton	1.27	BMW	0.81
SUZUKI	0.69	Pacific Industrial	1.21	Magneti Marelli	0.72
YAMAHA	0.69	General Motors	1.20	Yamaha	0.67
General Electric	0.55	Pirelli	1.16	Fiat	0.65
Lockheed Martin	0.55	Peugeot Citroën	1.12	Isuzu	0.60
Sanyo	0.50	Porsche	1.06	Detroit Diesel	0.57
Visteon	0.48	Sumitomo	1.03	Visteon	0.54
Valeo	0.40	Volvo	1.01	Volvo	0.52
Volvo	0.39	Hitachi	0.95	INTL Engine IP	0.52
Continental	0.38	Lear	0.78	Mazda	0.51
BAE Systems	0.38	Yokohama Rubber	0.66	Audi	0.46
Kia	0.36	Audi	0.58	Eaton	0.45
Eaton	0.36	Deere	0.57	Behr	0.41
Matsushita	0.36	Schrader	0.56	Keihin	0.37
Jungheinrich	0.34	Fuji	0.52	AVL	0.37
Porsche	0.34	Dana	0.51	Scania	0.36
Linde	0.33	Scania	0.46	Kia	0.35
Delphi	0.32	Visteon	0.45	Honeywell	0.31
Ballard	0.32	Kia	0.43	Pierburg	0.31
Bombardier	0.31	Mitsubishi	0.42	FEV	0.29
Michelin	0.31	Mannesmann	0.41	General Electric	0.27
Deere	0.29	Aisin	0.38	Valeo	0.24
Total (n = 25 444)	**100**	**Total (n = 15 061)**	**100**	**Total (n = 62 321)**	**100**

Note: Patentee names have been partially cleaned (name-matching).

Inside the AFV field, a small number of patentees dominate all the four major areas – electric, hybrid, electricity storage, and fuel cells. Toyota is a clear leader in the electric and hybrid field, with other Japanese and Korean firms also active. The patentees for inventions related to gaseous fuel/hydrogen systems are more mixed, coming from a wide variety of fields. This is also true of the patentees in the area denominated as "powered by force of nature". However, the latter area shows a very low degree of concentration, while the gaseous fuel/hydrogen area is very concentrated. It must be borne in mind that the counts are much lower in these two areas.

Table 3.5. **Major patentees for alternative fuel vehicle technologies: 1998-2007**
% share of patent applications (claimed priorities, worldwide) within the field, top forty applicants

Electric propulsion	%	Electricity storage	%	Hybrid propulsion	%
Toyota	11.77	Toyota	10.89	Toyota	13.17
Honda	7.57	Honda	6.91	Honda	7.57
Nissan	4.75	Hyundai	4.56	Nissan	5.59
Hyundai	3.41	Nissan	4.03	Ford	5.24
Gertrag Ford	3.27	Bosch	3.23	Bosch	4.14
General Motors	2.95	Ford	3.05	Hyundai	3.57
Bosch	2.39	Daimler/Chrysler	2.78	General Motors	3.14
Daimler/Chrysler	2.21	Denso	2.30	ZF Group	2.86
Hitachi	2.18	General Motors	2.14	Peugeot Citroën	2.71

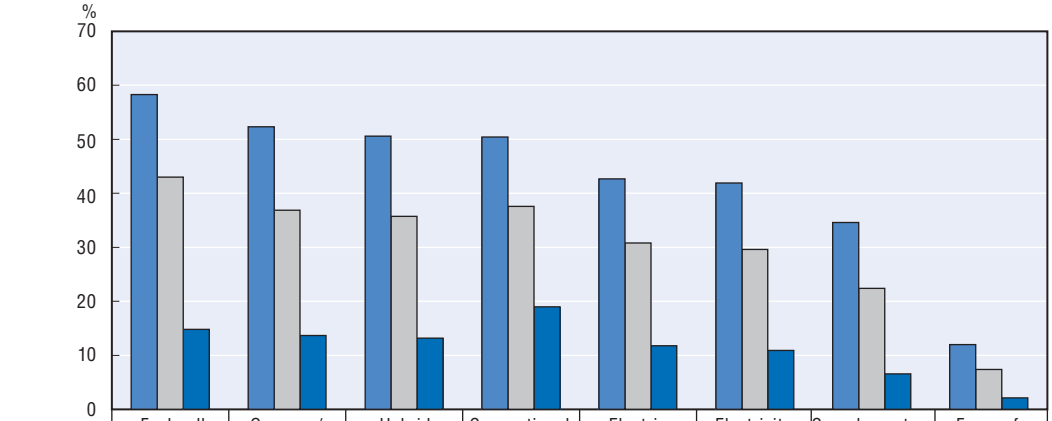
Table 3.5. **Major patentees for alternative fuel vehicle technologies: 1998-2007** *(cont.)*
% share of patent applications (claimed priorities, worldwide) within the field, top forty applicants

Electric propulsion	%	Electricity storage	%	Hybrid propulsion	%
Renault	2.15	Hitachi	1.99	Aisin	2.61
Aisin	1.80	Renault	1.91	Renault	2.42
Siemens	1.73	Kia	1.60	Hitachi	2.13
ZF Group	1.54	Sanyo	1.52	Luk	2.03
Mitsubishi	1.23	Matsushita	1.29	Daimler Chryler	1.96
Peugeot Citroën	1.01	Volkswagen	1.26	Volkswagen	1.45
Total (n = 11 621)	**100**	**Total (n = 3 135)**	**100**	**Total (n = 8 583)**	**100**
Fuel-cell vehicle	%	Gaseous fuel/hydrogen systems	%	Powered by force of nature (sun, wind)	%
Toyota	14.81	Exxon Mobil	13.68	Ford	2.09
Honda	8.40	BG Group (British Gas)	11.49	Honda	1.32
Renault	8.33	John Hopkins University	4.21	Outfitter Energy	1.32
Nissan	6.38	Ford	3.79	Webasto	1.32
General Motors	5.04	Xu Defang	3.68	Power Light	1.32
Daimler/Chrysler	4.48	BMW	3.33	Gericke de Vega, Dora Angelica	1.10
Siemens	3.47	Bosch	3.16	Nissan	0.88
Hyundai	2.98	Fiat	3.16	Bosch	0.88
Ballard	2.21	Toyota	2.89	ELK Premium Building Products	0.88
Bosch	2.19	Hyundai	2.89	Zhang Junjie	0.88
Delphi	1.98	Texaco Ovonic Hydrogen Systems	2.28	Toyota	0.77
Peugeot Citroën	1.75	Kia	1.84	Shanghai Jiaotong University	0.66
Farnow	1.61			Canon	0.66
Ford	1.53				
Emitec	1.51				
Total (n = 1 461)	**100**	**Total (n = 190)**	**100**	**Total (n = 454)**	**100**

Note: Patentee names have been partially cleaned (name-matching).

Figure 3.9 summarises the information concerning the degree of "concentration" of patentees in the different fields, including those which relate to the use of conventional fuels.

Figure 3.9. **Concentration in the market for AFV inventions: 1998-2007**
% share of the first, top five, and top ten patentees



	Fuel-cell vehicle	Gaseous/ hydrogen	Hybrid propulsion	Conventional (IED)	Electric propulsion	Electricity storage	Complementary (IVD)	Force of nature
% top ten	58%	52%	51%	50%	43%	42%	35%	12%
% top five	43%	37%	36%	38%	31%	30%	22%	7%
% top one	15%	14%	13%	19%	12%	11%	7%	2%

Government policies aimed at AFV technologies: An overview

There are a large number of market failures and barriers that affect markets for AFVs, including:

- Environmental externalities (local/regional, GHGs).
- Knowledge spillovers related to innovation in general.
- Network effects and monopoly conditions (infrastructure).
- Consumption externalities (slow "uptake" of innovations).
- Capital market failures (limited financing for high-risk investment).
- Market power within the manufacturing sector.

Governments employ a broad range of policies aimed at addressing these failures and barriers, including the following policy instrument types:

- Direct R&D support (public funding, fiscal incentives, prises).
- Performance standards (portfolio obligations).
- Pricing (fuel taxes, vehicle tax differentiation).
- Information-based measures (labels).
- Demonstration projects, public procurement.
- Investment in infrastructure.
- Anti-trust laws to ensure non-collusive behavior related to innovation.

In this report we focus specifically on those policies and measures that have the potential to spur innovation in motor vehicle technologies, and particularly those which are likely to encourage innovation in AFVs.

Direct support for R&D

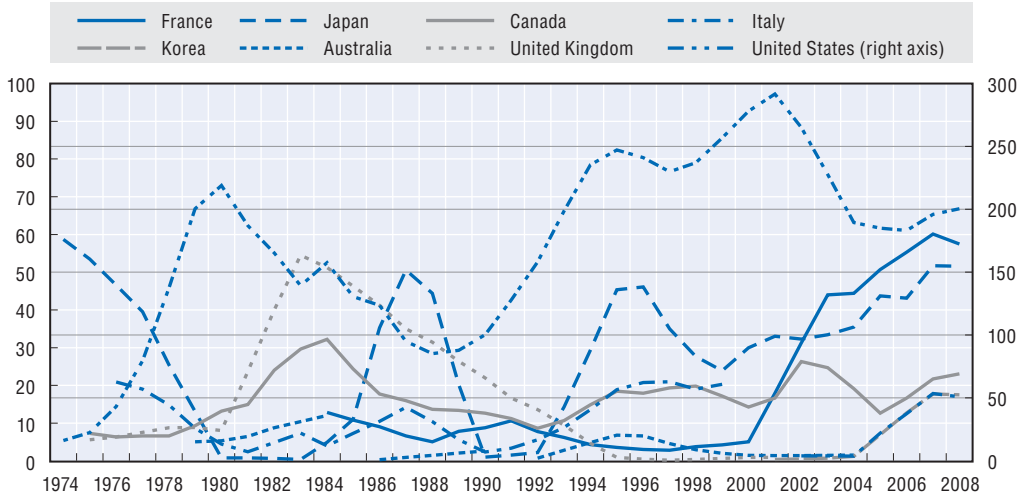
One of the most common ways of encouraging inventive activity is direct financial support for research and development using public sector budgets – *i.e.* grants or tax credits. Dedicated schemes of R&D subsidies for the development of alternative vehicle technologies have been put in place in a number of OECD countries. Some of the recent initiatives include: Japan's 2009 *Programme of Innovation for Green Economy and Society* which promotes development of high-efficient and low-cost solar batteries, low-cost and easy-to-use electric cars, as well as hydrogen production from non-fossil fuels;[6] the United States' 2007 *Energy Independence and Security Act* which includes provisions for the funding of research into hydrogen technologies (IEA, 2009a); the United Kingdom's 2007 *Low Carbon Transport Innovation Strategy* which provides government funding aimed at accelerating the development and market penetration of new lower carbon technologies (IEA, 2009a) (see also *www.dft.gov.uk/pgr/scienceresearch/technology/lctis/lowcarbontis*); and Canada's *Programme of Energy Research and Development* which supports early-stage and applied energy R&D aimed at clean transportation systems, including hydrogen and fuel cells, plug-in hybrid electric vehicles, advanced fuels and emissions reduction (see also *www2.nrcan.gc.ca/ES/OERD/english/View.asp?x=1317*).

Data on R&D expenditures related to alternative motor vehicle technologies is rare. However, some data is available on government R&D spending directed at improving energy efficiency in transportation. While the budget allocations have varied over time, in the recent years there seems to have been a general increase in many countries. For

example, spending has risen substantially in France, Korea, and Finland, and to a lesser extent in Japan, Canada, Italy and Sweden. On the other hand, spending has been decreasing in the UK, the Netherlands, Australia and Turkey. Figure 3.10 shows the series for selected countries. Perhaps the most surprising feature of the data is the high degree of volatility reported.

Figure 3.10. **Energy technology RD&D public budgets towards improving energy efficiency in transportation**

Million USD in 2008 prices and PPP, three-year moving average



Note: Data for Germany are not available.

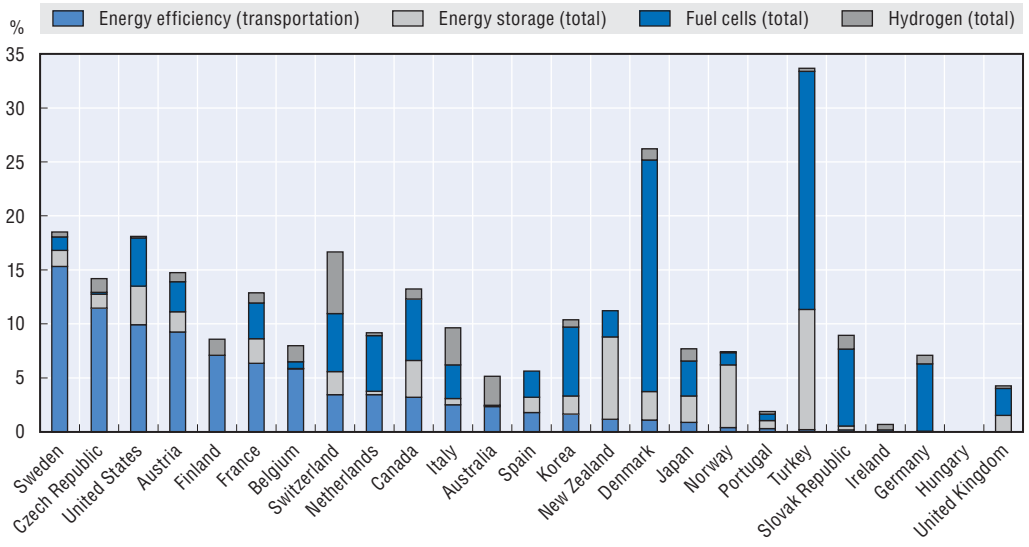
Source: *OECD.Stat* (*www.oecd.org/statistics*), *Energy Technology R&D Budgets*.

While there are large differences across countries in the size of energy R&D budgets (in absolute terms and as percentage of GDP), there are also differences in the priorities being funded. Figure 3.11 gives the proportion of total energy R&D directed at selected objectives of relevance to AFV development. For example, the greatest share of energy budgets is devoted to improving transportation energy efficiency in Sweden and the Czech Republic. The share of energy storage is highest in Switzerland and Italy, fuel cells in Turkey and Denmark, and hydrogen-related research in Turkey, New Zealand and Norway.

Recently, another means of directly encouraging R&D has been (re)discovered by OECD governments – inducement prises (see *www.ieahev.org/hybrid.html* for some examples). For instance, the United States' *H–Prise* is a competitive programme that awards cash prises to advance R&D, demonstration, and commercial application of hydrogen energy technologies (IEA, 2009a). Another example is the *EcoCAR Challenge* presented below. Newell and Wilson (2005) suggest that technology inducement prises could be a useful complement to standard R&D grants, and point out that there could even be conceptual advantages associated with (well-designed) inducement prises. These include, for example, rewarding output, risk borne by researchers, lower barriers to entry, and generally lower cost to government than direct contracts. On the other hand, Newell and Wilson point out that duplication of effort and up-front liquidity constraints are some of the potential disadvantages of inducement prises.

Figure 3.11. **Public R&D funding for specific energy technology areas: 2004-08**

As % share of total energy technology R&D public budgets



Source: OECD.Stat (*www.oecd.org/statistics*), *Energy Technology R&D Budgets*, 2010.

Box 3.1. **The EcoCAR challenge in the United States**

The EcoCAR Challenge is a three-year competition that builds on the 19-year history of the US Department of Energy advanced vehicle technology competitions by giving engineering students the chance to design and build advanced vehicles, with the goal of minimising the environmental impact of personal transportation. The technologies explored in EcoCAR are identical to those being investigated by the automotive industry, such as full electric, hybrid, plug-in hybrid, and fuel cell hybrid vehicles. The only fuels approved for use in EcoCAR are E10 ethanol, E85 ethanol, B20 biodiesel, compressed gaseous hydrogen, and the energy carrier electricity. By the end of the competition, the sponsors expect fully developed vehicles equivalent to prototypes ready for a production decision. Teams will receive USD 10 000 in seed money in Year One, a wide range of power-train components, a vehicle donated by GM, and technical and mentoring support from the competition sponsors. EcoCAR teams will also have a GM mentor knowledgeable in technologies relevant to the team assigned to assist them during the competition. Participating schools will be required to match cash seed money donations from EcoCAR sponsors and to provide class credit for students participating in the competition (IEA, 2009a) (see also *www.ecocarchallenge.org*).

Performance standards and portfolio obligations

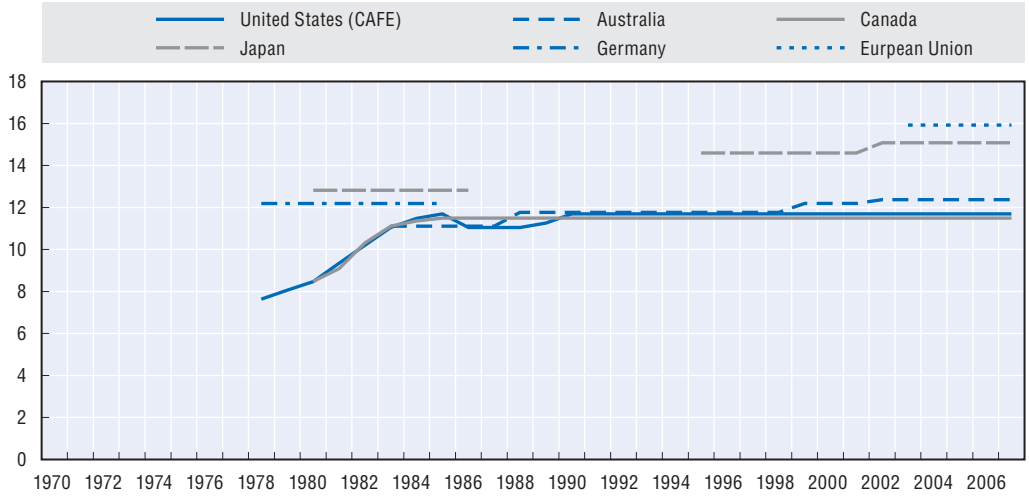
Vehicle performance standards typically set minimum limits on fuel efficiency, and more recently, maximum limits on CO_2 emissions. If a standard requires limits that are not possible to be met using current technology, the potential of the performance standard to spur innovation will be greatest (technology-forcing).

Mandatory fuel efficiency standards are rare. Until very recently, the only such example was the United States' Corporate Average Fuel Economy (CAFE) set of standards, enacted in 1975 and first applicable to 1978 models. After an initial increase in stringency, the gradual tightening was temporarily relaxed after 1984 when it began to be really binding. After many years when the US car fuel economy standard was unchanged and the

truck fuel economy standard was rising only slightly, in April 2010 the US Environmental Protection Agency and the US Department of Transportation announced a joint rulemaking to establish the first-ever US emission standards for greenhouse gases (GHG) and the biggest increase in CAFE standards in 30 years. By 2016, new light-duty vehicles (cars and light trucks averaged together) are projected to meet GHG and fuel economy standards of approximately 35 miles per gallon or about 6.7 litres per 100 kilometres (that is, 15 km per litre). This value represents a 23% reduction in GHG levels relative to new 2011 vehicles (USEPA/NHTSA, 2010). Following the adoption of the US CAFE standards in 1975, Australia and Canada adopted similar standards but only on a voluntary basis.

Figure 3.12. **Mandatory (US) and voluntary (other countries) fuel efficiency standards for passenger cars**

In kilometres per litre of fuel



Source: Data courtesy of Herman Vollebergh.

Even prior to these developments, voluntary fuel efficiency schemes were introduced around the oil crises of the 1970s in several OECD countries like Germany and Japan (OECD/IEA, 1984). In the mid-1990s, efficiency requirements for passenger cars were included in Japan's Top Runner Programme, at significantly more stringent levels than those above. As is the case for other product categories, the Programme requires that the currently most efficient technology becomes industry standard (average performance level) by a target date. In 2005, the Government of Japan drafted new fuel efficiency standards with the target year set at 2015 for passenger vehicles. Manufacturers and importers will need to achieve the average fuel efficiency levels, calculated as the harmonised weighted average of the fuel efficiency levels by the number of shipped vehicles. The standards are expected to result in a 23.5% improvement in the fuel efficiency of passenger vehicles by 2015, compared to 2004 levels. (OECD/IEA, 2009a) (see also *www.eccj.or.jp/top_runner/index.html*).

In 1990, the State of California (US) introduced the "Zero Emission Vehicle" (ZEV) regulation as part of its broader Low Emission Vehicle Programme. The direct objective of the regulation was development of zero-emission vehicle technologies that could be mass-produced and be affordable in the market as soon as possible. While the regulation set certain minimum technical requirements that were intended to make the vehicle attractive to the US consumers,[7] it left the choice of technology to meet the requirements with the manufacturers (technology neutrality). The ZEV regulation was clearly technology forcing

because no technologies capable of meeting the ZEV requirement were available at the time. While the original objectives have not been met as rapidly as initially intended, and the regulation has been amended several times to allow for certain flexibility in meeting the mandate, the goal towards commercialisation of ZEVs has been maintained. Indeed, there is evidence suggesting that the ZEV mandate played a major role in inducing the development of electric, and related, vehicle technologies.[8] (See Box 3.2 for further discussion).

Box 3.2. **The Zero Emission Vehicle (ZEV) regulation in California**

In 1990 the California Air Resources Board (CARB), a State agency responsible for ambient air quality oversight, adopted a plan to reduce vehicle emissions to zero and introduced the Zero Emission Vehicle (ZEV) regulation. Initially, the ZEV required that by 1998, 2% of the vehicles that large manufacturers produced for sale in California had to be ZEVs, increasing to 5% in 2001 and 10% in 2003. Manufacturers failing to meet the requirement could be fined up to 5,000 USD for each violation.

In 1996, the ZEV mandate allowed partial ZEV (PZEV) credits for "extremely" clean vehicles that were not pure ZEVs to meet the ZEV mandate during the initial period (1998-2003), but left in place the underlying goal of 10% ZEVs in 2003.

In 2001-03, in the face of cost, lead-time, and technical challenges, CARB amended the mandate in order to better align the regulation with the status of technology development: by 2003, only 2% of the cars would have to be pure ZEVs (that is, battery or fuel cell EVs), 6% could be PZEVs (that is, very low emitting conventional gasoline vehicles), and the remaining 2% could be met using advanced-technology PZEVs (that is, hybrid EVs, natural gas vehicles). In fact, it was the progress achieved in development of battery technology that (unexpectedly) benefited the development of hybrid cars (Calef and Goble, 2007).

In the 2009 review (*www.arb.ca.gov/msprog/zevprog/2009zevreview/2009zevreview.htm*) of the ZEV it was suggested that given the successful commercialisation of PZEVs* the CARB may consider removing the option to use PZEVs and AT-PZEVs to meet the ZEV mandate. Instead, it was proposed that efforts now concentrate on helping to move the pre-commercial pure ZEV technologies (battery EVs, fuel-cell EVs, plug-in hybrid EVs, and hydrogen internal combustion engine vehicles) from demonstration to commercialisation in 2015. In addition, complementary policies to develop the supporting infrastructure (electricity and hydrogen fuelling stations) are under consideration (CARB, 2009a).

In the late-2009 revision of the ZEV regulation, the option to use PZEVs has been retained but the overall standards have been increased – 11% for the 2009-11 model years, 12% for 2012-14, 14% for 2015-17 and 16% for 2018 and beyond. For the 2009-11 model years the minimum requirements are 2.5% ZEVs (or credits generated by ZEV vehicles), another 2.5% can be met with AT PZEVs (or corresponding credits), and the remainder of the manufacturer's ZEV requirement may be met using PZEVs. The proportion of the overall ZEV mandate that must be met by AFVs (that is, ZEVs or ATPZEVs) will increase over time eventually reaching 10% by 2018 (CARB, 2009b).

* Indeed, the PZEVs are considered as a collateral outcome of the ZEV regulation. In total, over one million PZEVs and 250 000 AT PZEVs have been delivered for sale in California as a result of the ZEV regulation, *www.arb.ca.gov/msprog/zevprog/2009zevreview/zevwhitepaper.pdf*.

Source: For further details see CARB (2009) at *www.arb.ca.gov/msprog/zevprog/background.htm*.

In Europe, voluntary agreements on fuel efficiency targets were first introduced in Germany, but other countries had comparable agreements, like Italy and Sweden (OECD/IEA, 1984). In 1998 the EU negotiated voluntary commitments with the industry. Failure to meet these targets led the EU to adopt a mandatory set of emission limits in 2009 (see Box 3.3 for further details).

Box 3.3. **Carbon dioxide emission limits in the European Union**[1]

Carbon dioxide emission targets for new passenger cars were first set in 1998/99 through voluntary agreements between the European Commission and the automotive industry. These agreements targeted fleet-average CO_2 emissions of 140 g/km by 2008/09. Initially, significant CO_2 emission reductions were achieved but after 2004 the targets were no longer met.[2] In response to the failure of the voluntary targets to achieve further reductions, the Commission developed a *mandatory* CO_2 emission reduction programme for passenger cars and light commercial vehicles in 2009.[3]

The new CO_2 standards are legally-binding and apply as of 2012. In the case of passenger cars, a fleet-average CO_2 emission target of 130 g/km is to be reached by each vehicle manufacturer by 2015. Further emission reduction of 10 g/km is to be achieved by measures, such as more efficient air-conditioning systems or tyres, and the use of biofuels. The new regulation makes these objectives binding for the average fleet of a given car manufacturer in successive stages: In 2012, 65% of their car fleet must meet the target, in 2013 75% and in 2014 80% and 100% from 2015. The regulation also defines a long-term target of 95 g CO_2/km to be reached from 2020, with the modalities for reaching this objective to be reviewed by the Commission by 2013.

Manufacturers who miss their average CO_2 targets are subject to *penalties*. Between 2012 and 2018, the penalties are EUR 5 per vehicle for the first g/km of CO_2; EUR 15 for the second gram; EUR 25 for the third gram. For emissions of more than 3 grams over the limit, EUR 95 is charged per newly registered vehicle. From 2019, the penalty will be EUR 95 per new car for every gram above the target.

In the initial period, certain types of vehicles receive additional incentives. For example, vehicles emitting less than 50 g CO_2/km receive *super-credits*. Each such vehicle is counted as 3.5 cars in 2012 and 2013, as 2.5 cars in 2014, 1.5 cars in 2015, and as 1 car from 2016. CO_2 emissions of vehicles capable of running on a mixture of gasoline with 85% ethanol (E85) are reduced by 5% until the end of 2015. This reduction applies only where at least 30% of the filling stations in a member state provide E85.[4]

The Programme also allows for certain *flexibilities* for manufacturers, including: *a)* several manufacturers may form a pool to jointly meet their CO_2 emission targets (pooling); *b)* manufacturers may apply for credits for innovative CO_2 reducing technologies which are not accounted for in the current test cycle (*e.g.* energy efficient lights), with the total contribution of such "eco-innovation" credits limited to 7 g CO_2/km in each manufacturers average specific target; and finally; and *c)* low-volume manufacturers (fewer than 10 000 new cars registered per year) may, under certain conditions, apply for a derogation from the specific emission targets.

1. Based on *www.dieselnet.com/standards/eu/ghg.php* and *http://ec.europa.eu/transport*.
2. According to one study (T&E, 2006) only three out of 20 car brands (Fiat, Citroën and Renault) were in 2005 on track to meet the 140 g/km commitment. Several manufacturers of large cars (BMW, Volvo, Audi) trail far behind, with brands such as Mazda, Suzuki and Nissan being the worst performers.
3. Regulations 443/2009/EC and COM(2009)593.
4. These provisions have been criticised by some environmental groups (see *e.g.* CE Delft, 2010).

In 2003 a voluntary target was put in place by the Australian automotive industry. Development of similar standards is currently underway in Canada (see also *www.ec.gc.ca/default.asp?lang=En&n=714D9AAE-1&news=29FDD9F6-489A-4C5C-9115-193686D1C2B5*). In the United States, following the "endangerment finding" (USEPA 2009), introduction of national regulatory standards for GHG emissions has been under consideration. Such standards could include GHG emission standards for new motor vehicles and new motor vehicle engines.[9]

Pricing policies

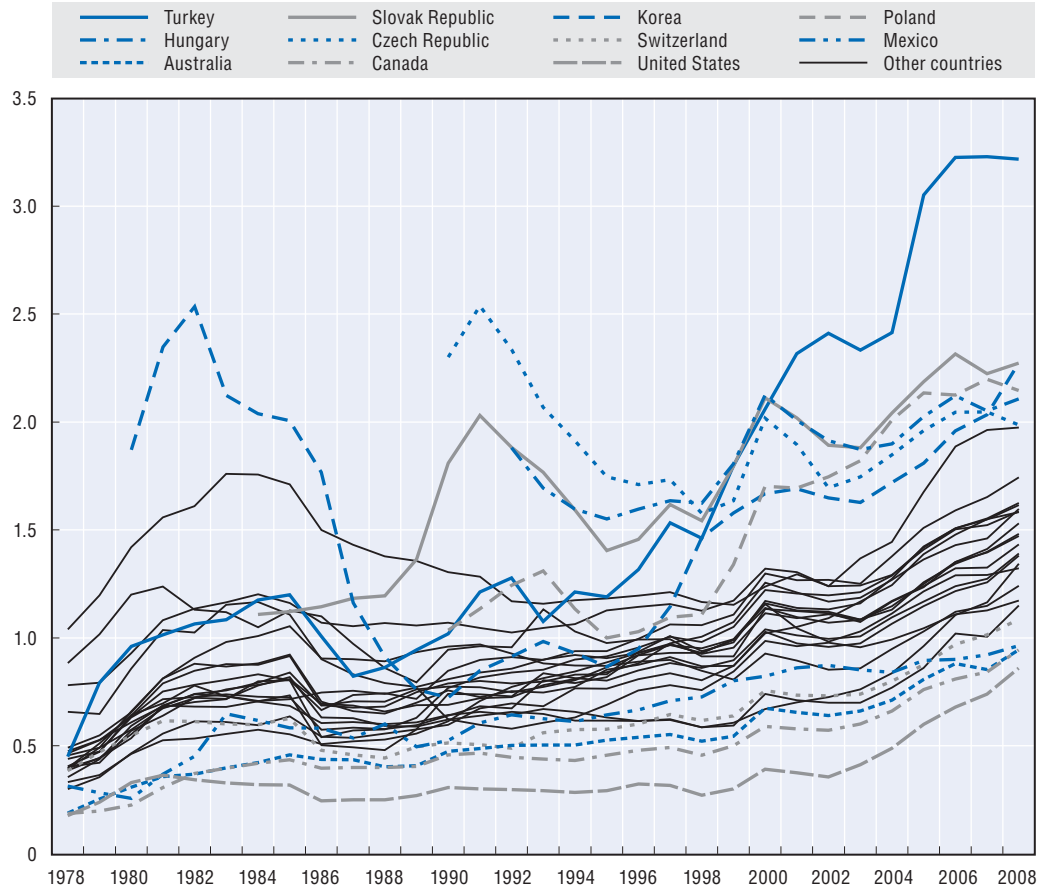
In this section policies and measures are discussed that aim at changing the relative prices of inputs (fuel taxes, CO_2 taxes, and taxes on energy carriers in general) and prices of outputs. Output taxes may be distinguished by their point of incidence – whether they impose a tax on the purchase (vehicle purchase taxes, tax credits, or subsidies), ownership (annual motor vehicle tax), or usage of a vehicle (kilometre tax, road usage taxes, pay-as-you-drive schemes, road pricing). In addition, emission trading schemes can be envisaged for large transport operators. All of these policies will – whether directly or indirectly – encourage the use of (and thus innovation in) AFVs.

Automotive fuel taxes

A comparison of automotive fuel prices gives an indication of pricing policy in OECD countries since the after-tax price of fuels reflects the effects of the imposition of excise taxes, value-added taxes, as well as various forms of price regulations. Gasoline prices (in PPP terms) have increased 2- to 5-fold in most OECD countries between 1978 and 2008. In Turkey prices have risen as much as a 7-fold (Figure 3.13).

Figure 3.13. **Gasoline prices in OECD countries**

End-use after-tax prices for households, in USD per litre using 2008 prices and PPP



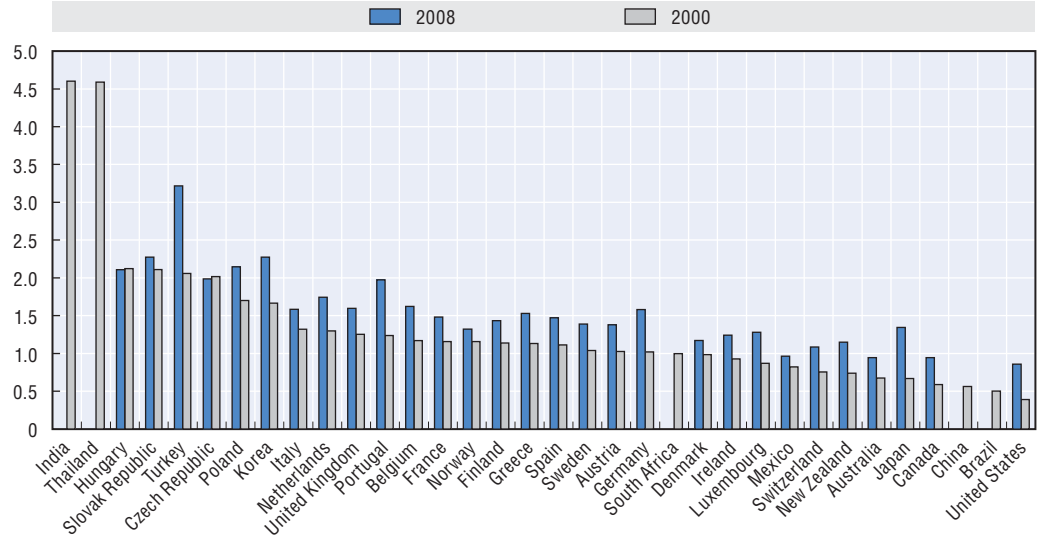
Note: Prices displayed represent the lowest-cost envelope of the fuel price range in a country; most of the time, this corresponds to premium leaded gasoline (prior to mid-1980s) and premium unleaded gasoline (95 RON) in Europe and regular unleaded gasoline outside of Europe.

Source: OECD.Stat, *Energy End-Use Prices* (3Q 2009)

Some data is also available for non-OECD countries (Figure 3.14). In 2000, consumers in India and Thailand paid by far the highest prices (on the PPP basis), followed by those in Hungary and the Slovak Republic. The lowest price levels (on the PPP basis) were observed in the US, Brazil, China, and Canada. During the period from 2000 to 2008, prices have generally risen (except for Hungary and the Czech Republic), with the highest absolute increases recorded in Turkey, Portugal and Japan, and highest percentage increases in USA, Japan, Portugal and Canada.

Figure 3.14. **After-tax gasoline prices**

End-use after-tax prices for households, in USD per litre using 2008 prices and PPP



Note: China 1998, Brazil 1994.

Source: OECD.Stat, *Energy End-Use Prices* (3Q 2009)

Similar developments have been observed for automotive diesel prices (Figure 3.15). During the period from 2000 to 2008, diesel prices have risen in all countries for which data is available, with the highest absolute increases recorded in Korea and Turkey and highest percentage increases in Korea, USA, and Japan (Figure 3.16).

In addition to explicit taxes on fuel inputs, some countries tax fuel through inclusion of transport emissions in their ETS schemes (see Box 3.4 for the example of New Zealand).

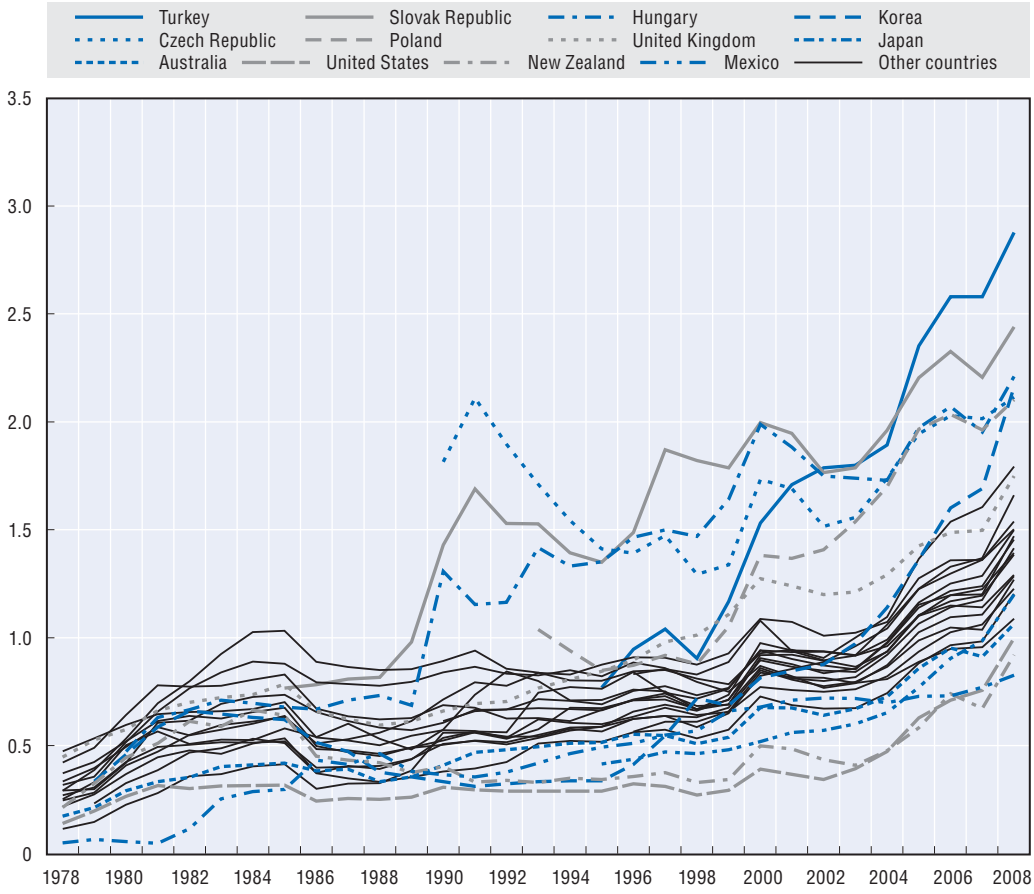
Vehicle purchase taxes and tax credits

A number of OECD governments have included fiscal incentives for the purchase of lower-emission vehicles in their vehicle purchase tax schemes. For example, in the framework of its "Environment Programme" (*Grenelle de l'environnement*), France introduced a "bonus – malus" scheme[10] that subsidises the purchase price of low-emission cars (ranging from EUR 5 000 for 0-60 g CO_2/km to EUR 100 for 111-120 g CO_2/km, based on the 2011-12 rates) while it imposes a tax on the price of the more polluting ones (ranging from EUR 200 for 151-155 g CO_2/km to EUR 2 600 for 240 g CO_2/km and over, based on the 2011-12 rates) (*www.legrenelle-environnement.fr/spip.php?rubrique195*). The scheme is intended to be broadly revenue-neutral.

In Japan, the *Scheme to Develop and Disseminate Low-Carbon Technologies* provides subsidies and tax breaks on the purchase of fuel-efficient vehicles.[11] In addition, Japan's

Figure 3.15. **After-tax automotive diesel prices**

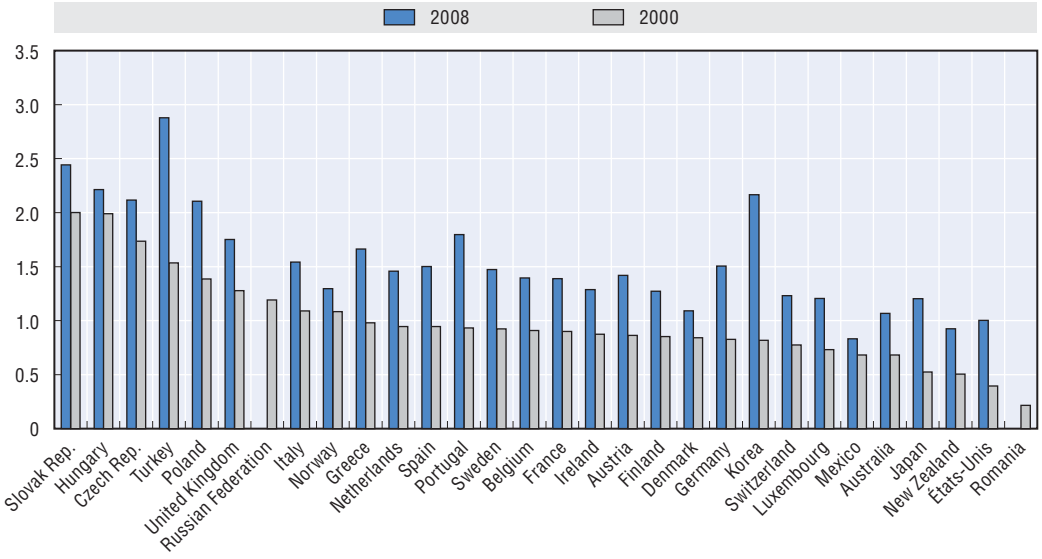
End-use after-tax prices for households, in USD per litre using 2008 prices and PPP



Source: OECD.Stat, *Energy End-Use Prices* (3Q 2009).

Figure 3.16. **After-tax automotive diesel prices**

End-use after-tax prices for households, in USD per litre using 2008 prices and PPP



Source: OECD.Stat, *Energy End-Use Prices* (3Q 2009).

Box 3.4. **Transport emissions in New Zealand's ETS scheme**[1]

As of November 2009 the New Zealand government has all but passed new legislation which will underpin the operation of a comprehensive emissions trading scheme (ETS) covering all sectors of the economy. Individual sectors are being phased in gradually between 2008 and 2013.[2] The transport sector, considered as one part of the "liquid fossil fuels" sector, will enter the NZ ETS on 1 July 2010. During a transition phase (until December 2012) ETS obligations will be implemented progressively requiring ETS participants to surrender only one unit for every two tonnes of CO_2-eq. emitted, and providing a NZD 25 fixed price option.

The ETS covers liquid fossil fuels used in New Zealand (incl. petrol, diesel, aviation gasoline, jet kerosene, light fuel oil, and heavy fuel oil). Biofuels are not included. The scheme applies to liquid fossil fuels as far up the supply chain as possible – in other words, when refined oil products leave the refinery or are imported. Consequently, it is the fuel suppliers who take fuel from the refinery or who import it who will be required to participate in the scheme. Individual vehicle users are not participants in the ETS.

1. Based on IEA (2009a) and *www.climatechange.govt.nz/emissions-trading-scheme/index.html*.
2. Personal communication, The Delegation of New Zealand to the OECD, Meeting of the WPNEP, November 2008.

Programme of Innovation for Green Economy and Society provides tax incentives for the development and diffusion of next-generation vehicles.[12]

In the United States, the *Energy Policy Act* of 2005 provides a tax credit for buyers of dedicated alternative fuel vehicles up to a maximum value of USD 4 000. The fuel cell vehicle tax credit is available up to a maximum of USD 8 000, the hybrid vehicle tax credit is up to USD 3 400.[13] More recently, the 2009 *American Recovery and Reinvestment Act* provides for approximately USD 30 billion in the form of tax-based incentives to support clean energy research, development, and deployment. In addition, a plug-in hybrid electric vehicle consumer tax credit (up to USD 7 500) is available (IEA, 2009a).

Annual motor vehicle ownership taxes

Many OECD countries have in the past imposed taxes on vehicle ownership with the tax rate determined on the basis of vehicle weight and engine size. More recently, the basis of vehicle tax is now based on CO_2 emissions (for example, this is the case of Germany[14] and Italy[15]). Such moves to link car taxes wholly or in part to the CO_2 emissions from new cars are being encouraged by the European Commission also in other EU member states. For example, the United Kingdom has already responded to this request from the European Commission by linking the vehicle holder's tax (road tax) and the addition to taxable income for private use of a company car to the CO_2 emissions. In doing so, the UK intends to help ensure that 10% of all new cars sold in the UK in 2012 will produce CO_2 emissions of 100 g/km or less (IEA, 2009a). In addition, the UK has reformed its annual vehicle tax by incorporating incentives favouring low-CO_2 vehicles (see Box 3.5).

Kilometre (road usage) taxes

The primary objective of road pricing policies, in addition to raising funds for road maintenance, is to encourage a modal shift away from personal transport. Hence, while road pricing may impact the overall volume of traffic, it is unlikely to provide incentives for

Box 3.5. **Vehicle excise duty in the United Kingdom***

All cars in the UK are subject to an annual tax called the Vehicle Excise Duty (VED). While in the past the same flat rate applied for all cars, starting in 2001 the VED was reformed to incentivise fuel-efficient and low-carbon vehicles. Under the new scheme, newly registered cars were placed into VED rate bands according to their CO_2 emissions. Within each band, alternatively fuelled cars, including hybrid vehicles, benefit from a discount. The excise scheme is designed to be revenue-neutral.

In 2006, the tax rate for the lowest emission cars (band A: 0-100 g/km) was reduced to zero, while tax rate for the most polluting cars (band G: 226 g/km and higher) was increased to GBP 300 from 2007 and to GBP 400 from 2008.

In 2009, a major overhaul of the VED system took effect, expanding to 13 bands differentiated according to CO_2 emissions. The new system increases the number of bands for the more polluting vehicles and sets lower tax rates for alternative fuel cars.

Vehicle tax rates (2010/11) for cars registered on or after 1 March 2001

Band	CO_2 (g/km)	Standard rate	Alternative fuel rate
A	Up to 100	£0	£0
B	101-110	£20	£10
C	111-120	£30	£20
D	121-130	£90	£80
E	131-140	£110	£100
F	141-150	£125	£115
G	151-165	£155	£145
H	166-175	£180	£170
I	176-185	£200	£190
J	186-200	£235	£225
K	201-225	£245	£235
L	226-255	£425	£415
M	Over 255	£435	£425

The new system provides also additional incentives for purchasing low-emission cars. Tax rates for new cars when they are first registered ("first-year rates") are now set such that the difference between the least and the most polluting vehicles is accentuated. This is intended to send a stronger signal to the buyer about the environmental implications of their car purchase.

Vehicle tax rates (2010/11) for new cars

Band	CO_2 (g/km)	First-year standard rate	First-year alternative fuel rate
A	Up to 100	£0	£0
B	101-110	£0	£0
C	111-120	£0	£0
D	121-130	£0	£0
E	131-140	£110	£100
F	141-150	£125	£115
G	151-165	£155	£145
H	166-175	£250	£240
I	176-185	£300	£290
J	186-200	£425	£415
K	201-225	£550	£540
L	226-255	£750	£740
M	Over 255	£950	£940

* Based on IEA (2009a) and *www.direct.gov.uk/en/Motoring/OwningAVehicle/HowToTaxYourVehicle/DG_172916*.

reducing per-unit fuel consumption and CO_2 emissions. However, these schemes can be modified in order to provide such incentives. For example, an interesting and innovative policy is to be implemented in the Netherlands. It will impose a tax on road usage (kilometres driven annually) applying a differentiated tax rate which varies by the type of vehicle reflecting its CO_2 emissions. Such policy thus combines elements of a pure kilometre tax and a pure CO_2 emissions tax. (See Box 3.6 for more details.)

Box 3.6. **Road usage tax in the Netherlands***

Faced with increases in road traffic, congestion, and the associated environmental problems, the Dutch government (after consultation with automotive and industry associations, trade unions, and environmental organisations) introduced a tax per kilometre to be charged for vehicles on Dutch roads, differentiated by time, place and other environmental factors. The pricing system will rely on satellite technology to operate. After an initial trial period, the system is scheduled to be operational in 2011 (freight transport) and 2012 (personal transport) (IEA, 2009a).

With the introduction of the kilometre tax, the former fixed car taxes (annual motor vehicle tax and vehicle purchase tax) are being abolished. Consequently, the tax burden will shift from car ownership to car usage. Under the new scheme, motorists will thus only pay for the kilometres actually driven. A base rate per kilometre driven in the Netherlands will apply. The base rate will be differentiated on the basis of vehicle's CO_2 emissions. In addition, a per-kilometre surcharge may apply for driving particularly busy routes during rush hours. This is intended to both reduce CO_2 emissions and reduce traffic (especially during peak hours). It is expected that reducing the number of cars on the road during peak commute by 10% will eliminate traffic jams. The policy is intended to be revenue-neutral.

* Based on *www.verkeerenwaterstaat.nl/english/topics/mobility_and_accessibility/road_pricing/index.aspx*.

Information-based measures

The presence of information asymmetries between buyers and sellers leads to inefficient market outcomes because buyers are unable to purchase goods with the bundle of attributes that correspond to their preferences. In addition to such market imperfections, certain types of goods may not be offered in the market at all (incomplete markets).

In the markets for new cars, both types of market failures may be present. Lacking or unclear information about vehicle characteristics may discourage consumers from purchasing a fuel-efficient or a low-CO_2 vehicle. To mitigate such situations, many OECD governments have introduced policies that allow consumers make informed choices (*e.g.* product labelling) and that influence consumers to purchase more fuel-efficient products (*e.g.* green vehicle guides, free advice to consumers). In addition, such measures may help mitigate the problem of incomplete markets because they allow other policies to be "tied" with these information measures (for example, providing a price bonus/subsidy for the purchase of a vehicle with a low-CO_2 label).

Product labelling

In Australia, fuel consumption labelling (litres per 100 km) has been mandatory since 2001. It applies to new passenger vehicles, four-wheel drive and light commercial vehicles sold in the domestic market. Since 2004 the label must also carry a CO_2 emissions

(g/km) figure. The scheme now applies to all vehicles up to 3.5 tonnes of gross vehicle mass (incl. some larger off-road vehicles) (IEA, 2009a) (see also *www.environment.gov.au/settlements/transport/fuelguide/label.html*).

In New Zealand, fuel economy labels must be displayed on new and used (manufactured after 2000 for which data is available) passenger cars at the point of sale. The fuel economy information is expressed in three different ways: *i)* fuel economy cost per year; *ii)* fuel economy rating out of six stars; and *iii)* fuel consumption in litres per 100 km (IEA, 2009a) (see also *www.rightcar.govt.nz* and *www.fuelsaver.govt.nz*).

In Japan, a fuel efficiency labelling system was introduced in 2004 to promote public awareness of vehicles that achieved the Top Runner fuel efficiency standards. The labelling discloses fuel economy performance with an identifiable sticker, indicating either the status of "fully compliant" or "plus 5%", "plus 10%" or "plus 20% higher fuel efficiency compared to the standard" (IEA, 2009a) (for further details see *www.eccj.or.jp/summary/local0703/eng/02_04_06.html*).

Similar schemes have been introduced also in other countries, including the US where every new passenger car and light truck sold in the domestic market is required to have a fuel economy window sticker label, listing the fuel economy estimates (city and highway) (IEA, 2009a). Mandatory fuel economy and CO_2 emissions labelling scheme has also been put in place in the EU. As of 2008, fuel efficiency and CO_2 emissions labelling of new vehicles is mandatory also in Korea[16] and Turkey (see also *www.sanayi.gov.tr*) (IEA, 2009b).

Consumer education

To further help consumers choose fuel-efficient and lower-CO_2 vehicles, many governments have issued consumer guides and set up programmes that offer free advice to households and businesses on how to improve their fuel economy and CO_2 emission performance. For example, consumer guides have been published in the United States (see Box 3.7) and Australia (see *www.greenvehicleguide.gov.au* and *www.environment.gov.au/*

Box 3.7. **Fuel economy guide and green vehicle guide in the United States**[*]

The joint US Department of Energy and the US Environmental Protection Agency programme has been in place since 2000, producing a yearly Fuel Economy Guide, and maintaining a website that provides information on fuel efficiency for new vehicles (*www.fueleconomy.gov*) The Fuel Economy Guide provides consumers with detailed information about fuel consumption, carbon footprint, and air pollution score for the newest model year vehicles, as well as information about hybrids, alternative fuel vehicles, electric vehicles, and fuel cell vehicles. A list of fuel economy leaders, ranking the top model year performers, is also included.

The Green Vehicles Guide is designed to provide consumers with fuel economy and emission information for all cars and light trucks sold in the United States. Consumers can use the Green Vehicle Guide to find the cleanest, most fuel-efficient vehicle that meets their needs. Each vehicle is given an Air Pollution Score and Greenhouse Gas score on a scale of 0-10, with 10 being the best. Users can compare individual vehicles or vehicle types in terms of fuel efficiency and emissions. It provides information about the fuel economy, air pollution emissions, and greenhouse gas emissions for specific models and configurations of vehicles.

[*] Based on (IEA, 2009a). For details see *www.fueleconomy.gov/feg* and *www.epa.gov/greenvehicles*.

settlements/transport/fuelguide/index.html), and in Canada free advice is provided to households (see also *www.ecoaction.gc.ca/ecoenergy-ecoenergie/personalvehicles-vehiculespersonnels-eng.cfm*) and businesses (see Box 3.8 for details). In addition, some countries have been actively promoting changes in driving habits that contribute to increased fuel efficiency, so-called "eco-driving" (*e.g.* Japan, Canada, Finland, and the Netherlands) (see also *www.ecodriving.org*, *www.hetnieuwerijden.nl*, *www.asiaeec-col.eccj.or.jp/eng/e3105promo_ecod.html*, *www.ecoaction.gc.ca/ecoenergy-ecoenergie/personalvehicles-vehiculespersonnels-eng.cfm*).

Box 3.8. **Advice for the freight sector in Canada**

The commercial highway freight sector is responsible for about 10% of Canada's greenhouse gas emissions. The "ecoENERGY for Fleets" programme introduces fleet operators to energy efficient practices that can reduce fuel consumption and emissions. Free practical advice is offered on how energy-efficient vehicles and business practices can reduce fleet operating costs, improve productivity and increase competitiveness. The Programme helps to ensure fleet vehicle owners and managers are aware of the fuel efficiency benefits of new and developing technologies. It is expected that more than 200 000 professional drivers – of heavy trucks, buses, construction and other vehicles – will receive training in energy efficient vehicle operating techniques over the four years of the programme (IEA, 2009a) (see also *www.ecoaction.gc.ca/ECOENERGY-ECOENERGIE/fleets-parcsvehicules-eng.cfm*).

Demonstration and deployment programmes

Public procurement can be an effective means of encouraging innovation with respect to AFV vehicles. Since there are important positive externalities and economies of scale associated with the fuelling infrastructure, "take off" in the market may be dependent upon a significant purchaser taking the lead (network effects). Moreover, there may be important demonstration effects (demand-side information externalities). Faced with co-existence of the network and demonstration effects, public programmes to purchase a fleet of AFVs can provide a spur to adoption by private buyers, thus inducing innovation (see OECD, 2003 for a discussion of the types of goods for which public procurement is likely to be an effective means of inducing innovation). Several examples of such programmes are reviewed next.

Following the introduction of the ZEV regulation in California in 1990, the French government initiated a national programme to develop and deploy electric vehicles in 1992. As part of the programme domestic car manufacturers pledged to develop electric vehicles and the national electric utility set out to build the appropriate charging infrastructure. The formal agreement signed in 1995 aimed at 100 000 electric vehicles on France's roads by 1999 and 5% of newly registered vehicles being electric. In addition, it set a target of 10% of public sector vehicle fleets to be electric. One year later the target was increased to 20% for government agency fleets of at least 20 vehicles. The procurement programme was complemented with several rental programmes intended to familiarise the public with AFVs as well as to foster behavioural changes of car users (car-sharing). Despite these efforts, by the end of 2002, about 7 500 electric vehicles were on France's roads (over 90% in fleets of municipalities and public utilities) – much less than the initial objective of 100 000, but still more than any other industrialised country at the time (there

were about 3 500 electric vehicles in the rest of Europe) (Calef and Goble, 2007) (see also Richard, 1992 and Groupe Interministériel Véhicules Électriques, 1995).

In 1993, Sweden decided to launch its own "Electric and Hybrid Vehicle" RD&D programme. In addition to technology development, it also included test-driving of vehicles for private and commercial purposes, and experimenting with infrastructure for recharge, battery exchange, and servicing. The goal was to evaluate the possibility to introduce AFVs to the Swedish market on a larger scale. In the course of the programme, the number of electric and hybrid vehicles used in the country went up from zero in 1993 to 650 in 2000 (KFB, 2000).

In 1995, Japan initiated a procurement programme aiming to replace 10% of vehicles in public fleets with AFVs by 2000 (battery, hybrid, and fuel cell electric vehicles, CNG and LPG vehicles, and methanol-fuelled vehicles qualified). In 2001, the goal was extended for all vehicles used by government with AFV by 2004. According to Åhman (2006), this first procurement programme did not meet the target as only a few AFVs were in use in 2000, mostly due to public budget constraints. The procurement programme complemented a number of promotional, leasing, and purchasing incentive programmes in operation since 1976. For example, the 1996 "Purchasing Incentive Programme" subsidised 50% of the incremental purchasing price of a battery-powered electric vehicle (BPEV). Initially only a small number of BPEVs were put in use (655 BPEVs between 1977 and 1996, mostly re-converted conventional vehicles) but starting 1997 the numbers began to rise faster following an expansion of government policies which now covered also hybrid vehicles. As Åhman (2006) points out, this helped Japan to become the first country to have a hybrid electric model on the passenger car market. In 2001, there were over 50 000 hybrid electric vehicles in use in Japan. As a next stage, by 2010 about 50 000 fuel cell electric vehicles should be introduced in fleets of public utilities and industry (Åhman, 2006).

More recently, other OECD countries have launched new or extended the existing public procurement programmes in order to accelerate market introduction of AFVs technologies. These include, for example, the United Kingdom (for example, see the "Low Carbon Vehicle Procurement Program" at *www.dft.gov.uk/pgr/scienceresearch/technology/lowcarbonvehicleprocurementprog*), United States (for example, see the Clean Cities Programme of 1993 at *www1.eere.energy.gov/cleancities*), Japan (for example, see the Green Procurement Law of 2000 at *www.env.go.jp/en/laws/policy/green* and the Plan to Control GHG Emissions at *www.env.go.jp/earth/action*), Australia (New South Wales) and Korea. For recent reviews of worldwide initiatives to increase "uptake" of AFVs see IEA (2009c) and SEI (2008).

Measures improving co-ordination

Demand-side infrastructure development

Markets for alternative fuel vehicles suffer from significant network externalities (re-fuelling infrastructure). Addressing these market failures is critical to achieving diffusion or "uptake" of the innovation. Besides achieving environmental objectives, a broad diffusion will create market demand which itself will provide continuing incentives for further product innovations (and thus allowing government to withdraw from supporting R&D).

For example, the United States' *American Recovery and Reinvestment Act* of 2009 provides an "alternative refuelling property credit" – a tax credit to businesses (*e.g.* fuel distribution stations) that install alternative fuel pumps, such E85 fuel, electricity, hydrogen, and natural gas (IEA, 2009a).

Another example is the German *National Development Plan for Electric Mobility (2010-20)* which, in addition to supporting R&D in batteries and electric car designs, targets developing the necessary infrastructure for a large-scale introduction of battery-powered vehicles in Germany. This includes the use of renewable energy and intelligent charging of batteries to stabilise power grid and integrate fluctuating renewable energies. Another important goal is to achieve international standardisation (technical norms) of charging infrastructure and associated vehicle components with the aim of reducing the overall infrastructure investment cost and increasing consumption spillovers. The Plan's stated goal is to have 1 million electric vehicles on German roads by 2020, and 5 million by 2030.[17]

An ambitious technology diffusion project has been adopted in Portugal. The 2009 *National Programme for Electric Mobility* aims at creating a nation-wide infrastructure that would allow a large-scale diffusion of electric vehicles. The goal is to develop a fully integrated and totally interoperable system, allowing any individual the access to any provider of electricity in any charging point exploited by any service operator. The goal is to ensure transparency in the market and thus low entry barriers and competition along the value chain. The Portuguese electric mobility network is projected to comprise 1 300 slow-charge and 50 fast-charge points, installed across the country over the next two years. Another objective of the plan is to achieve integration of the system with increasing renewable electricity production.[18]

In sum, national governments are currently taking steps that will shape the future electric vehicle market. As much as each of these steps is an important individual contribution to achieving wide market diffusion, co-ordination between national governments is desirable – notably to achieve a certain degree of interoperability of the national systems. For example, this can be achieved through harmonisation of technical norms (*e.g.* charging infrastructure). However, it is important that standardisation is not done too hastily and that the benefits of standardisation are weighted against its costs (*e.g.* reduced competition, risk of technology lock-in).

Supply-side innovation platforms and industrial networks

In addition to network externalities affecting the demand side, markets for innovation frequently suffer co-ordination problems resulting in high transaction costs. A *National Platform on Electric Mobility* envisaged in the above-mentioned German *National Development Plan for Electric Mobility* is an example of a measure intended to reduce these costs.

In the UK, the "Low Carbon Vehicles Innovation Platform" has been set up under the umbrella of the "Technology Strategy Board" which plays a leadership role in providing greater co-ordination of various government agencies and research institutions with the aim of stimulating business R&D and innovation, in particular through co-ordination of support for RD&D, combined with better co-ordination of policy and regulation, linked through to public procurement opportunities (IEA, 2009a) (see also *www.innovateuk.org* and *www.innovateuk.org/ourstrategy/innovationplatforms/lowcarbonvehicles.ashx*).

Measures taken in some non-OECD countries

In China, vehicle excise tax rates, fuel efficiency standards, and differentiated VAT rates are applied. Excise tax rates for vehicles have been proportional to engine size since 1994. As of 2006, the range of tax rates was broadened accentuating the differences between cars with small and large engines. Mandatory fuel efficiency standards for passenger cars, established in 2004, classify vehicles into 16 categories based on vehicle

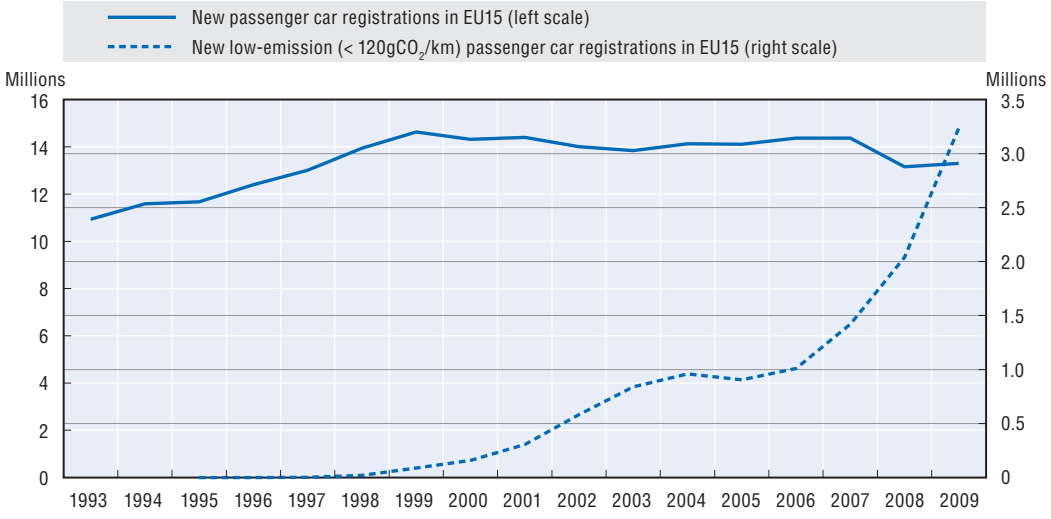
weight. Different standard apply to vehicles with manual and automatic transmission. The standard values are maximum allowable limits for each vehicle type, not the limits for the fleet average of the categories. Differentiated value added tax rates are applied to purchase of vehicles – 3% VAT for less than 1.5 litres of cylinder volume and 20% VAT for 4 litres and above (IEA, 2009a).

In many other non-OECD countries policies have been put in place to improve fuel efficiency of conventional vehicles [*e.g.* in India (*www.dhi.nic.in/autopolicy.htm*) and South Africa (*www.polity.org.za/pdf/notice3324.pdf*)]. Moreover, several non-OECD countries appear to place a strong emphasis on steering their car markets towards ethanol and other biofuels as well as on increasing their domestic biofuels supply. Policies aimed at developing the markets for electric and hybrid vehicles seem to be of lesser importance or are lacking. This is in clear contrast with many OECD countries and may be linked to the status of technological development as well as natural resource factors. Biofuels policies, have been put in place for example in Brazil (biodiesel R&D, mandatory ethanol and biodiesel blending content) (*www.iea.org/textbase/pm/?mode=cc&id=4109&action=detail*, *www.iea.org/textbase/pm/?mode=weo&id=3437&action=detail*; see also *www.mme.gov.br/site/home.do* and *www.anp.gov.br*), India (ethanol production subsidies, mandatory blending) (*www.iea.org/textbase/pm/?mode=cc&id=3840&action=detail*; *planningcommission.nic.in/reports/genrep/cmtt_bio.pdf*), South Africa (biofuels strategy) (*www.dme.gov.za*), and China (pilot cities for using ethanol fuel) (*www.china5e.com/laws/index2.htm?id=200503220009*).

Adoption of AFV technologies

There is clear evidence that adoption of fuel-efficient lower-CO_2 vehicles (including those using conventional engines) has intensified and market shares have increased substantially in recent years (Figures 3.17 and 3.18). For example, in the course of three years the sales of lower-emission cars (less than 120g CO_2/km) in the European Union (EU15) have increased from 9% in 2006 to 25% in 2009.

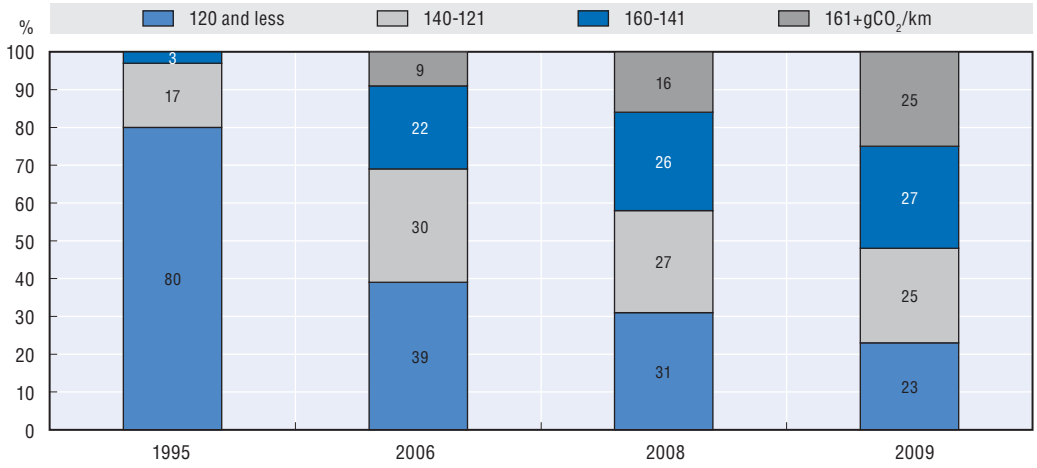
Figure 3.17. **Adoption of fuel-efficient vehicle technologies**



Source: ACEA (2010).

Figure 3.18. **Adoption of fuel-efficient vehicle technologies**

New passenger cars sold in the European Union (EU15) classified by CO_2 emissions (g CO_2/km)

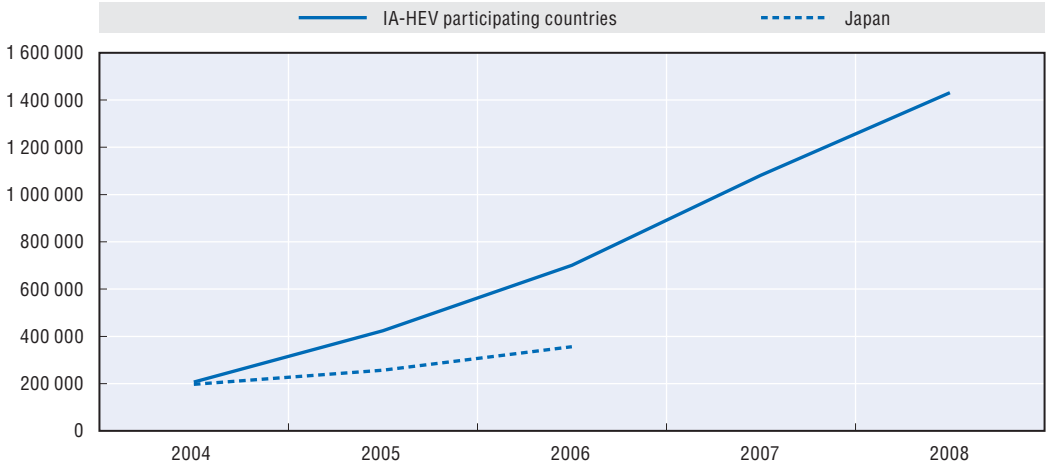


Source: ACEA (2010).

When it comes to alternative fuel vehicles, the limited evidence available suggests that while the sales of AFVs (mostly hybrid vehicles) have been growing rapidly (Figure 3.19), their market share remains rather low (*e.g.* 2.8% in the US, *www.electricdrive.org/index.php?ht=d/Articles/cat_id/5514/pid/2549*).

Figure 3.19. **Adoption of hybrid electric vehicles in selected countries**

Size of vehicle fleet



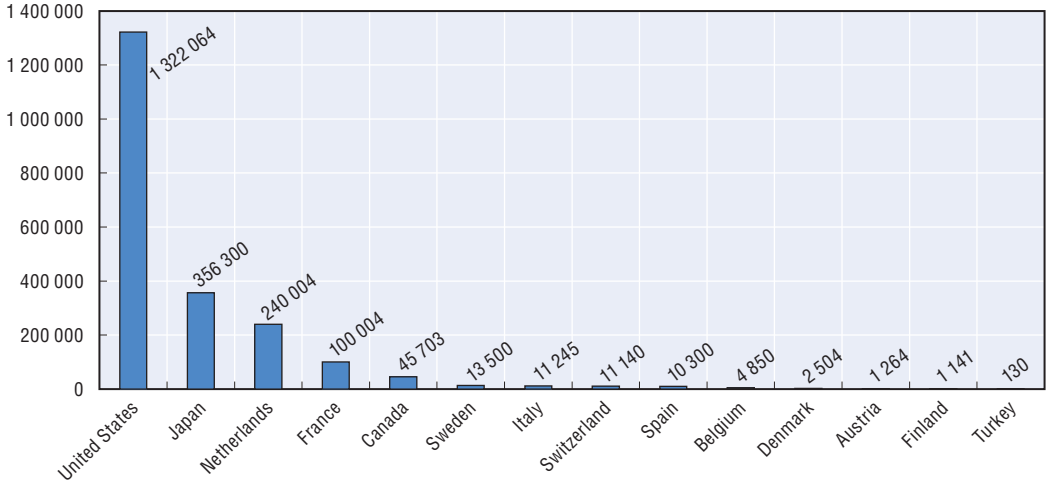
Note: Countries participating in the IA-HEV include: Austria, Belgium, Canada, Denmark, Finland, France, Italy, the Netherlands, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States.

Source: IEA's Implementing Agreement on HEVs (*www.ieahev.org/evs_hevs_count.html*).

According to the IEA's Outlook for Hybrid and Electric Vehicles, the United States, Japan, and the Netherlands have currently the greatest fleets of hybrid electric vehicles (Figure 3.20). The IEA expects that the growth in the share of hybrid cars worldwide is expected to continue and reach 2.2 million units by 2012, but remain below 10% of new car sales in 2015 (partly due to production restrictions, *e.g.* batteries). The share of electric cars is expected to be well below the share of hybrid cars in 2015 (IEA, 2009b).

Figure 3.20. **Adoption of hybrid electric vehicles in selected countries**

Stock of vehicles in 2008 or the latest available year



Note: Data for Japan and France for 2006; Sweden, Austria and Turkey for 2007.

Source: IEA's Implementing Agreement on HEVs (*www.ieahev.org/evs_hevs_count.html*).

Innovation effects of government policies: Empirical evidence based on patent data

In this section we provide preliminary evidence on the effects of policy measures (such as those discussed in Chapter 4) on inventive activity. While it is impossible to develop comparable data across all policy types, countries, and years we focus on the effects of pricing policies, standards and public R&D expenditures. However, a more informal comparison of some measures introduced in individual countries with innovation rates is possible.

As noted above, patent counts have been developed for AFVs based on extractions from the *PATSTAT Database* (EPO, 2009). We constructed a panel of 17 countries[19] and 25 years (1983-2007), however due to many missing observations for the R&D variable (Germany in particular) only 337 observations are retained for regression estimation. The dependent variable is constructed as the share of AFV patenting on sectoral patenting. This approach is suitable because: *i)* the denominator is well-defined in this case (unlike in some previous studies[20]); and *ii)* AFV patenting represents only a relatively small share of the sector overall. We verify that the estimation panel is non-stationary. We then estimate a fixed-effects panel data OLS with heteroskedasticity-robust standard errors.

We test several policy hypotheses. We regress the share of AFV on sectoral patenting on explanatory variables which include public R&D expenditures on fuel efficiency improvements in transportation (in millions USD using 2008 prices and PPP, obtained from the IEA's *Energy Technology R&D Budgets Database*). We also include after-tax gasoline and diesel prices (in USD per litre using 2008 prices and PPP, obtained from the IEA's *Energy End-Use Prices Database*). In both cases the expected sign is positive. Our third policy hypothesis is about the effect of the Zero Emission Vehicle (ZEV) regulation adopted in 1990 in California (USA) which targeted specifically the development and commercialisation of an electric vehicle.[21] This hypothesis is tested by controlling for the effect of the other vehicle fuel efficiency standards in place.

The ZEV standard mandates the percentage of manufacturers' future sales that must be ZEV-qualified vehicles. Over time, several amendments of the initial ZEV standard were adopted. Given this, a continuous variable is constructed as the upper "envelope" of the discounted (at 10%) stream of ZEV mandates applicable for a given year.[22] As such, the variable represents the "implicit" stringency of the series of ZEV mandates over time. And finally, the model also includes variables representing the various fuel efficiency standards (mandatory and voluntary standards, measured in km/l, lagged three years). The descriptive statistics for the panel dataset are provided in Table 3.6.

Table 3.6. **Descriptive statistics for the panel dataset**

Variable	Unit	N	Mean	Std. dev.	Min.	Max.
Share of electric vehicle patents on sectoral patenting	Count of claimed priorities	337	0.0186	0.0304	0	0.2553
Share of hybrid vehicle patents on sectoral patenting	Count of claimed priorities	337	0.0118	0.0266	0	0.25
Public R&D spending on energy efficiency in transport	mln USD 2008 PPP	337	23.12	51.46	0. 05	305.53
Gasoline price	USD per litre 2008 PPP	337	0.7964	0.2776	0.245	1.59
US-ZEV standard	Stringency index	337	3.27	2.29	0	7.51
US-CAFE standard	Km per litre	337	11.28	0.80	8.47	11.70
JP-CAFE standard	Km per litre	337	8.96	6.72	0	15.08

Note: Panel of 17 countries and 25 years (1983-2007).

The regression results (reported in Table 3.7) provide strong evidence of a positive and statistically significant effect of R&D spending on inventive activity both in the electric and hybrid technologies (given that our R&D variable is rather generic – it does not distinguish between spending on electric *versus* hybrid technologies – it not surprising that results do not vary much across the models estimated). We also find that fuel prices have a positive and significant effect on inventive activity in hybrid propulsion but no such evidence has been found for electric propulsion. Finally, we find that the ZEV standard has had a positive and statistically significant effect on inventive activity in electric propulsion, while the effect on hybrid inventions is insignificant. These results suggest that targeted R&D will encourage invention in both types of technologies. However, while fuel pricing is more likely to have an effect on technologies that are closer to the market (hybrids), technology standards appear to be necessary in order to incentivise invention in technologies further from the market, or more "radical" technologies (electric).

Table 3.7. **Regression estimates of the effect of standards, R&D, and prices on AFV inventive activity**

Dependent variable: Share of AFV on sectoral patenting	Electric		Hybrid	
	(1)	(2)	(3)	(4)
Specific public R&D expenditures	5.75e-05*	6.46e-05**	9.63e-05***	9.63e-05***
Gasoline price	0.0004	0.0058	0.0272*	0.0272*
US-ZEV standard	0.0029*	0.0026*	0.0005	0.0005
US-CAFE standard	0.0012	0.0011	0.0012	0.0012
JP-CAFE standard		–0.0002		–2.07e-06
Intercept	–0.0059	–0.0064	–0.0267	–0.0267
Country fixed effects	Yes	Yes	Yes	Yes
N	337	337	337	337

*** < 0.1%, ** < 1%, * < 5%. Panel of 17 countries and 25 years (1983-2007).

An alternative explanation is possible, namely that while a policy may induce advances in the development of an "electric" vehicle, they may not go far enough in order to constitute the "critical mass" of inventions necessary to producing an "electric" vehicle. However, such "partial" advances may turn out to be sufficient to produce a "hybrid" vehicle. (According to this line of thinking, hybrid vehicles would be a means for a partial cost recovery on the way to a full electric vehicle, thus allowing reducing the risk associated with such radical innovation.)[23]

No statistically significant effect is found for the US-CAFE standards. Similar results are obtained if the Canadian or the Australian standards are included instead (not reported); this not surprising given the high correlation with the US-CAFE standard. In the case of the Japanese and European standards no evidence of an effect is found. In alternative specification of the models, we also included the fuel efficiency standards one-by-one (US, JP, AU, CA, EU), and all together as one variable (assuming autarky[24]), but our findings remain unchanged. While no statistically significant effect of the CAFE standards on electric/hybrid patenting was found, these standards may have had an effect on inventive activity to improve fuel efficiency of conventional vehicles – the original target of the standards (hypothesis not tested here).

In sum, these estimates provide evidence that technology standards may have an effect on inventive activity provided they are sufficiently stringent. One could speculate that the differential effect of the standards on different technologies is due to differences in: *i)* the degree of stringency of a standard; *ii)* their mandatory or voluntary character; and *iii)* distance from the externality targeted (electric *versus* hybrid *versus* conventional).

Additional robustness checks were performed using alternative specifications of the model. The qualitative findings for standards and prices remain unchanged when the R&D variable is dropped from the model, thus allowing Germany to be included in the estimation sample because R&D data for Germany are missing. The same holds when an alternative R&D variable is included instead (we used "total energy R&D" expenditures; the estimated coefficient is insignificant, suggesting that the significant effect of the more targeted R&D variable – reported in Table 3.8 – is not a simple coincidence).

Table 3.8. **Estimated elasticity of patenting activity in electric and hybrid vehicles with respect to changes in standards, R&D and fuel prices**

	Electric		Hybrid	
	(1)	(2)	(3)	(4)
Public R&D exp.	0.0714*	0.0802**	0.1887***	0.1886***
Gasoline price	0.0158	0.2469	1.8357**	1.8325*
US-ZEV standard	0.5134*	0.4575**	0.1357	0.1365
US-CAFE standard	0.7145	0.6745	1.1040	1.1046
JP-CAFE standard		–0.1153		0.0016

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

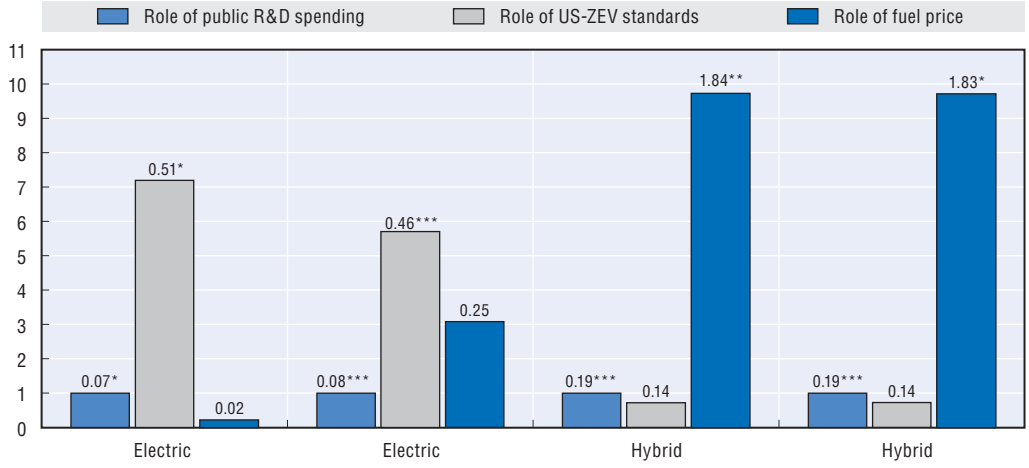
In addition, the dynamic effects have been examined more broadly. For example, lags of the US-CAFE standard ranging from 1 to 5 years yield similar results; lagging the R&D and price variables does have a cost in terms of lower significance levels of these regressors suggesting that there are short time lags between changes in these variables and invention, or that these changes are already integrated in inventors' expectations.

In order to facilitate interpretation of results (and their implications for policy design), we compute the marginal effects and elasticities corresponding to selected models reported in Table 3.8. The estimated elasticities suggest that for a 1% change in the stringency of the ZEV standard the level of inventive activity in electric propulsion will increase by about 0.5%. Similarly, for a 1% change in fuel price levels, invention in hybrid propulsion will increase by about 1.8%. However, both electric and hybrid patenting is rather inelastic with respect to public R&D expenditures because for a 1% rise in public R&D spending invention will increase only by 0.07-0.19%.

Overall, these results provide empirical evidence that the elasticity of inventive activity in electric vehicle technologies with respect to a standard is positive but relatively inelastic. Development of hybrid vehicle technologies is highly fuel price-elastic. And finally, for both types of technologies increases in public R&D budgets have positive but relatively minor effects.

To illustrate this point more clearly, in Figure 3.21 these elasticities are shown as multiples of the effect of R&D (normalised to R&D=1). This shows that the effect of fuel prices on "hybrids" patenting is 9-10 times greater than the effect of public R&D spending for an equal percentage marginal change, and that the effect of the ZEV standards on "electric" patenting is 6-7 times greater than the effect of public R&D.

Figure 3.21. **Effect of technology standards and fuel prices relative to the effect of public R&D (normalised to R&D = 1)**



Note: The histogram shows empirical elasticities, evaluated at sample means, and normalised in terms of the effect of "public R&D spending" (R&D = 1.0). Bars shown "without fill" represent estimates that are not statistically significant at the 5% level. Numbers above the bars give the actual elasticity estimates.

The implications of comparing a percentage change in R&D spending with a percentage change in stringency of a technology standard is difficult to translate directly into practical policy advice. With this in mind, we conducted calculations where rather than setting the change in policies to an equal percentage change and calculating the end results, we did the contrary – we first "fixed" the end result to be equal across the policy scenarios and then calculated the change in policies necessary to obtain this (fixed) end result. The aim is to illustrate the relative importance of the different policies in achieving

a given goal. In other words, we asked the question: "What change in policies would be needed in order to obtain an equal (and infinitesimal) change in inventive activity?"

- For example, to induce a 1% increase in *electric* vehicle innovations, the alternatives are:
  - Increase the stringency of ZEV by 2% (*)[25] – that is, require a 3.33% mandate instead of 3.27% mandate, on average).
  - Increase public R&D by 14% (*) – that is, spend USD 26 mln instead of USD 23 mln per year per country, on average).
- Similarly, to induce a 1% increase in *hybrid* vehicle innovations, the alternatives are:
  - Increase fuel price by 5% (*) – that is, USD 0.84 instead of USD 0.80 per litre of gasoline, on average. However, the actual increase in fuel taxes would have to be higher, depending on the share of fuel taxes on the final price of automotive fuels. Since the tax share is approximately 50% in OECD countries, fuel taxes (value-added and excise taxes) would thus need to rise by about 10%, on average.[26]
  - Increase R&D by 53% (***) – that is, spend USD 35 mln instead of USD 23 mln per year per country, on average.

In sum, these results indicate that relatively minor changes in a technology standard or automotive fuel prices would yield effects that are equivalent to a much greater increase in public R&D budgets. However, it is important to note that the "political" feasibility of these alternatives is not equal, and may vary across countries. Therefore, while in theory two policies an equivalent level of stringency and with the same incidence (targeting the same externality) would be expected to have the same effect on innovation, the policies we observe (our empirical data) do *not* have the same level of "implicit" stringency and hence their effects are different.

Moreover, in practice policies are usually implemented as a "mix" of various policy instruments, partly a consequence of division of responsibilities between various government agencies[27] with imperfect co-ordination of policy-making (the "mixes" may be to varying degrees intended, or unintended). There may be positive or negative interaction effects between policy instruments included in a policy "mix". For instance, on the one hand public investment in R&D of frontier technologies may allow for more stringent regulation, on the other hand more stringent regulation may necessitate supporting R&D in selected technological areas in order to facilitate compliance by the private sector. (These interactions may be dynamically complicated and are not further addressed here.)

And finally, the "policy objectives" may vary across the policies examined with implications for both effectiveness and efficiency. For instance, technology standards and R&D spending place emphasis on inducing innovation. They have only indirect (and in the case of R&D, perhaps positive) effect on car ownership and car use. Conversely, fuel prices are often primarily intended to affect changes in car ownership and use, and the impacts on innovation are "incidental" (but potentially significant). Nevertheless, our results show that even slight changes in policies for which innovation effects may be secondary may stand as an attractive innovation-inducing alternative to increased public spending.

This work could be extended in several directions. For example, a case could be made to set up the estimation models in a conceptually different manner. The automotive industry is, for the most part, a highly concentrated and intensely multinational sector. Therefore, rather than examining the determinants of inventive activity (by inventor countries), it may be interesting to also examine "adoption" of inventions in different

countries (patent jurisdictions). This would allow studying the effect of domestic *versus* foreign policies on international patenting more directly.

Conclusions and policy implications

There are a number of market failures and barriers which affect the markets for AFVs. These include at least the following:

- environmental externalities associated with emissions of local and regional air pollutants, as well as greenhouse gases;
- network effects and monopoly conditions associated with the infrastructure needed to fuel different vehicle types;
- consumption externalities which can result in slow take-up of "innovative" vehicles whose characteristics have not been fully demonstrated in the market; and
- capital market failures which can result in limited financing for high-risk investments (such as those associated with R&D in AFVs).

In order to overcome these market failures and barriers, government policies need to provide a whole spectrum of incentives from encouraging invention to commercialisation and diffusion. In designing such policies, several general principles should be borne in mind:

- The optimal mix of policies should address the different failures and barriers listed above – *i.e.* R&D support (upstream knowledge spillovers), prices (downstream externalities in use), labels (information failures) and procurement (network and demonstration effects).
- Policies whose environmental objectives are determined the basis of abatement costs using existing technologies are unlikely to stimulate innovation. Policies need to be sufficiently stringent to "force" technological change. This can be achieved through performance standards, awards and subsidies, and environmentally-related taxes. The latter are likely to be less demanding in terms of information requirements, but there may be political barriers to their implementation.
- Policies should create opportunity costs that provide incentives for innovators to drive emissions down to zero ("depth" of incentives). Such policies have the potential to encourage "radical" innovations, which have not been foreseen by policymakers.
- Policy flexibility is important so that a wide spectrum of technological options is examined – this applies to AFV relative to other fields as well as within the AFV field. The danger of "picking winners" (*e.g.* through public procurement, R&D support, standards) can result in early technological lock-in.
- Finally, and perhaps most importantly, continuous commitment to the policy objective is key. In order for innovators to take the necessary risks, they need a credible and predictable policy framework.

Notes

1. For example, widespread use of E85 could significantly increase local air pollution due to emissions of formaldehyde and acetaldehyde with ozone-related negative health effects (Jacobson, 2007).
2. According to Masters and Ela (2008) proton-exchange-membrane (PEM) cell, also called polymer-electrolyte membrane cell, is the most appropriate for vehicles.

3. Both, a fuel cell and a battery function on a similar principle as they convert chemical energy directly into electric energy. The difference is that batteries can be regenerated when charged, while fuel cells require re-fuelling.

4. For example, the data suggest that a conventional gasoline-fuelled engine is a rather inefficient way of converting the chemical energy stored in fuel into motion because only about 11% (urban area) to 20% (highway) of energy is actually used to move the vehicle.

5. Another example would be production of methanol from natural gas which yields no improvement in CO_2 emissions on a well-to-wheel basis (OECD, 2004).

6. Personal communication, The Delegation of Japan to the OECD, Meeting of the WPNEP, April 2009.

7. For example, it required a minimum driving distance of 100 miles on a single charge, later amended to 50 miles (Calef and Goble, 2007).

8. For example, see Calef and Goble (2007) for a discussion of ZEV's innovation effects. See also Gruenspecht (2001) and Calef and Goble (2007) (and references cited therein) for suggestions on improvement of the policy.

9. Personal communication, The Delegation of the USA to the OECD, Meeting of the WPNEP, November 2008.

10. Personal communication, The Delegation of France to the OECD, Meeting of the WPNEP, November 2008.

11. Personal communication, The Delegation of Japan to the OECD, Meeting of the WPNEP, November 2009.

12. Personal communication, The Delegation of Japan to the OECD, Meeting of the WPNEP, April 2009.

13. Personal communication, The Delegation of the United States to the OECD, Meeting of the WPNEP, April 2010.

14. Personal communication, The Delegation of Germany to the OECD, Meeting of the WPNEP, November 2008.

15. Personal communication, The Delegation of Italy to the OECD, Meeting of the WPNEP, May 2007.

16. Personal communication. The Delegation of Korea to the OECD, Meeting of the WPNEP, April 2009.

17. Personal communication, The Delegation of Germany to the OECD, Meeting of the WPNEP, November 2009. See also *www.bmu.de/english/mobility/doc/44799.php*.

18. Personal communication, The Delegation of Portugal to the OECD, Meeting of the WPNEP, April 2010. See also the "MOBI.E" pilot-project (*www.mobi-e.pt*) and the "National Energy Strategy for 2020" (*www.portugal.gov.pt/pt/GC18/Governo/Ministerios/MEI/ProgramaseDossiers/Pages/20100415_MEID_Prog_ENE2020.aspx*).

19. Including Austria, Australia, Belgium, Canada, Switzerland, Germany, Denmark, Spain, Finland, France, Italy, Japan, the Netherlands, Norway, Sweden, the United Kingdom and the United States.

20. For example, innovations in air and water abatement as well as waste management (AWW), discussed in Chapter 2 of this book, are relevant to many "sectors". As such defining the denominator corresponding to AWW patents is complicated.

21. This assumes that California's ZEV mandates were of broad relevance for the entire United States and even internationally. For empirical evidence of such "California effect" see, for example, Perkins and Neumayer (2011).

22. Only mandates to be met with electric and hybrid vehicles were considered (pure ZEVs and ATPZEVs); proportion of the mandate allowed to be met by sales of vehicles with conventional engines, although fuel-efficient (PZEVs), were disregarded.

23. Indeed, it has been suggested that hybrid vehicles (referred to as "advanced-technology partial ZEVs" or ATPZEVs) could be considered a collateral outcome of California's ZEV regulation. According to one report, about 250 000 ATPZEVs have been delivered for sale in California as a result of the ZEV regulation (*www.arb.ca.gov/msprog/zevprog/2009zevreview/zevwhitepaper.pdf*).

24. In this latter case it is assumed that only "domestic" effects of policy are possible. This is in contrast to the former variables which are constructed assuming non-autarky – meaning that a country's policy may have an effect on activity at home as well as abroad.

25. Asterisks indicate statistical significance, with *** < 0.1%, ** < 1%, * < 5%. The numeric values used here refer to averages based on the estimation panel.

26. Among the OECD countries, the polar cases are a tax share of 67% in Germany and the UK, and 17% in the US.

27. For example, fuel taxation is typically in the domain of Ministries of Finance, while emission standards may fall under Ministries of Environment, and R&D grants may be disbursed by the Ministry of Transport.

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Chapter 4

Diverting Waste: The Role of Innovation

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Encouraging innovation in material recycling and waste management technologies has been on the agenda in many countries for several decades. In this chapter, the data presented indicate the possibility that the first wave of policies (end of the 1980s, beginning of the 1990s) has produced an innovation response, but their effect is now less pronounced. Technological maturity of this sector, relative to other areas of environmental innovation, is one possible explanation for this finding. Nonetheless, in many countries recycling rates have increased and waste generation per unit of economic activity is beginning to fall. It is likely, that for mature sectors responses to environmental policy shocks may be reflected in behavioural and organisational innovations, rather than in terms of technological inventions.

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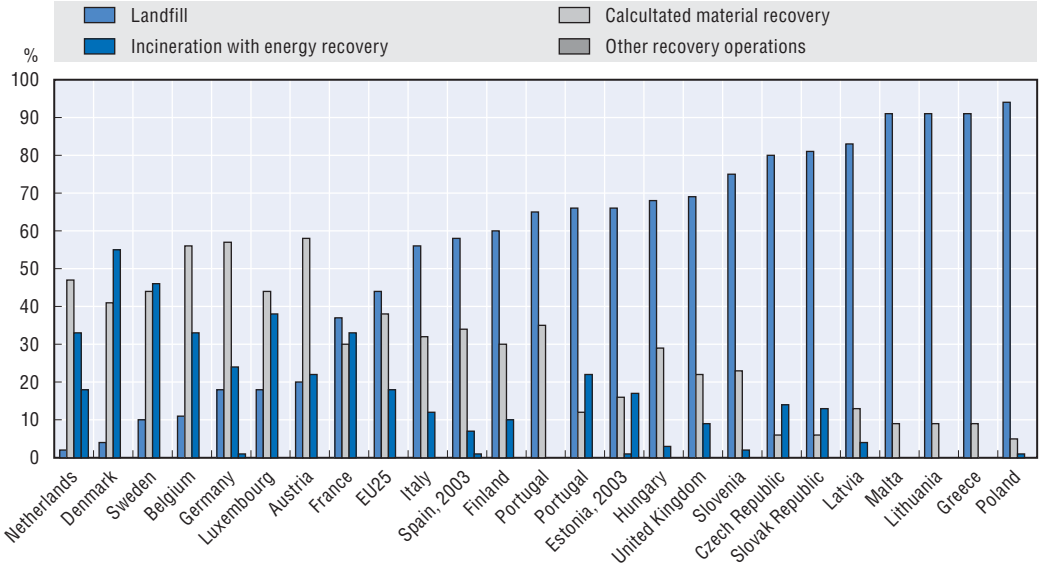
Introduction

In the last twenty years, environmental policies have been increasingly oriented towards a reduction in the amount of municipal solid waste landfilled and the promotion of other forms of waste disposal, such as incineration and recycling, as well as upstream prevention. The constantly increasing price of land in densely populated areas and a growing consciousness of the health and environmental consequences related to the various forms of waste recovery have placed landfill reduction as one of the primary aims of OECD solid waste policies.

The total amount of waste in OECD countries is increasing and not decoupling from consumption expenditure, and this will pose even more focus on the need of a more stringent regulation. The EEA (2007) notes that "waste volumes in the EU are growing, driven by changing production and consumption patterns". In the United States "solid waste generation has increased, from 3.66 to 4.50 pounds per person per day between 1980 and 2008" (USEPA, 2008). In Japan, the Basic Law for establishing the Recycling-Based Society was introduced in order to deal with rising volumes of waste (JEA, 2000).

Landfill diversion and waste prevention are the priorities in the waste management hierarchy. However, landfilling remains the most important waste management option in most OECD countries, albeit with significant differences across countries. Figure 4.1, referring to the year 2004, shows that in Europe, despite an average of 45 per cent of waste landfilled and 18 per cent of waste incinerated, there are some countries, like the

Figure 4.1. **Use of landfilling, incineration and material recovery as treatment options in 2004**



Source: EEA (2007).

Netherlands, Denmark, Sweden and Belgium that have already very low landfilling rates, combined with an important role of incineration and material recovery (EEA, 2007).

Moreover, among the remaining countries, there are important differences in the choice of waste management strategies. The remaining countries can be divided into two groups: the first one including nations like Italy, the United Kingdom, Portugal, Ireland and Finland that show a predominant use of landfill accompanied by significant recycling and incinerating activities, and a second group of countries, including the Czech Republic, Malta, Poland and Greece, in which landfill accounts for 80% of the recovery strategy or even more.

In each country there is usually a mix of command and control instruments, aimed at regulating specific aspect of the waste disposal. This includes bans on landfilling of specific materials, technical requirements for the construction of landfill sites and incineration plants, specific limits on the heavy metal contain in plastic and paper packaging, etc. Furthermore, many countries have shifted the responsibility from the consumer to the producer, as in the case of the automobile sector and plastic and paper packaging. Finally, often legislations impose specific performance targets (such as a share of waste to be recycled), with flexibility in the adoption of the preferred technology.

The motivation for policy efforts which encourage diversion is due in part to the negative environmental impacts of landfilling (Pearce, 2004; El-Fadel *et al.*, 1997; Eshet *et al.*, 2004). While landfill activities remain the most common means of waste disposal, and in many cases continued landfilling is economically justified, it is not necessarily the most efficient strategy for certain waste streams where it remains the dominant practice. The costs and benefits of different waste management strategies are influenced by economic and technological factors that should be taken into account. Economic assessments of different waste management strategies are well described, among others, in the contributions of Pearce (2004) and Dijkgraaf and Vollebergh (2004).

Although waste prevention is at the top of the waste hierarchy, there are no regulations in OECD countries which explicitly mandate such a strategy. This is due in part to the costs of implementing and monitoring such an approach, except in specific cases. For this reason, the first phase of policy implementation in most OECD countries has focused on landfill diversion and promotion of material recycling, energy recovery, and incineration, and not on waste prevention.

New waste management options arose during the 1990s, due in part technological change. Our objective in this study is to test the effect of various environmental policies on innovation. While there is some empirical evidence to support the general theory that environmental policies stimulate innovation (see Jaffe, Newell, and Stavins, 2002 for a literature review), there are no known examples of analysis applied to the waste sector. Nevertheless, it is reasonable to think that a more stringent regulation may have spurred innovation in emerging sectors like recycling and incineration. In particular it is expected that activities like separate collection, sorting, composting and recycling that were relatively new in the 1980s, may have evolved rapidly after the introduction of the first legislative instruments. Moreover, this work studies technological change in the waste sector from a process point of view, in a manner similar to the work on pulping technologies reported in Popp and Hafner (2008).

This approach provides us with some interesting insight on the role of policy stringency on a sector that has changed significantly in the last thirty years. Furthermore,

the use of data drawn from the *EPO Worldwide Patent Statistical Database (PATSTAT)*, allows us to study how waste-related technologies have changed over the period 1970-2007. In the study we focus on different waste streams: paper and plastic packaging waste, end-of-life vehicles, composting, as well as recycling and solid waste management more generally.

Indicators of innovation for the specific waste streams were constructed on the basis of counts of patent applications. The data were extracted from the *PATSTAT Database*, selecting the relevant categories among all the possible IPC classes (see Table B.9). On this basis we have been able to create a dataset containing patents relevant to the following technologies: recycling, composting, paper packaging, plastic packaging and end-of-life vehicles recycling activities. Moreover, another count which covers all patents relevant for municipal solid waste technologies (*i.e.* the sum of recycling, landfill and incineration technologies) has been created. The Table 4.1 shows the patent classes used in the definitions of different waste technologies. For example, plastic patents are the sum of all the patents included in the categories B29B17 and C08J11, while municipal solid waste is the sum of all groups, minus the two related to end-of-life vehicles (because ELVs are usually considered hazardous wastes).

Table 4.1. **Key regulations in each country and brief description**

European Union	1985 – Directive on beverage containers: promoted recycling and reuse, with a strong focus on packaging waste. 1994 – Second Packaging Directive: This Directive set minimum recycling and recovery targets for packaging waste. Strong focus on the importance of promoting recycling activities. 1999 – Landfill Directive: Set stringent technical requirement for landfill sites with the aim of preventing or reducing the adverse effects of the landfill of waste on the environment and, contextually, incentive recycling.
Germany	1990 – Packaging regulation ("Töpfer" Act): producer pays principle for packaging waste, stringent recycling and reuse target. Strong focus on Recycling.
Japan	1991 – Recycling Law. Set recycling target for many different waste streams, giving a strong incentive at the growth of the sector.
United States	1976 – Resource, Conservation and Recovery Act. Aimed at reducing the amount of waste generated and promoting environmental friendly management solution, like recycling.

In the first section we present an analysis of the effect of over-arching waste policies on general recycling innovation. In this context the intention is to provide a preliminary assessment of the relationship between policy action and waste technology innovation. The next section will focus on two specific waste streams: plastic and paper packaging. The importance of these two sectors arises from the large amount of packaging material produced every year, and the high level of recyclability of both plastic and paper wastes. The next section will focus on recycling of end-of-life vehicles. This case is of interesting since the type of materials contained in cars may be very polluting and health-damaging and for this reason have to be regulated, but a high proportion of an end-of-life vehicle may be recycled or recovered. In the final section innovation related to composting activities is analysed. Composting is becoming increasingly important since it is perceived to be a "green" way to handle bio-wastes, responsible for the production of methane in landfills.

General waste recycling patent trends

In this first section, we focus on patent applications related to waste recycling technologies in general. We are interested in assessing whether trends in innovation are correlated with the introduction of significant environmental policy measures aimed at promoting a more efficient waste management through landfill diversion and promotion

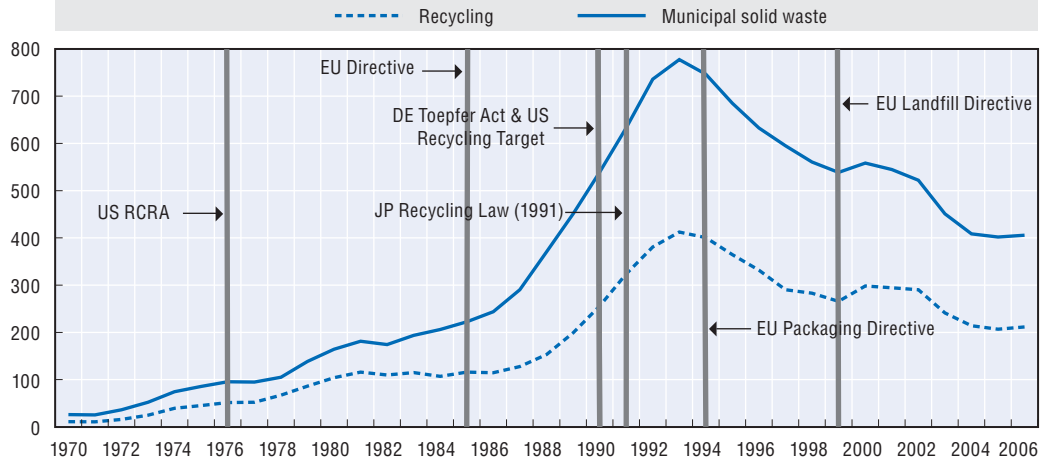
of recycling. The policies considered are briefly explained in Table 4.1. Given the nature of the analysis we have included broad policy instruments that may have caused a shift in waste management composition, inducing innovation in the sector in general, and particularly in recycling technologies.

We expect in fact a more stringent regulation in a given country which is intended to promote recycling activities to be positively correlated to innovative performances in the sector in that country. However, it has to be noted that any of the policies analysed influence directly all the countries analysed. In some cases, they affect directly only one country, like in the German and Japanese case, and in some other cases they affect the majority of the countries, as in the case of European Directives.

The trend of these two variables over the period 1970-2006, as well as the year of introduction of the main policy measures is shown in the table below. As we can see, the trend for recycling and municipal solid waste technologies can be divided in two parts. Before 1998 both variables follow a linearly increasing trend, associated with elasticity below unity. Subsequent to year 1988, both technologies exhibit a bell-shaped path, associated with a rapid increase up to year 1993, and then a regular decrease, until reaching in year 2006 the same level of the beginning of the 1990s.

Figure 4.2. **Solid waste management and recycling patents**

3-year moving average



This first evidence suggests that the sectors seem to have reached a high level of maturity, characterised by a stable or even falling rate of technological change (see Chapter 1 for a comparison with air and water pollution abatement innovation). Moreover, it is not clear that this has been affected by the introduction of a number of significant policies. However, some interesting insights might be derived from the analysis of the more specific waste streams. For this reason, the next three sections will expand this discussion, analysing the innovative and regulatory trend in three specific waste streams: Packaging, ELVs and composting.

Packaging waste innovation and policies

Packaging waste is a growing and important waste stream, which accounts for between 15% and 20% of total municipal solid waste in different countries. The word

"packaging" usually refers to any material which is used to contain, protect, handle, deliver and display goods, *i.e.* empty glass bottles, used plastic containers, food wrappers, cans, etc. From a waste management point of view, packaging waste has some important and well-defined characteristics which require specific treatment, and as a consequence, also specific policies and regulations.

Firstly, even though packaging wastes arise from a wide range of sources such as households, hotels, hospitals, supermarkets, manufacturing industries and restaurants, it is still considered as municipal waste, and for this reason has to be collected and disposed.

Secondly, and more importantly, the management of packaging waste can be undertaken in a number of ways, such as prevention or reuse (usually the preferred options), or alternatively through recycling and recovery, as a second best option. An empty bottle of water made of glass can be, for example, collected separately and then after a specific treatment refilled directly by the producer, or alternatively can be sent to a glass recycling plant. Alternatively, there could be information campaigns at a national or regional level which encourage the use of tap water, reducing the production of packaging wastes directly at the source. Moreover, some countries may recover energy from packaging waste through their incineration. And finally, landfilling remains an important management option for packaging waste in some OECD countries.

Thirdly, under the general name of "packaging waste" several materials are included with very different physical and chemicals characteristics which have to be treated in different ways. While there are some complementary processes which are common to all materials, there are some aspects of recycling glass, metals, paper and plastic require which differ in terms of technologies and management practices. For all these reasons, packaging waste has always had its own policies and regulation, distinct from other waste streams.[1]

In addition, the policies which related to this waste stream can set very different targets and promote alternative ways of handling the problem. A policy could, for example, be strictly oriented towards the reduction of the packaging waste production at its source, through the promotion of reuse or prevention, or it could promote recycling or energy recovery, or a mix of all these elements. For instance, Germany and Austria are tackling the packaging waste issue by promoting recycling, while other countries, like the Netherlands and Denmark have extensive incineration plants with energy recovery systems (EEA, 2005). In this context, technological change plays an important role.

Regulation

The increasing trend of municipal waste generation and the growing awareness of the risks and the costs associated with landfills have generated pressure on governments to tighten waste regulations, and those which affect packaging waste in particular, starting from the late 1970s. At European level, the first Directive regarding packaging waste was Directive 85/339 concerning containers of liquids for human consumption. This Directive, issued in 1985, covered all the liquid beverage containers and its objective was to encourage the reuse and the recycling of such containers, promoting a general energy saving and a reduction of entropic pressure on raw materials. Nevertheless, the impact of this first Directive was limited.

For this reason, a new Directive was drafted with more precise waste performance goals. In particular, this new policy instrument, issued as Directive 94/62, has the primary objective of reducing the amount of waste generated and of harmonising national measures for

managing packaging and packaging waste. It imposes targets for recovery and recycling, but not for prevention. More precisely, the Directive is made up of three different instruments: specific quantitative targets for recycling and recovery, differentiated by material and by country and increasing through time (generally between 55% and 60%); requirements to be fulfilled in order to place packaging on the European market; targets for the concentration of heavy metals in packaging. So the European Union is on the one hand trying to set common standards for packaging waste in the European Union, and on the other hand promoting more environmentally-sound management options. We can expect that this may induce innovation encouraging more efficient forms of recycling.

Many European countries have their own packaging waste regulations. In some cases this is merely the transposition of the Directive into national law, but in other cases the policies preceded the last European Directive. Germany, for example, issued a decree in 1990 (approved in 1991) that proposed one of the most stringent packaging regulations worldwide. This decree, based on the polluter pays principle, imposed the responsibility on the producer under the form of deposit and take back schemes, unless the industry establishes alternative collection and recycling systems that meet precise collection and sorting goals from 1993.

By that year 50% of all packages had to be recycled, while by 1995, at least 80% of all packages had to be recycled. Moreover, this law set quantitative for the sorting of the collected materials (90% glass and metal, 80% other materials) and required industries to use at least 72% of returnable containers for beer, water, soft drinks, fruit juice, and wine and 17% for milk. Furthermore, even before the decree, in 1990 the German packaging industry developed an eco-labelling system, called "green dot", which indicates the packaging products that are eligible for collection. More recently, in 1998, Germany adopted a new packaging ordinance, amended in 2008, which set new targets for re-use, recovery and recycling but which does not alter significantly the overall country strategy.

In 1989 in Italy imposed a tax on plastic shopping bags, and in 1988 were set up precise targets to be achieved by 1993 on glass (50%); metals (60%); plastics (40%); and mixed materials (40%). Moreover, a National Waste Framework Law (D.Lgs. 22/1997) transposed Directive 94/62/EC, establishing a consortium (CONAI) for the management of packaging and packaging waste. In 1988 the Netherlands established targets for the prevention and recycling of 29 waste streams, among which packaging was one of the first priorities (with a target of 60% in recycling by the year 2000), while Denmark adopted a ban on non-refillable containers for beer and soft drinks in 1982 and introduced a tax on beverage containers in 1977. Like Denmark, both Finland and Sweden introduced deposit-refund schemes and taxes on packaging for liquid beverages starting from the early 1970s. Later on, during the 1990s, all northern European countries introduced new regulations to ensure compliance with the Directive. These followed the general European guidelines, *i.e.* producer responsibility, low concentration of heavy metal in packaging, promotion of recycling, and increasing policy stringency through time.

In 1990 in Japan an Industrial Structure Commission constituted by the Government established precise recycling targets for the different types of waste streams, ranging between 40% and 60%; while in Canada in the same year a National Packaging Protocol was proclaimed, which aimed at reducing the amount of the packaging waste produced by 50% by the year 2000, setting intermediate targets and entitling the manufacturer of this responsibility. Following this Protocol the targets had to be met one half through new source reduction and reuse measures, and the other half through recycling.

The case of the United States is more difficult to illustrate: there the regulatory effort is traditionally both at State and a local responsibility. For this reason, the essence of the American regulation is harder to trace and summarise, but according to McCarthy (1993) by 1971 ten states had already established compulsory refunds for beer and soft drink containers. However, it was between 1987 and 1992 that the biggest legislative effort was undertaken, with the result that 22 States have enacted laws to promote recycling collection programmes at local level, and legislation to regulate the use of heavy metal in packaging.

In 1993 Korea adopted a policy to reduce the impact caused by over-packaging, banning the use of some materials like PVC lamination and synthetic resins, applying restrictions on the packaging-space ratio and the number of packaging layers (two) for specific types of food product, and setting targets on the reuse of packaging for specific products. More recently, in 2000 China promoted specific technical policies for municipal solid waste disposal and the prevention and control of pollution, restricting over-packaging.

Summarising, this first wave of policies dating from the end of the 1980s and the beginning of the 1990s, focussed mainly on setting recycling targets, on addressing the presence of heavy metals in packaging waste, and the application of the producer responsibility principle. After this first set of policies, in the last 15 years, policy action has largely continued the approach adopted in the past, but with increasing levels of stringency.

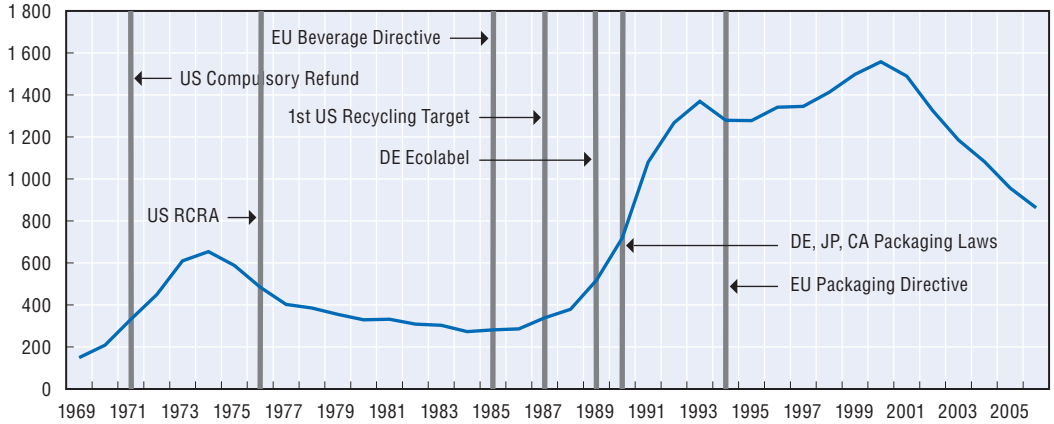
The first signal of a change in the direction came probably from the European Union's 2008 "Waste Framework Directive" (2008/98/EC), which states that member states shall establish waste prevention programmes by December 2013. Even though there may be some anticipatory actions, it is not yet possible to assess the effect of this new Directive on the waste sector in terms of prevention and innovation. Apart from this Directive, examples of policies strictly directed at waste prevention remain scarce.

Innovation trends

The Figure 4.3 illustrates the total number of patent applications that have been filed in all countries in relation to plastic and paper recycling. For both the elements the analysis starts in 1970. It is important to stress the difference in magnitude of the two areas: patents in the plastic sector outnumber the patents related to paper waste by four.

Figure 4.3. **Evolution of patent applications for plastic recycling technologies (worldwide)**

3-year moving average



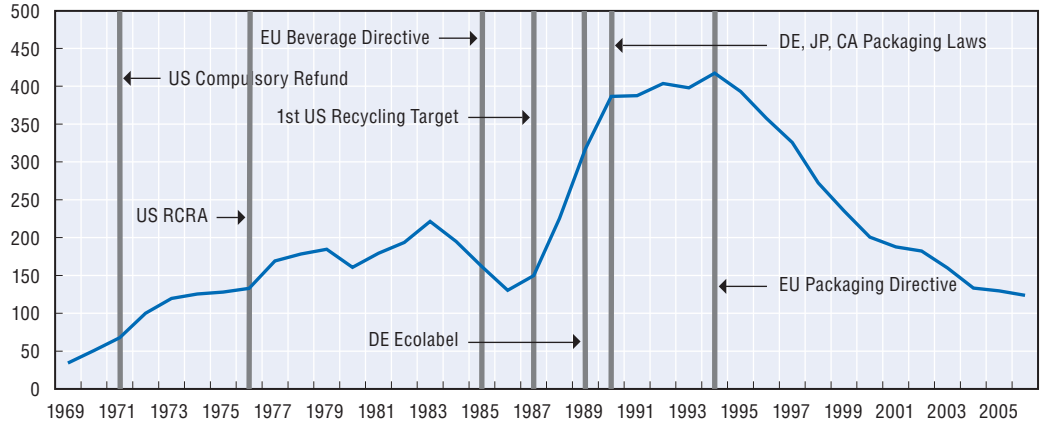
At first glance, the two graphs show a very similar tendency, the trend is stable or slightly increasing until the end of the 1980s and then between 1988 and 1994 the number of patents grew very quickly. After this sudden rise, at the end of the 1990s patenting activities started to decrease in both cases. Even though the trend is very similar, some differences can be observed. The rise in patenting in the paper recycling sector started probably a couple of years earlier than the rise in the plastic sector, while its decline started in 1995 instead of 2001.

Both plastic and paper recycling are governed by packaging policies, and this may partly explain the similarity in innovation trends. Starting from 1970, a first set of policies had been introduced in some American states, and it is plausible to think that the slightly increasing trend which can be seen in both series starting from that year may be due to this first legislative effort in the US. Furthermore, besides the packaging policies illustrated above, in 1976 the "Resource, Conservation and Recovery Act" was introduced in the US, and this may have contributed in some way to the increasing path of patenting registered in the area of paper.

Conversely the European Directive on Packaging of Beverages (1985) does not seem to have an impact on the patenting activities, but the relative weakness of this instrument is well-documented. A more prominent effect seems to be associated with the next wave of regulations which were implemented in the US, Japan, Germany and Europe between 1987 and 1992. As it is possible to see in the following two graphs, there is a high concentration of policies in these years, as well as a rapid increase in patenting for both plastic and paper waste sectors. Given the nature and the type of patents used in this work, that generally refer to new ways of recycling plastic and paper wastes, this trend in patent data was expected, considering that all the packaging related policies here analysed tend to promote and encourage recycling, and consequently to induce innovation in relevant technologies.

Figure 4.4. **Evolution of patent applications for paper recycling technologies (worldwide)**

3-year moving average



The data can be disaggregated by individual intellectual property office, to allow for cross-country comparisons. In particular, in the following three graphs we show how patenting activity responded to different conditions and policies implemented in countries for the most important offices, considering the total patents (singular, CP and duplicate).

The first two graphs relate to plastics recycling innovation and the third one to paper recycling, covering the period from 1970 to 2006 for those OECD countries that produced the most patents in plastic and paper recycling technologies.

In the first graph plastic recycling patent applications for Japan, the United States, Germany and Canada are presented. Before the introduction of strict policies, all four offices exhibit a flat trend in patenting. Coinciding with the introduction of policies in the period 1989-91, patenting activity registered a big expansion in all the countries considered, with Germany anticipating the others countries by about one year, and Japan and Canada following one year after.

In contrast, countries like Korea and China,[2] whose trend is shown in Figure 4.6, exhibit a completely different trend in patenting activities. The first group of countries

Figure 4.5. **Evolution of patent applications at main offices for plastic recycling technologies**

3-year moving average

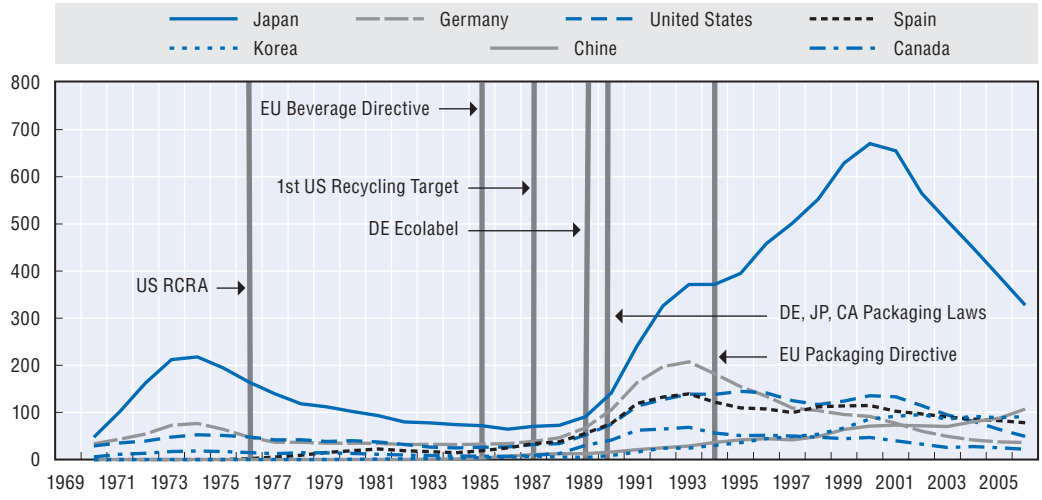
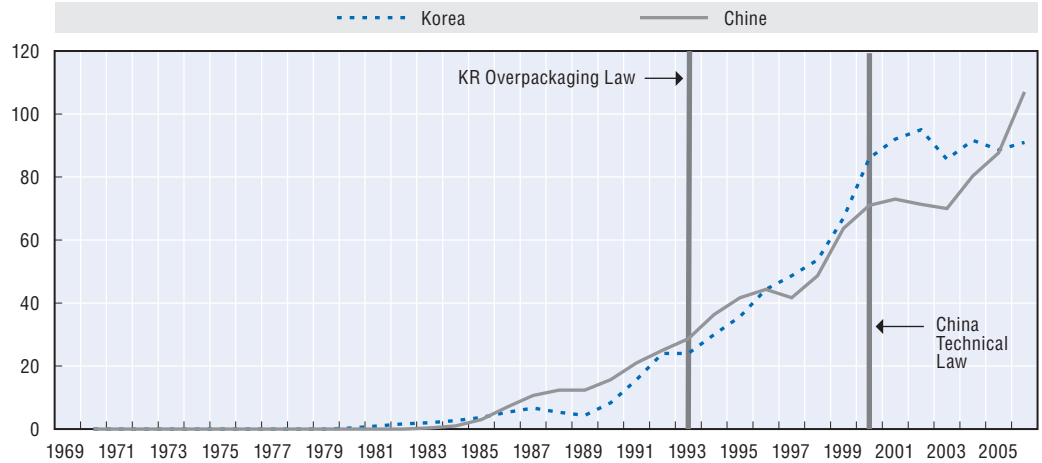


Figure 4.6. **Evolution of patent applications at Korean and Chinese offices for plastic recycling technologies**

3-year moving average

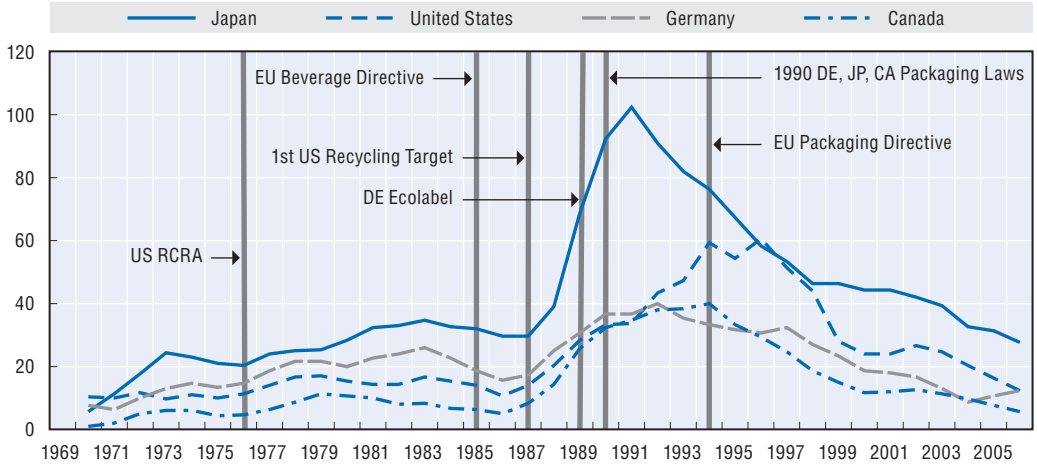


analysed show in fact a bell-shaped trend that increased in 1989 and tended to diminish after year 2000. Korea and China have very flat performances until the beginning of the 1990s, and then start to grow at an increasing rate. This is probably due to two main different forces: on one hand, it is in line with the general increasing trend in patenting in China and Korea in the last fifteen years, but on the other hand this increasing trend is correlated with the somewhat later implementation of a set of policies aimed at the regulation of the waste sector in general, and to the packaging sector in particular.

This last factor is especially relevant for Korea, which enacted a strict policy for the reduction of over-packaging in 1993, in line with the shift registered by the patenting series. In China formal waste regulation started in 1995, but it is only from 2000 that Chinese policies started to focus directly on packaging waste. Paper technologies follow the same trend as plastic, but surprisingly, the rapid explosion registered in patenting in both technologies happened one year earlier for paper than for plastic, showing how the paper sector seems to respond more rapidly to policy stimulations, even though it is characterised by a smaller number of total patents applications. This is confirmed by Figure 4.5 which presents the trend in patenting for the four main countries. In this case China and Korea, registering very low counts in patenting activities, play only a marginal role, and for this reason have been excluded from the graph.

Figure 4.7. **Evolution of patent applications at main offices for paper recycling technologies**

3-year moving average



Up to this point, this analysis has excluded European Patent Office applications in order to avoid double-counting. For this reason, applications at the EPO are presented separately in the following two graphs that present the trend of patent applications for the main European countries at the EPO for plastic and paper recycling technologies. These results show that the EPO count is dominated by patents filed by German inventors, reaching a peak in 1994 for plastics, and in 1991 for paper, following the more general bell-shaped path encountered before. All the other countries have very low counts, and do not exhibit any particular trend.

Figure 4.8. **European countries at the EPO for plastics recycling technologies**

3-year moving average – Germany on the right axis

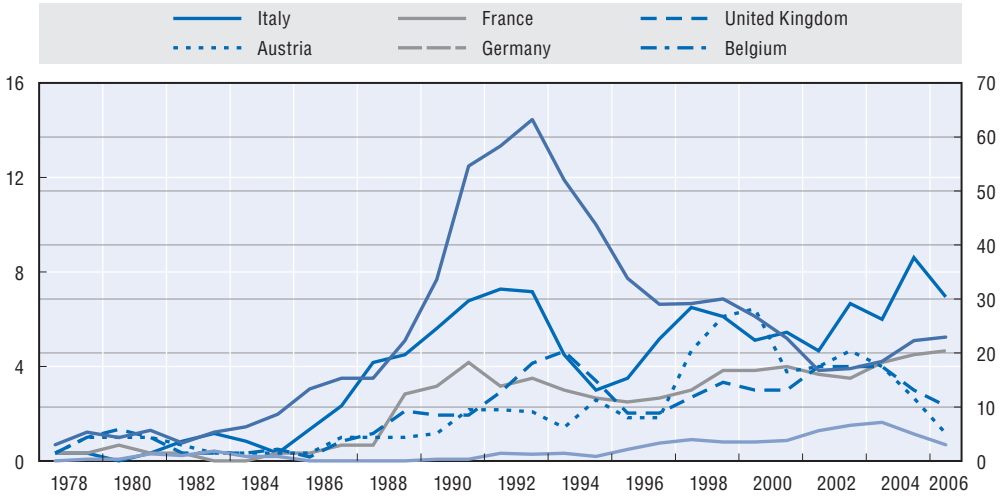
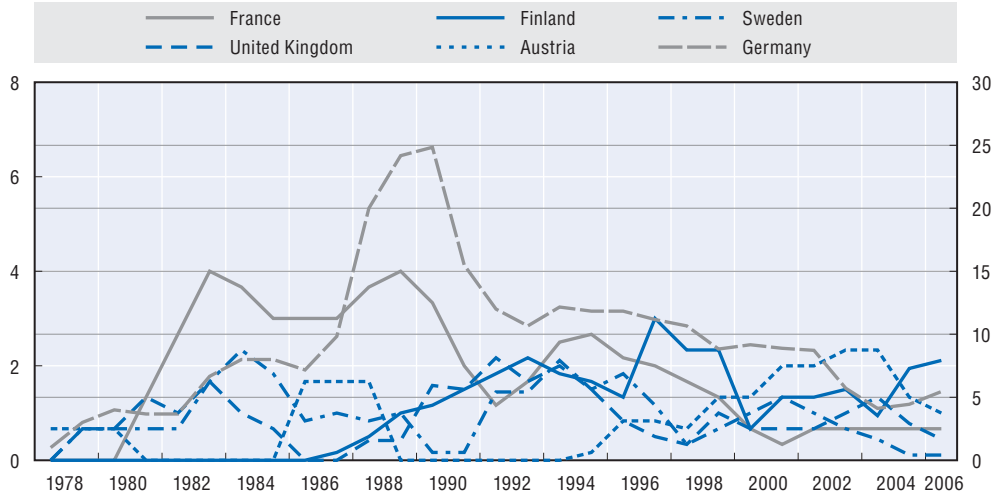


Figure 4.9. **Main European countries at the EPO, paper recycling technologies**

3-year moving average – Germany of the right axis



Assignees

The next two tables show the assignees owning the most patents in each of the top inventor countries. The first table specifically refers to plastic waste recycling inventions, while the second one refers to paper waste. Along with the total number of patents, expressed as sum of fractional counts, the share of total patents owned by every single firm is included. For what concerns plastic, innovations came mainly from the chemical industries and plastic producers and only in some cases from specialised research centres. Chemical companies are more prominent in Germany, while in the US the process is driven mainly by packaging and plastic industries.

Similar observations can be made in relation to the paper waste sector. In this case, almost all patents came from chemical or packaging firms, with the exception of the US, where three of the top domestic patent assignees are paper producers. This result is in line

with the previous results of Popp and Hafner (2008) related to pollution abatement in the pulp industry, which also found that the innovations only rarely originate from the regulated sector itself. However, it is in contrast with the findings reported in Popp (2006) analysis of patent activities for NO_X and SO_2 control. Finally, we can see that there is higher degree of concentration of innovation for paper recycling technologies than for plastic recycling technologies. In the former case the most important assignee owns 43% of the German patents, 25% of Japanese patents, and 26% of Canadian patents.

Table 4.2. **Top domestic patent assignees – plastic recycling technologies**

Firm name	Number	Total (%)
Germany		
Basf AG	251.0	7.0
Der Grune Punkt – Duales System Deutschland Aktiengesellschaft	126.4	3.5
Bayer AG	271.1	7.5
Hoechst AG	85.6	2.4
Fraunhofer Gesellschaft	43.5	1.2
Japan		
Panasonic	106.9	6.8
Bridgestone	22.0	1.4
Canon	23.0	1.5
Ein Engineering CO. LTD.	49.0	3.1
Sony Corp.	42.0	2.7
Hitachi Zosen Corp.	75.3	4.8
United States		
EI Du Pont De Nemours and Company	170.1	5.4
Eastman Chem Co.	98.1	3.1
Xyleco, Inc.	77.3	2.5
Gen Electric Corp.	63.5	2.0
Goodyear Tire and Rubber Co.	63.0	2.0
The Dow Chemical Company	50.0	1.6
The Coca Cola Company	56.5	1.8
Canada		
Emery Microwave Management Inc.	18.0	6.8
The Fulford Group Inc.	10.0	3.8
Phoenix Fibreglass Inc.	10.0	3.8
The University of Toronto Innovations Foundation	8.3	3.1
Du Pont Canada Inc.	9.0	3.4

Table 4.3. **Top domestic patent assignees – paper recycling technologies**

Firm name	Number	Total (%)
Germany		
JM Voith GMBH	638.4	43.8
Henkel	158.3	10.9
Sulzer-Escher Wyss GMBH	132.0	9.1
Basf AG	31.8	2.2
PWA Industriepaper GMBH	31.0	2.1

Table 4.3. **Top domestic patent assignees – paper recycling technologies** *(cont.)*

Firm name	Number	Total (%)
Japan		
Kao Corp.	71.8	24.7
Seed Co., Ltd.	25.0	8.6
Ein Engineering Co. Ltd.	27.0	9.3
Lion Corp.	12.0	4.1
Nippon Hasahi	14.0	4.8
United States		
Nalco Chemical Company	77.1	5.7
Kim Berly-Clark Corp.	107.0	8.0
International Paper Co.	49.0	3.6
Betz Laboratories Inc.	65.0	4.8
Marcal Paper Mills Inc.	45.0	3.3
Beloit Corporation	59.0	4.4
Canada		
Domtar Inc.	38.0	26.4
Knowaste Technologies Inc.	12.7	8.8
Le Groupe Recherche ID Inc.	16.0	11.1
Reed Ltd.	13.0	9.0

End-of-life vehicle innovation and policies

End-of-life Vehicles (ELVs) are usually defined as cars and light trucks that are considered waste and must be disposed.[3] Automotive recycling started to become an issue in the 1960s, due to the increasing number of abandoned vehicles in the countryside (Blount, 2006). The first example of ELV regulation was enacted in Sweden in 1975 in an effort to address the problem of illegal dumping.

Subsequently, the focus shifted from the problem of illegal dumping to concerns about the polluting component of ELV waste. Cars are in fact composed of many different materials that have a significant impact on the environment such as mercury, cadmium, hexavalent chromium, anti-freeze, brake fluid and oils, and should not be disposed directly in normal landfill sites. Besides, automobiles contain steel and aluminium (about the 75% of its weight) and a significant part of plastic, which are materials that can be recycled.

As such, from a waste management point of view, the concerns related to ELV waste are two-fold: on the one hand about the 25% of this waste is considered hazardous, and on the other hand an important part of this waste flow can be recycled. For all these reasons policies for ELVs are generally have the following attributes: joint targets for recycling and reuse; bans or regulations on the disposal of hazardous waste; obligations for producers to regulate the use of specific materials in particular car components (for instance lead and mercury).

Moreover, these policies usually follow the polluter pays principle, which in this context means that producers are responsible for the cost to take back their products. In other terms, the regulatory framework is very similar to the packaging case, and therefore it is instructive to determine whether the introduction of a regulation may have induced innovation in the sector. On the one hand, ELV regulation may provide incentives to car producers to develop products that are easier to recycle or that contain less polluting material; or on the other hand, may provide incentives for the development of new and

more competitive ways of recycling end-of-life vehicles. This last case in particular is of interest for our analysis, and will be the focus of this section.

Regulation

At the European level the first Directive regarding ELVs was Directive 2000/53/EC, first drafted in 1997. This Directive sought to harmonise the different country level legislation on ELVs, encouraging the adoption of regulatory measures in those countries that still did not a have a well-defined regulation. This Directive follows the scheme common to all recent EU waste legislative instruments, promoting the polluter pays principle and encouraging reuse and recycling. In particular, the Directive makes the producer responsible for the cost to take back used cars and lorries, including those already on the market. Moreover, the Directive sets precise targets for recycling and reuse, with increasing stringency through time (the first target for 2006 was for 85% of recovery and 90% of recycling). The Directive had to be implemented at country level by 2002, but some countries experienced delays in adoption.

In addition to this EU level regulation, some countries introduced state level policies starting from the early 1990s. For instance, in 1992 in Austria[4] an agreement between the Federal Economic Chamber of Commerce ("*Wirtschaftskammer Österreich*"), the Ministry of the Environment and the Ministry for Economic Affairs, set the first national rules for recovery and take back of ELVs. Then, in 2002 a second law was enacted, transposing the European Directive. The transposition of the Directive in Germany was enacted in 2002, and then was amended in 2006 to meet the European target.

However, before that date, Germany already had a set of different instruments to regulate the sector. At the beginning of the 1990s a voluntary agreement between the government and many producers' associations introduced the concept of producer responsibility, stimulating recycling and encouraging producers to reduce the quantity of dangerous material used in automobile construction. This voluntary agreement also set precise targets for reuse, recycling and disposal (Lucas, 2001). A few years later, in 1998, an end-of-life ordinance was enacted, which set precise minimum technical requirements for the treatment/recovery of ELVs, including recycling and recovery targets.

Innovative examples of ELV regulation in Europe were enacted in the Netherlands and Sweden. The Netherlands introduced a scheme of free take-back on a voluntary basis in early 1990s, while Sweden adopted a law in 1975 in order to address the problem of illegal dumping of automobiles in the countryside. Later, in 1998 Sweden adopted an ordinance to promote producer responsibility, and finally in 2001 transposed the EU Directive into national law.

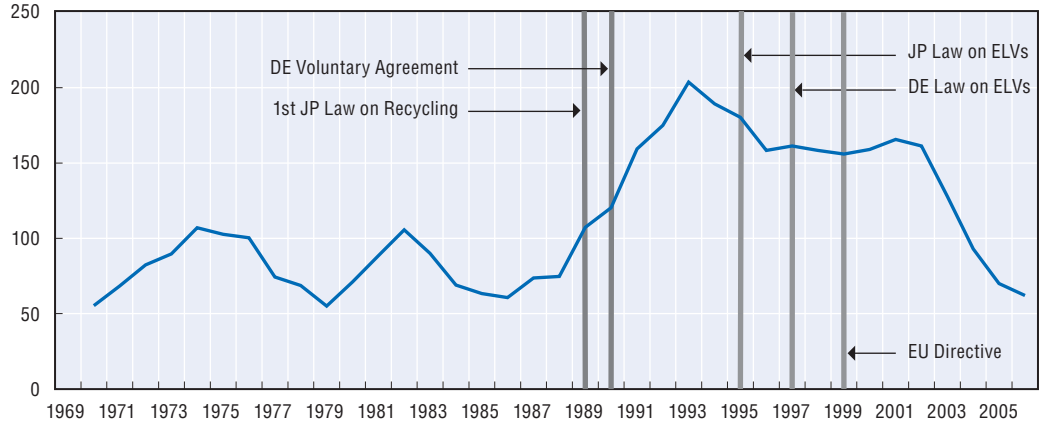
In 1990 Japan enacted legislation to promote recycling and the use of recycled material, with a strong focus on the automotive industry, while in 1996 a law specifically targeting ELVs was introduced. This legislation set clear targets to reduce the amount of lead in new vehicles and set targets for recycling. Finally, in 2002 a new Law on Recycling of End-of-Life Vehicles was introduced: it specifies new technical requirements for both dangerous materials and recycling and compared the Japanese framework to the European one. In the US, there is no specific legislation on ELVs at the national level, and ELV management has been addressed mainly at the state level.

Innovation trends

The Figure 4.10 presents data on the total number of patent applications in all patent offices. In this case we have considered all the type of patent (CP, singular, duplicate), in order to obtain an indication of the overall trend of patenting activity in the sector. Similarly to the plastic and paper recycling case, the patents related to ELV recycling activities had a stable trend until the end of the 1980s, and then registered a rapid increase. Moreover, after the explosion in patenting activities, the trend reached a peak in 1993 and then started to decrease gradually, returning to the 1970s level, after 15 years of growth.

Figure 4.10. **Evolution of patent applications, end-of-life vehicles**

3-year moving average



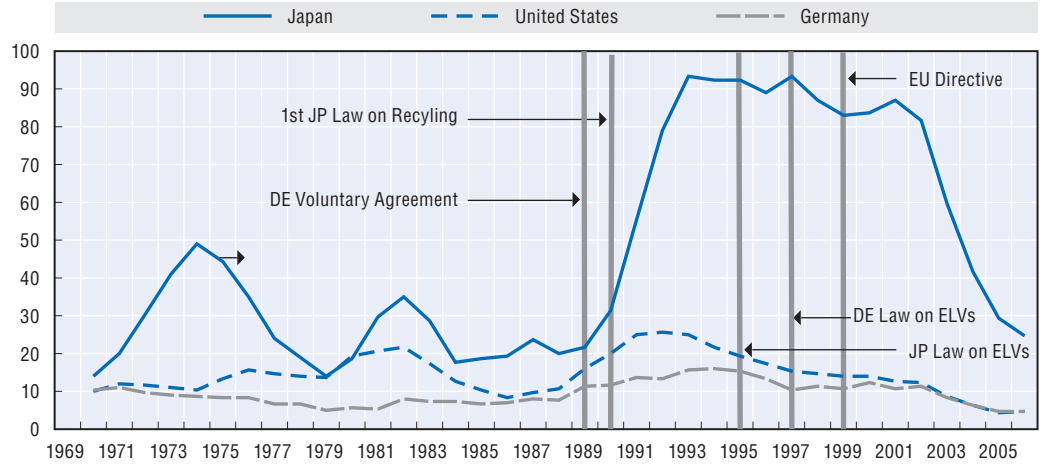
In this case the link between policy effort and patenting activities is not evident. If from a theoretical point of view the hypothesis that an increasing stringency in ELVs legislation may induce innovation seems reasonable, the data show a more complicated relationship. In particular, the first two policies, the Japanese law and the German voluntary agreement may probably have had an effect on patenting, but the link is not evident in the case of the European Directive and the more recent German and Japanese regulations. At first glance, this aggregate analysis seems to confirm the more general finding that the sector has reached a level of technological maturity, and the policy effect on innovation is decreasing in strength.

The three main countries, in terms of number of patent applications in this field are Japan, Germany and the US, which together account for nearly the 65% of total patenting in the sector. This result was expected if we consider that these three countries have both a high propensity to invent (and to patent inventions), as well as a well-developed automobile industry. It is reasonable to suppose that national regulations in Japan, Germany or the United States have an impact on patenting levels internationally.

The US data does not follow the aggregate tendency closely, not exhibiting a discernible trend over the time period. Germany seems to have a weaker response to the regulations introduced in the early 1990s, but we should bear in mind that this graph does not include German inventors that filed at the EPO, whose inclusion would increase the German count.[5] Interestingly, from this graph it seems that early regulation in Japan may have spurred additional innovation significantly, but as mentioned before the legislative measures which followed in 1996 and 2002 do not correlate with innovation performance.

Figure 4.11. **Evolution of patent applications, main offices, end-of-life vehicle technologies**

3-year moving average



Assignees

The range of assignees in this case is in line with our expectations based on other waste streams (plastic and paper). In this case, with the exception of Honda in Japan, nearly all patents came from equipment producers or from firms which specialise in recycling technologies and services, like *Metso Lindenmann* in Germany. Finally, we can also see that in the US there is a lower concentration of patenting activity, with the most important firm owning only 2.1% of total patents. This is different from the situation in Germany and Japan, where about the 25% of total patents are held by two firms.

Table 4.4. **Top domestic patent assignees – ELVs**

Firm name	Number	Total (%)
Japan		
Honda Motor	18.75	15.9
Tezuka Kosan	17	14.4
Ngk Insulators, Ltd.	8	6.8
Riken Keikinzoku Kogyo KK	5	4.2
Fuji Electric Co., Ltd.	4	3.4
Germany		
Metso Lindemann	50.3	12.3
Lindemann Machinenfabrik	50	12.2
Thyssen Industrie	17	4.1
Svedala Lindeman	16	3.9
United States		
Aluminium Company of America	8	2.1
Ara Services, Inc.	6	1.6
Can and Bottle Systems, Inc.	4	1.0
Kurt Manufactoring Company, Inc.	4	1.0
Labounty Roy E	5	1.3
Logemann Brothers Company	4	1.0

Composting innovation and policies

Composting is usually defined as the biological process that transforms – through anaerobic or aerobic decomposition – different kinds of biodegradable waste. There are several different kinds of biological processes, as there are many different bio-wastes. The most common waste types are food and garden waste, which can be completely assimilated to municipal waste. Specific regulations for the waste stream are quite new, but in the past their management has been regulated under more general solid waste management laws and Directives. For instance, the European Union does not have a specific regulatory framework for bio-waste, even though the Waste Framework Directive (2008/98/EC) underlined the importance of this waste stream and requested that the Commission prepare a plan to address the problem.

One of the main issues in relation to biodegradable waste is the danger associated with their disposal in traditional landfill sites. When buried, biodegradable waste produces methane, which is estimated to account for about 3% of total greenhouse gas emissions. The most commonly used alternative disposal options are incineration, separate collection, biological treatment and mechanical-biological treatment. According to the *European Green Paper on the Management of Bio-waste in the European Union*, composting is the most common biological treatment option and is best suited for green waste and woody material. As a result of the composting process, the compost may be used on land, or alternatively may be used as pre-treatment before landfilling or incineration.

On the other hand, mechanical-biological treatment covers techniques which combine biological treatment with mechanical treatment, like for example composting. For all these reasons, even if the presence of specific bio-waste policies is still rare, much other waste legislation includes regulation on composting. In particular, biodegradable waste has been regulated under broader landfill policies, as in the case of European Union, or inside general waste policies that included targets for separate collection and recycling, as is the case of Japan.

In this last section, we will focus in particular on technologies and patent related to biological treatment and mechanical-biological treatment, trying to assess if waste policies have been able to spur innovations in these quite new fields, analysing the trend in patenting activities across OECD countries from 1970 to 2007, following the same procedure developed in the previous two sections.

Regulations

As mentioned before, the European Union still does not have any specific policy on bio-waste, even if the *Green Paper* may be seen as a first step in the development of a common strategy for biodegradable waste in the EU. Nevertheless, this waste stream has been regulated under Directive 99/31/EC, better known as the Landfill Directive. This Directive was intended to reduce the negative externalities related to landfill activities, setting precise and stringent technical requirements. In relation to bio-waste, the Directive sets very precise targets, obliging member states to reduce the amount of biodegradable waste landfilled to 35% of 1995 levels by 2016.

Some other countries, both European and non-European, adopted legislation related to bio-waste starting from the beginning of the 1990s. A first example is Germany, which enacted a very stringent law on packaging waste in 1991 (discussed in Chapter 2), which

provided incentives for separate collection and recycling, increasing the quantity of separate bio-waste collection from 1 million tons in 1990 to 4 million in 1995. Later, in 1998, an Ordinance on Bio-waste, set very precise technical requirements for composting activities, in order to regulate the sector, and eliminate the health risks associated with composting activities. Finally in 2005 Germany adopted a set of limits for the landfill disposal of waste with organic content. In particular, this last instrument mandates that organic waste be landfilled only after the waste has been treated in a way that meets the target value set for the specific waste category.

In 1991 Japan adopted an environmental law for the promotion of effective utilisation of resources, whose purpose is to promote reuse and recycling. Once again this policy does not have a specific focus on composting, but it is reasonable to think that in the intention to promote recycling and separate collection this measure may have influenced composting activities. Later on, in 2000, Japan promoted recycling activities, through two important laws: the Law for Promotion of Effective Utilisation of Resources and the Fundamental Law on the Establishment of a Sound Material-Cycle Society, both oriented towards the promotion of recycling activities.

A similar path has been followed by Korea, which enacted the Law on Promotion of Saving and Recycling of Resources in 1992, and then in 1998 introduced legislation on food and energy that set targets for the discharge of food waste, with obvious connections to composting activities. China's first important legislative effort in the field of bio-waste dates from 2000, when the Ministry of Construction, the Ministry of Science and Technology and the State Environmental Protection Administration promulgated the "Technical Policies for the Municipal Refuse Disposal and the Prevention and Control of Pollution", that specified among the other things, technical requirements for landfill sites, with the intention of promoting recycling and composting activities.

Innovation trends

The following graphs present the trend for patent application worldwide first, and then for the main inventor countries. Global patenting shows a trend very similar to the ones studied before: the path is stable until the beginning of the 1990s, and then there is a sudden rise in the total amount of patent applications. Analogously, the effect of the main policies seems to have a link to patenting activities only in a first phase, and then this effect seems to have weakened. Looking at the graph in fact we can see that Japanese and German regulations are correlated with the change in the global trend of patent applications, while the EU Landfill Directive does not seem to have affected the relationship in a significant way.

Analysing the trend for individual countries yields further insights. If we look first at the graph for Japan and Germany, we can see as both countries' patenting performances started to increase at the end of the 1980s and beginning of the 1990s. However, Germany seems to have preceded Japan by about four years. Germany counts started to rise in 1988, and Japan around 1991. For both countries, the two main policies are depicted, the first dated 1991 for both countries, and the second ones in 1998 for Germany and 2000 for Japan. With the exception of the German 1998 Law on Bio-waste, all the other policies included incentives for recycling. Nevertheless, we can see a positive link between legislative effort in the first wave of policies, and no relationship in the second wave.

Figure 4.12. **Evolution of patent application, compost, worldwide**

3-year moving average

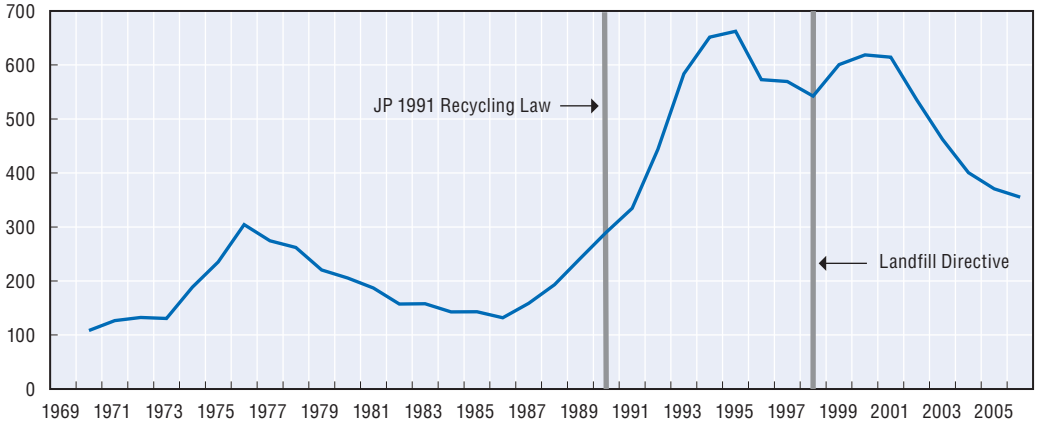
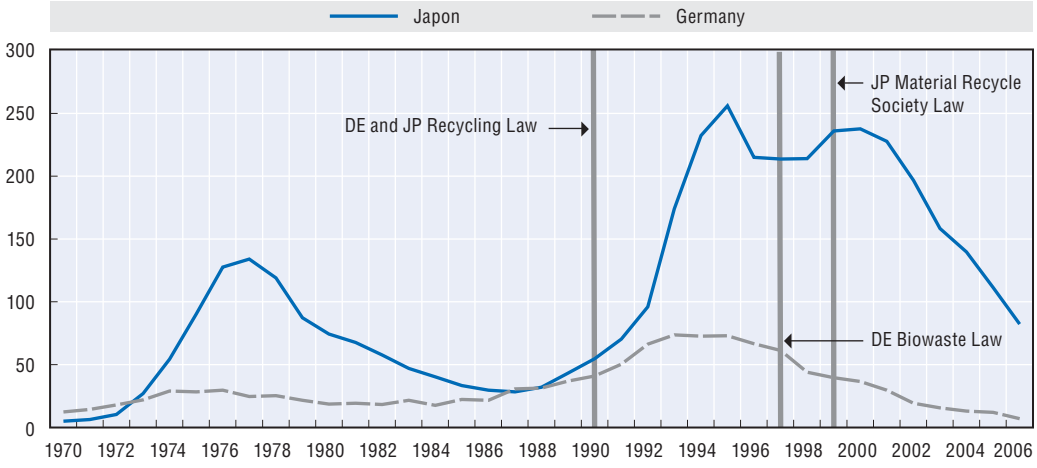


Figure 4.13. **Evolution of patent applications, composting, Germany and Japan**

3-year moving average



Korea and Japan had little patenting activity until the beginning of the 1990s, but starting from then they have increased their performances significantly. In this case it is possible to distinguish two different policies for Korea, one in 1991 and the other one in 1998 that in both cases seem to have in some way anticipated and stimulated the patenting performances. Even more interesting is probably the case of China. While the trend of composting patent applications reflects the more general country performance, the graph below also shows that after the introduction of the 2000 technical requirement for landfill sites, the rate of innovation has accelerated, a consequence perhaps of the new standard imposed by the legislation and the consequent impulse given to composting activities.

Finally, in Figure 4.15, we have disaggregated the total patent applications at the EPO among European countries, in order to see if the exclusion of the EPO from the previous analysis affects our results. The biggest source of patent applications at the EPO is Germany. Interestingly the level of German applications at the EPO has an increasing trend from the beginning of the 1980s, then they reach a peak in 1996 and start to decrease. This

Figure 4.14. **Evolution of patent applications, composting, Korea and China**

3-year moving average

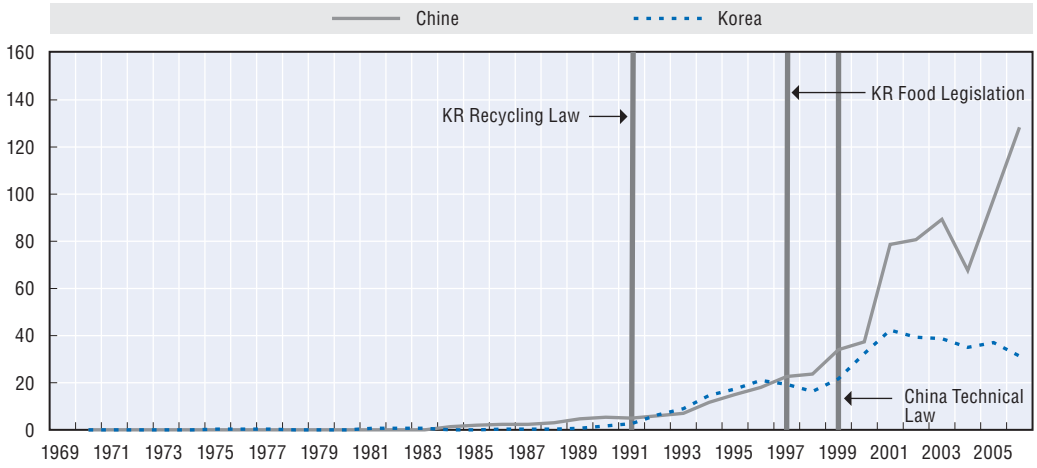
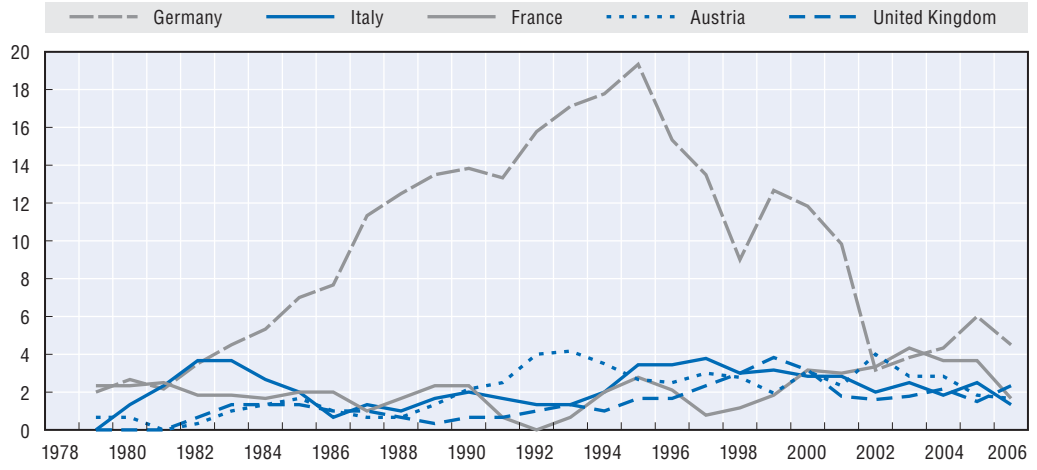


Figure 4.15. **Evolution of patent application for composting a the EPO**



is slightly different to our findings from other areas. Other important inventor countries at the EPO are Italy, France, Austria and the UK, even though they show no discernible trend in patent applications, in contrast to Germany.

Assignees

In terms of assignees the greatest share of all patents comes from equipment producers or firms specialised in waste management technologies, such as Herhof Umwelttechnik in Germany and Ebara Corporation in Japan. The level of concentration of patenting activities at the country-level can be divided in two sub-groups, a first one that comprises Germany, Japan and China, in which the main investors own an important share of the total patents (around 10% each), and the case of Korea, where only one firm exceeds the threshold of the 2% of total patents.

Table 4.5. **Top domestic patent assignees – composting**

Firm name	Number	Total (%)
Germany		
Herhof Umwelttechnik GMBH	123.1667	9.1
Grabbe, Klaus	28.5	2.1
Metallgesellschaft AG	27	2.0
Basf AG	21	1.5
Fritz Schaefer Gesellschaft Mit Beschraenkter Haftung	20	1.5
Friederich Bachus	18	1.3
Japan		
Sanyo	34	8.8
Ebara Corp.	23.5	6.1
Matsushita Electric Works Ltd.	18.5	4.8
Sapporo breweries limited	11.16	2.9
Hitachi Ltd.	11	2.8
Tanaka Sangyo Co., Ltd.	8	2.1
Korea		
Daewoo Electronics Co., Ltd.	8	2.1
Kumkangsanland Co., Ltd.	6	1.6
Kim, Tae Hwan	5.5	1.5
Samsung Electronics Co., Ltd.	5	1.3
Hyundai Co., Ltd.	5	1.3
China		
Huang Lihai	90	10.5
Tianjin Hangu District Fuxiang Fertiliser Process Factory	10	1.2
Tianjin Normal University	9	1.0
Hunan Univ.	9	1.0
Tongji University	8	0.9
Zhejiang University	8	0.9

Conclusions

This study has examined the effect of environmental policies on innovation in the area of recycling technologies for recycling and waste management in general, as well as some of the main waste streams: paper and plastic packaging waste, end-of-life vehicles, composting. The study covers a cross-section of OECD countries over the period 1970-2007. The analysis has been conducted through a descriptive analysis of the correlation between the introduction of important policy measures and patent counts for different waste streams. While the evidence has to be considered still very preliminary, it is possible to make some observations:

- As in other studies on environmental innovation, regulation does seem to play an important role in the promotion and diffusion of innovation, but this results have to be interpreted carefully, and further analysis is needed.
- A graphical inspection of patent trends across the different waste streams seems to suggest that the waste sector has reached a degree of technological maturity, and it is now experiencing a decreasing trend in patenting activities. It is possible to that in a business as usual scenario the decreasing rate of patenting activities might have been bigger in the absence of policy interventions.

- The results suggest that it might be that the first and older wave of policies (end of the 1980s beginning of the 1990s) have produced a technological shock in the system and now their effect is less pronounced. This result is especially underlined in the last three sections, in which for all the four specific waste streams analysed, there seems to be a strong and positive link between policy action and innovation performance at the beginning of the 1990s, but this link is less clear in the last fifteen years.
- Generally, in this sector, innovation came mainly from equipment producers and in some cases from specialised research centres, rather than the waste management sector itself. This result is in line with the nature of the patents analysed, that refer to process innovations embodied in capital equipment which are likely to be linked with a globalised equipment manufacturing sector.

Notes

1. That is not to say that packaging waste is not affected by more general policies such as unit-based waste fees.
2. Korea and China rank respectively 6th and 7th among the top innovator countries in the field of plastic recycling technologies.
3. The threshold size is usually eight passengers in addition to the driver in the car case, and a maximum mass of 3.5 tonnes for trucks Eionet, waste definitions (available at *www.eionet.org*).
4. Policy Department, Economic and Scientific Policy, End-of-life Vehicles (ELV) Directive, An assessment of the current state of implementation by member states (IP/A/ENVI/FWC/2006-172/ Lot 1/C1/SC2) (2006).
5. The graph for EPO applications is not included in the analysis since the he total counts of patents filed at the EPO in relation to ELVs is very low. However, Germany has the biggest share.

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Chapter 5

Innovation in Selected Areas of Green Chemistry

by
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Improving the environmental performance of chemical processes and feedstocks has become an objective of the chemical industry and policymakers alike In this chapter, indicators of innovation in selected fields of green chemistry are proposed using patent data. Among these, biochemical fuel cells and green plastics are the two areas that have shown the most growth, while totally chlorine-free pulp and paper and biodegradable packaging are past their innovation peak. Patenting in industrial biotechnology has increased but no more than for the chemistry sector overall. Qualitative review of the role of public policy indicates that innovation in this area requires avoiding differentiated treatment of new versus *existing chemicals. In addition, the frequent use of support measures (R&D support, public procurement, grants, and awards) means that policy makers face a difficult task in identifying particular technologies or activities to be supported in the face of imperfect information and uncertainty over future trajectories.*

* The contribution of James Clark (University of York, the UK) and Ivan Haščič (OECD Environment Directorate) to the development of search strategies is gratefully acknowledged. Additional inputs were provided by Julie Zimmerman, Evan Beach and colleagues at the Center for Green Chemistry and Green Engineering at Yale University (*http://greenchemistry.yale.edu/*).

Introduction

Modern lifestyles have been made possible through a vast range of chemicals that improve many aspects of our lives including the medicines we consume, the dyes in our clothes and the fertiliser used to grow our food. Unfortunately, in some cases these same chemicals have also led to undesirable environmental and health consequences. Chemical releases into the atmosphere, water bodies and land can be harmful to ecosystems and human health.

Nature uses a narrow range of environmentally common elements, while the chemical industry utilises the broad spectrum of elements in the periodic table for chemical transformations. The effect of these environmentally rare chemicals on natural systems is often unknown (Collins, 2001). Many chemicals which have been released into receiving environments have later been shown to be toxic or to cause environmental damage. For instance, phthalates used widely in plastics are believed to cause hormonal disruption. In the past, CFCs (chlorofluorocarbons) were widely used in aerosol cans and for refrigeration. It was not until 1970s that CFCs were linked to the hole in the ozone layer, and eventually phased out under the Montreal Protocol.

Green chemistry[1] holds the promise of providing significant environmental and health benefits relative to standard chemical practices. It aims to avoid harm to people and the environment by changing chemical products and processes: it strives to achieve sustainability through design at the molecular level, focusing on inherent hazards of chemicals rather than the circumstances of exposures. Green chemistry principles address the root causes of physical, toxicological, and global hazards, including fires, explosions, acute and chronic toxicity, depletion of limited resources, and greenhouse gas emissions.

Formally, the OECD defines "green" chemistry as "the design, manufacture and use of efficient, effective, safe and more environmentally benign chemical products and processes."[2] Green chemistry involves the manufacture of products that are less harmful to human health and the environment: *i)* by the use of less hazardous and harmful feedstocks and reagents; *ii)* by improving the energy and material efficiency of chemical processes; *iii)* by using renewable feedstocks or wastes in preference to fossil fuels or mined resources; and *iv)* by designing chemical products for better reuse or recycling. These categories encompass all parts of a chemical lifecycle, from the raw materials and manufacturing to use and end of life.

The twelve principles of green chemistry developed by Anastas and Warner (1998) provide a practical definition (Box 5.1). The goal of these design criteria is to provide guidelines for sustainable design. Green chemistry is distinct from environmental chemistry. While green chemistry concentrates on avoiding pollution, environmental chemistry focuses on monitoring the fate and transport of chemicals in ecosystems and the clean-up of chemical pollution.

Box 5.1. **Twelve principles of green chemistry (Anastas and Warner)**

1. **Prevention**

   It is better to prevent waste than to treat or clean up waste after it has been created.

2. **Atom economy**

   Synthetic methods should be designed to maximise the incorporation of all materials used in the process into the final product.

3. **Less hazardous chemical syntheses**

   Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.

4. **Designing safer chemicals**

   Chemical products should be designed to effect their desired function while minimising their toxicity.

5. **Safer solvents and auxiliaries**

   The use of auxiliary substances (*e.g.* solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.

6. **Design for energy efficiency**

   Energy requirements of chemical processes should be recognised for their environmental and economic impacts and should be minimised. If possible, synthetic methods should be conducted at ambient temperature and pressure.

7. **Use of renewable feedstocks**

   A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.

8. **Reduce derivatives**

   Unnecessary derivatisation (use of blocking groups, protection/deprotection, temporary modification of physical/chemical processes) should be minimised or avoided if possible, because such steps require additional reagents and can generate waste.

9. **Catalysis**

   Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.

10. **Design for degradation**

    Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.

11. **Real-time analysis for pollution prevention**

    Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.

12. **Inherently safer chemistry for accident prevention**

    Substances and the form of a substance used in a chemical process should be chosen to minimise the potential for chemical accidents, including releases, explosions, and fires.

Source: Anastas, P.T. *et al.* (1998).

Green chemistry initiatives

The notion of making production processes less polluting through innovations in the use of chemicals has been around a long time. The identification of green chemistry as a specific policy objective can be traced to the late 1980s when governments shifted the focus of their environmental policies toward prevention. For instance, in the mid-1980s, the United States Environmental Protection Agency (EPA) began to shift its focus from pollution control to pollution prevention (Linthorst, 2010). This was formalised with the passage of the 1990 Pollution Prevention Act. In 1988 the American Chemistry Council launched the Responsible Care initiative, which encourages industry-wide adoption of environmental management practices and information disclosure. In Europe, the 1996 Integrated Pollution Prevention and Control Directive (IPPC) emphasised the move towards pollution prevention (*http://eippcb.jrc.es/*).

The growing interest in green chemistry can be seen to have emerged from this increased emphasis on pollution prevention rather than control. In the US, the Environmental Protection Agency inaugurated the Green Chemistry Programme officially in 1993. This programme continues to promote green chemistry with grants, education and with the Presidential Green Chemistry Challenge Awards (for the list of winners see: *www.epa.gov/greenchemistry/pubs/pgcc/past.html*). Other recognition efforts include the Green and Sustainable Chemistry Awards in Japan (*www.gscn.net/awardsE/index.html*), the European Sustainable Chemistry Award (*www.euchems.org/esca/*) and the Royal Australian Chemical Institute Green Chemistry Challenge awards (*www.raci.org.au/national/awards/greenchemistry.html*).

In 1997 the Green Chemistry Institute, a non-profit institution, was launched to promote green chemistry (*www.epa.gov/gcc/pubs/gcinstitute.html*). It became part of the American Chemical Society in 2001. The Green Chemistry Institute has chapters in more than 20 countries, including Argentina, China, India, South Africa and Chinese Taipei. In addition there are green chemistry networks in a number of countries for the purposes of information dissemination and education. In the UK the Green Chemistry Network was established within the Royal Society of Chemistry. From here, the successful journal *Green Chemistry* emerged in 1999. In Italy, INCA (International Network for Culture and Arts) a multi-university consortium of universities established in 1993 consolidated links between research teams, with green chemistry one of their key areas (Hjeresen, 1999). Initially 5 universities were involved, now there are 31 Italian university members.

In Japan, the Green and Sustainable Chemistry Network (GSCN) was launched in 2000 with the focus of promoting research and development in green chemistry (*www.gscn.net*). In 2005, the Mediterranean Green Chemistry Network (MEGREC) was established to encourage research and education links between European and Arab countries. That same year, the G8 nations established the International Green Network linking eight research centres, one in each country, with the aim of improving research, education, regulation and public policy in the green chemistry area.

Other specialised research centres have been established worldwide. In China, there are more than a dozen universities with "key labs" in green chemistry that are supported at national or provincial levels. Many of the key labs are associated with a specialty area, for example green polymer materials, clean energy from biomass, or green synthetic techniques. Host universities include Qinghua University, Peking University, Sichuan

University, Zhejiang University of Technology, Wuhan Institute of Technology, and Tianjin University.

In the United States, the National Science Foundation has funded research centres focusing on green chemistry challenges such as environmentally benign solvents (*www.nsfstc.unc.edu/*). Monash University in Australia has a Green chemistry research centre funded by the government for basic research and for establishing combined industry and university projects. The Danish government has funded a Centre for Green Chemistry and Sustainability. In Canada, Queen's University has recently inaugurated the Green Centre Canada, funded by government and industry partners, which is devoted to the development and commercialisation of green chemistry technologies. A large number of universities in the OECD have incorporated "green chemistry" in their standard chemistry courses, and there has been a rapid growth in the dedicated academic journals.

The chemicals sector has also actively encouraged the growth of green chemistry. Companies have introduced green principles into their production and invested in sustainable research and development. In Europe, two industry groups Cefic and EuropaBio along with the EC have established the European Technology Platform for Sustainable Chemistry (*www.suschem.org/*) to encourage chemical research and development in Europe. In Germany, DECHEMA founded a working group "Sustainable Chemistry Measurement and Metrics" integrating key industrial players.

Important areas of green chemistry

Given the breadth of the areas covered by green chemistry it is difficult to completely circumscribe the field. As noted above, key areas of green chemistry include the efficient exploitation of alternative feedstocks, the development of novel, environmentally benign synthetic pathways and the use of alternative solvents.

Feedstocks

Petroleum-based feedstocks are the current basis of the chemical industry with 90% of all organic chemicals derived from oil. Furthermore, 90% of the world's energy needs are met by non-renewable resources (*www.eia.doe.gov/emeu/international/*). Indeed, it has been estimated that energy demand is to grow by more than 50% by (Ragauskas, 2006). Thus, there is enormous interest in covering future energy demands by using alternative, renewable energy sources. Environmental concerns associated with the use of petroleum and coal also include their contribution to climate change through CO_2 emissions. One of the benefits of using renewable resources is that they are potentially carbon neutral, and their use would mitigate greenhouse gas burdens in the atmosphere.

Recently, advanced biofuels have been developed that use food crops such as corn or sugarcane. This biomass, rich in carbohydrates, is most commonly converted to ethanol by fermentation (McMillan, 1997; Kim and Dale, 2004). Central to future research are alternative waste feedstocks that avoid competition with food production. They include agricultural waste, lignocelluloses, lignin (*e.g.* waste parts of plants and trees after paper production) and chitin (*e.g.* shells). For example, lignin is usually burned to support the energy need of other processes. However, the useful carbon content of this material and woody biomass in general should be more efficiently exploited by converting them to either liquid transportation fuels or useful chemicals. These materials are however, chemically complex in nature, so new technology is required for their effective utilisation.

Although the possibility of ethanol production (Galbe and Zacchi, 2007) or liquefaction by pyrolysis (Carlson *et al.*, 2009) represent recent progress in this field, further innovations are needed in order to achieve desired product streams (Huber *et al.*, 2007).

Apart from chemically converting non-edible biomass, some of its components can potentially be also used as value added chemicals. For example, waxes have been extracted from wheat straw using supercritical CO_2. The waxes can be used as a base for cosmetics, while other chemicals have pharmaceutical and agrochemical potential (Deswarte *et al.*, 2006). Chitin is an abundant biodegradable material that can be processed into chitosan. This biopolymer has a wide range of current and potential uses such as crop pest control, water treatment and as a substitute for traditional polymers in industrial applications (Rinaudo *et al.*, 2006). Bio-based feedstock can also be used for the production of non-toxic, biodegradable plastics (Belgacem and Gandini, 2008).

Solvents

Solvents are a great challenge for green chemistry, since in the production of fine chemicals and pharmaceuticals they frequently account for the vast majority of waste. Many conventional solvents are harmful to human health and the natural environment. They are often toxic, flammable and/or corrosive and volatile. To reuse or recycle these solvents, energy-intensive operations are required, such as distillation. Therefore alternative solvents that are non-toxic and represent no additional waste are being developed (Anastas and Eghbali, 2010). There are also research efforts underway to develop solvent-free processes, or the use of biphasic systems which allow for immobilisation of catalysts and recycling of products. In principle, any green solvent needs to be a functional replacement for conventional organic solvents, in addition to reductions in intrinsic hazard (Beach *et al.*, 2009).

Water, because of its obviously non-toxic nature is a very popular green solvent. A variety of reactions (oxidation, reduction, C-C bond forming) have shown to be compatible with this medium (Li, 1993; Li, 2005; Li, 2006). Water is a good polar solvent which is often shown to be beneficial for reactivity. In addition it offers the possibility of easy separation of organic product phases. In some cases, for example in biomass transformations, supercritical water is used.

Supercritical solvents are a suitable alternative to classical organic solvents. Especially supercritical carbon dioxide has proven to be a unique and safe reaction medium (Leitner, 1999; Jessop and Subramaniam, 2007; DeSimone, 2000; Leitner, 2000). Due to its critical point, the supercritical state is easy to achieve and the removal of solvent occurs just by cooling and depressurising the reaction vessel. In addition, by variation of temperature/pressure parameters, its density, and the outcome of reactions, can be easily tuned (Leitner, 2002). This medium has already found its commercial applications in decaffeination of coffee (replacing the toxic and hazardous solvent dichloromethane) and as an alternative to harmful perchloroethylene in dry-cleaning of clothing.

Ionic liquids are likely to replace conventional solvents in many applications (Rogers and Seddon, 2003). They are considered "designer solvents" in green chemistry because a huge variety of different structures can be explored to tune their physical and chemical properties. They are liquid salts at room temperature with practically no vapour pressure, which also makes them ideal candidates for liquid-liquid biphasic reactions, and immobilisation of catalysts (Welton, 1999; Wassercheid and Welton, 2007). Another

example of biphasic mixtures are perfluorinated solvents. Usually, they are not miscible with organic solvents at room temperature, but form a single phase at slightly higher temperatures, allowing for the reactions to take place. The separation of the products will then occur by subsequent cooling, largely simplifying the purification process (Gladysz *et al.*, 2004).

Alternate synthetic pathways and catalysis

In order to achieve sustainability through design at the molecular level, significant innovation is necessary on a fundamental scientific level. To meet the challenges described in the 12 principles of green chemistry, new energy-efficient reaction pathways should be designed. At the same time, generation of large amounts of side products and unnecessary functionalisation should be avoided and the number of reaction steps minimised. Numerical tools have been developed that help assess chemical reactions in terms of waste prevention. The Environmental Impact Factor (Sheldon, 1992; Sheldon, 2007) is a metric to quantify total amounts of waste generated, and Atom Economy (Trost, 1991; Trost, 1995) measures how efficiently starting materials are incorporated into the final product.

Molecular catalysis plays a central role in design of novel green reactions (Anastas, 2009). The use of catalysts instead of stoichiometric reagents greatly reduces waste and in most cases improves product selectivity, atom economy and energy efficiency. The most powerful catalytic processes include hydrogenations (Noyori, 1987), C-H activation (Crabtree 2001), C-C coupling reactions (Bower and Krische, 2009), and olefin-metathesis (Vougioukalakis and Grubbs, 2010 and Trnka and Grubbs, 2001).[3] Biocatalysis is another green strategy, relying on natural or modified enzymes (Silverman, 2002; Bommarious and Riebelin, 2004). More recently, white biotechnology offers attractive catalytic routes to useful chemicals (Schaefer, 2010).

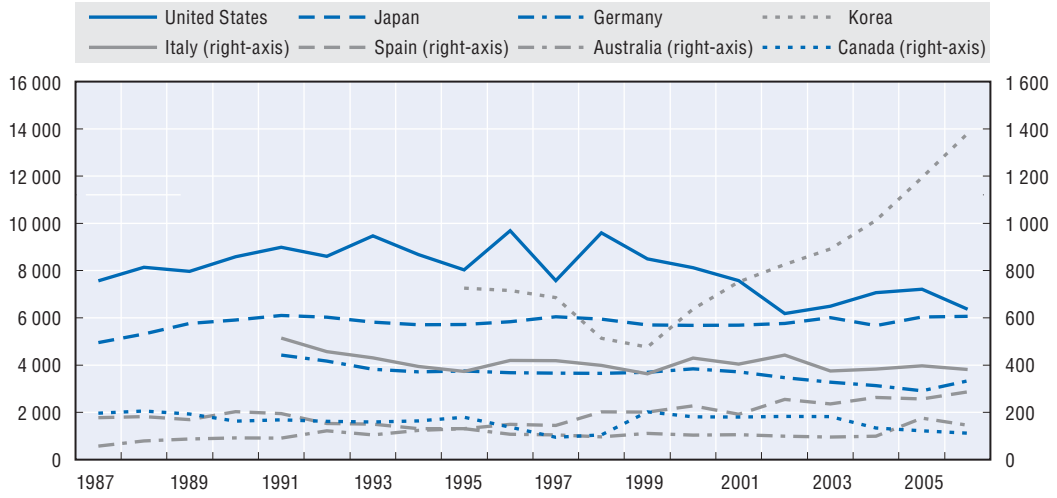
Stoichiometric reactions can also be designed to meet green chemistry criteria. Highly atom economical reactions include Diels-Alder reactions (Brummond and Wach, 2007), multi-component reactions (Domling and Ugi, 2000) and various rearrangements (Leung *et al.*, 2007). Click chemistry (Kolb *et al.*, 2001) strives to develop reactions with no side products and a 100% utilisation of starting materials. A number of chemical engineering technologies for the use of microwave or ultrasound in chemical synthesis have emerged to improve yields and facilitate reactions (Strauss and Varma, 2006). Advances have also been made in the field of micro-reactor technology and high throughput screening that allow for efficient catalysis and process optimisation and testing (Mason, 2007).

Measuring innovation in green chemistry

There are a number of measures which can be used to document innovation trends, including R&D expenditures, scientific personnel, publications, and patents. Figure 5.1 provides data on R&D expenditures by the chemicals sectors (ISIC 24) in the time period from 1987-2007. Germany (the biggest EU producer) and the US have declining R&D expenditures in the sector starting from 2001. Korea has been rapidly increasing since 1999, while the trend in Japan is more or less static.

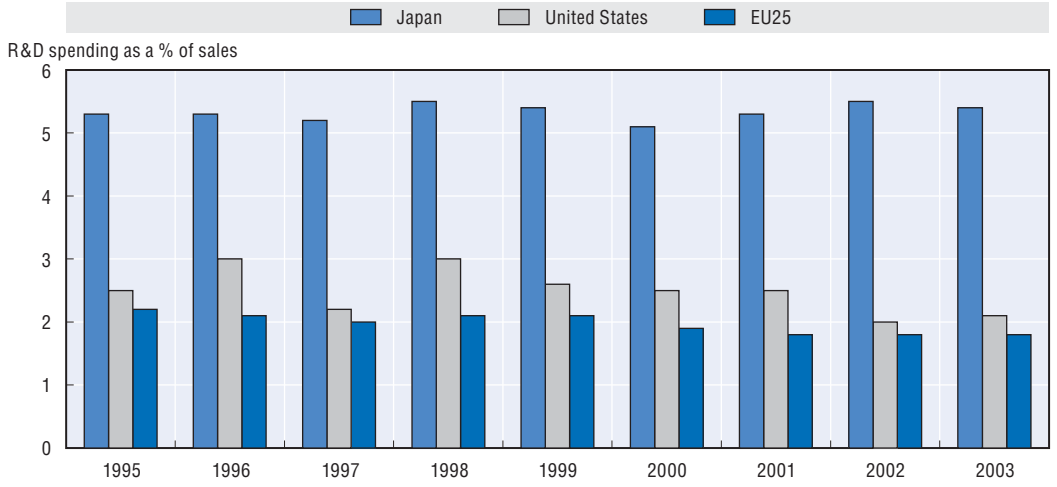
CEFIC provides data on R&D spending as a percentage of sales for the EU25, the United States and Japan over the period 1995-2003. Japan has the highest ratio, followed by the United States and then Europe. There has been a degree of convergence between the latter two (see Figure 5.2).

Figure 5.1. **STAN R&D in chemicals (excluding pharmaceuticals) (million USD 2000 PPP)**



Source: OECD.Stat, ANBRED Statistics.

Figure 5.2. **Chemical industry R&D spending in EU25, the US and Japan 1995-2003**



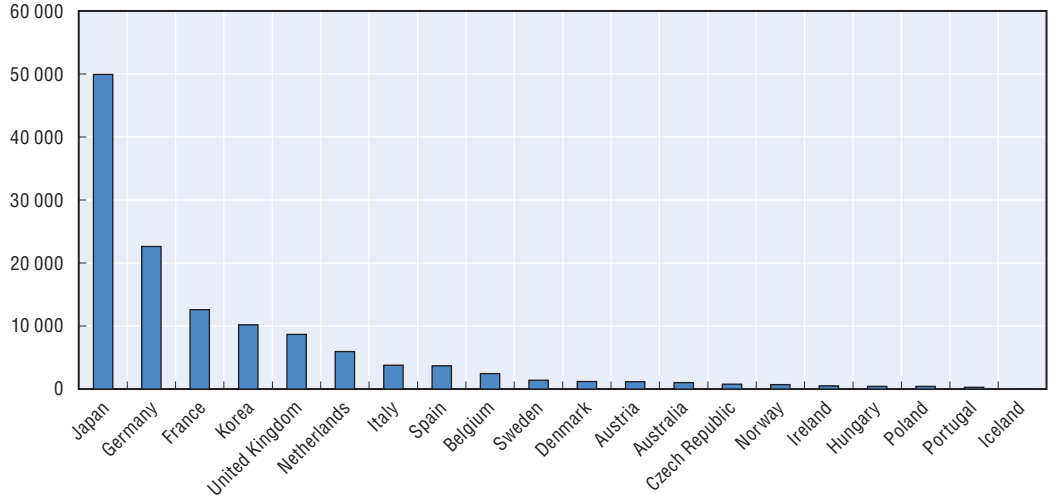
Source: *www.cefic.be/factsandfigures/level02/investment_index.html.*

Data on scientific personnel by industrial sector is also available. Figure 5.3 presents data on the number of full-time employee equivalents who are classified as R&D personnel or researchers in the ISIC 24 sector (excluding pharmaceuticals).

However, in all these cases the data refers to all R&D activities within the sector, and not that which is specifically related to "green" chemistry. While there is data on public R&D expenditures by socio-economic objective (including control and care for the environment), this is not disaggregated by sector. However, the classification systems used when delimiting the claims of patent applications allows for the identification of inventions which relate specifically to "green" chemistry. As such, the remainder of this section addresses the following questions:

- Why use patents to measure chemical innovation?

Figure 5.3. **Number of R&D personnel and researchers in the chemicals sector (excluding pharmaceuticals) in 2006**



Source: OECD.Stat, ANBRED Statistics.

- What are the overall trends in patenting, and how do these related to current trends and drivers in the chemical industry?
- Which green chemistry indicators can be created from patent data?

Why use patents to measure chemical innovation?

Patenting is an important strategy for the chemical industry. The propensity to patent both product and process innovations is higher in the chemical industry than in other sectors. A Carnegie Mellon survey on Industrial R&D in the US manufacturing sector (Cohen *et al.*, 2000), carried out in 1994 found that on average manufacturers applied for patents for 49% of their product innovations and 31% of their process innovations. However the propensity to patent varied widely between different manufacturing sectors. For the chemical industry the rates were much higher – 65% and 54% for product and process inventions respectively.[4]

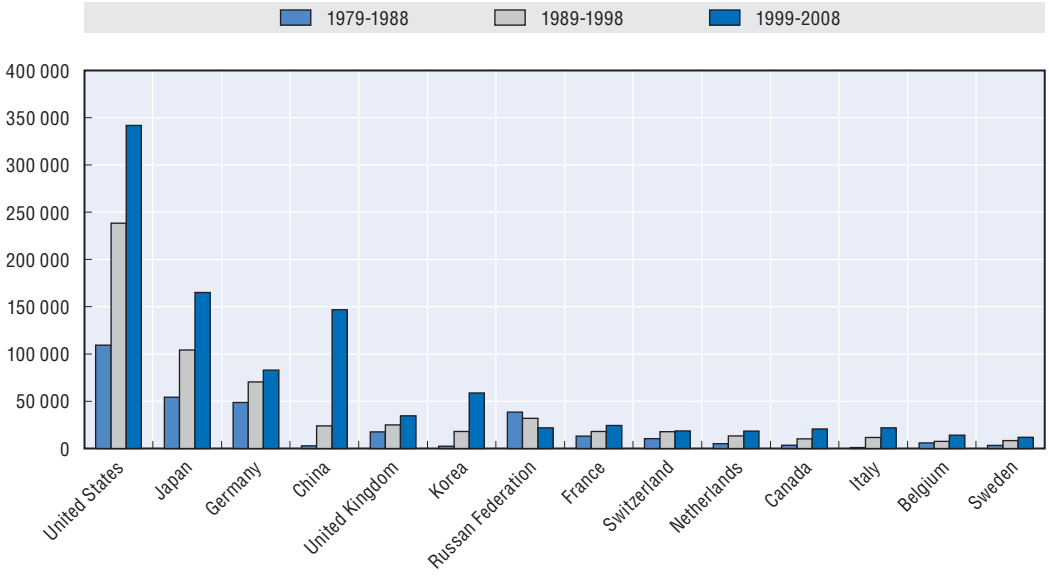
Three reasons have been forwarded as to why patenting is a particularly common strategy for the chemical industry. First, the chemicals industry has used patents to protect their inventions for well over a century, and so there is a high degree of familiarity with the use of IPRs (Arora and Gambardella, 1998). Second, chemical inventions are considered suitable to IP protection because they are easy to define – and thus defend legally- since chemical inventions can be described using engineering principles and physical and chemical laws (Arora and Gambardella, 1998). For instance, reaction pathways and operating conditions can be clearly specified.

Third, patents are vital for licensing agreements and licensing is widely used as an industrial strategy in the chemical sector. Licensing is also a significant source of revenue and used as a way to earn rents from Research and Development expenditure (Arora and Gambardella, 1998).[5] For instance, in 2008 DOW Chemicals earned USD 307 million from patent and technology royalties.[6]

Trends in chemistry patenting

Data for this report has been extracted from the *EPO Worldwide Patent Statistical (PATSTAT) Database* (EPO, 2009).[7] An indicator of patent counts for all chemical inventions (*ALL CHEMISTRY*) has been drawn from the *PATSTAT Database*. Figure 5.4 gives the count of patent applications (CPs and SING) for each of the last three decades for the most important inventor countries. As in most fields the United States, Japan and Germany dominate. Moreover, the Japanese figures are under-estimates since there many patent applications filed at the JPO data for which the inventor country is missing in PATSTAT. China and Korea have shown particularly rapid growth. Other important chemical product manufacturing countries (*e.g.* Switzerland, Belgium and Italy) also feature.

Figure 5.4. **Patent counts (CP + SING) by inventor country**



Normalised trends are shown in Figure 5.5. Note that the rate of applications for chemistry has followed a similar pattern to that for all technology field (*ALL SECTORS*), with approximately 50% more applications in the 2000s than in 1988. However, *ALL SECTORS* has increased nearly 20% since 2000 while *ALL CHEMISTRY* has remained static.

In February 2001 the EU published a *White Paper* entitled "A Strategy for a Future Chemicals Policy" (*www.isopa.org/isopa/uploads/Documents/documents/White%20Paper.pdf*) which suggested that the uncertainty associated with the negotiations leading up to the passage of REACH had slowed innovaton in the field. Prior to 2001 chemicals patents were rising faster than for all sectors combined, but slower thereafter. This is likely primarily due to other factors.

For Japan, the chemical patenting rates have stayed in line with overall patenting – but have diverged since 2005. In the US, chemical and overall patenting had a similar pattern until 2003 where subsequently chemical patenting has not kept pace with overall patenting. For Europe, chemical patenting has been in line with overall patenting, however, neither has attained the growth rates of both Japan and the US.

Figure 5.5. **Patent counts (CP + SING) – 3 year moving average indexed on 1997 (= 1.0)**

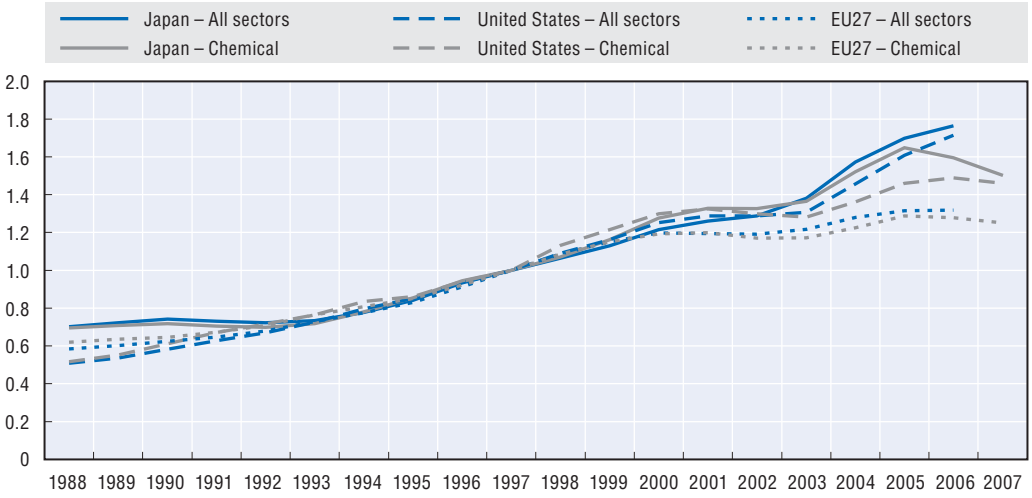
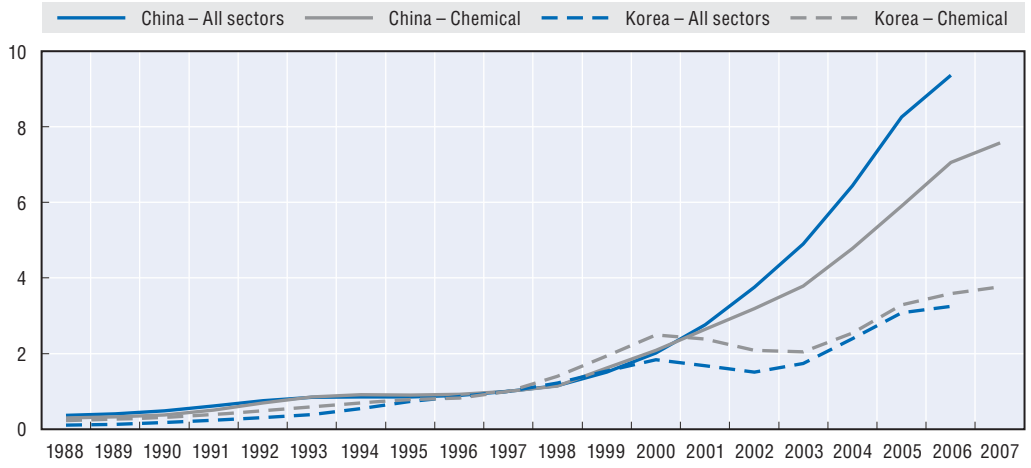


Figure 5.6. **Patent counts (CP + SING) – 3 year moving average indexed on 1997 (= 1.0)**



The picture differs markedly for Korea and China, where the growth in patenting rates have been spectacular. For China overall patent counts were 9 times higher in 2006 than in 1997. Although the rate of growth of chemical patents has fallen short of that of all patents, there is still impressive growth. For Korea, chemical and overall patenting rates follow a similar pattern; growing overtime but stagnating for a short period after 2000. The chemical patenting rates were nearly 4 times the level in 2007 than in 1997.

Green chemistry patents

Nameroff (2004) conducted a study of green chemistry patents study using a detailed abstract and title search on key words such as "benign". While the study covered a wide range of green chemistry patents, it was restricted to patents filed at the United States Patent Office and thus did not allow for cross-country comparisons. For international comparisons, data based upon the International Patent Classification system (IPC) is more appropriate.

As a consequence, the patent counts for the different green chemistry fields covered in this report are based on IPC codes. Unfortunately we are not able to identify a broad all-encompassing green chemistry indicator due to the nature of the IPC system. Instead we have investigated selected technologies which can be identified reliably using IPC classes, with the exception of the *green plastics* area which uses a key word search based on patent application titles. It should be emphasised that these are by no means intended to be representative of green chemistry as a whole. However, they do provide a restricted cross-section of relevant areas. (The areas investigated in this paper are summarised in Table 5.1.)

Table 5.1. **Green chemistry areas covered in the report**

Selected area	Description, including the relevant International Patent Classification (IPC) codes used to identify relevant patents[1]	No. of patent applications 1970-2007
Biochemical fuel cells	Biochemical Fuel Cells, also known as Microbial fuel cells (MFCs), drive a current from bio-electrochemical systems which mimic bacterial interactions. They are a clean and efficient way of producing energy. Many organic materials can be used to feed the fuel cell including waste material such as wastewater.[2] (IPC = H01M8/16)	572
Biodegradable packaging	Biodegradable packaging covers packaging that involve disintegrable, dissolvable or edible materials and thus are designed so they do not accumulate in the environment. (IPC = B65D65/46)	4 823
Aqueous solvents	Many solvents are damaging to the environment (from water to the ozone layer) and harmful to humans. Organic solvents are prevalent in paint thinners, nail polish removers, glue solvents, industrial and household cleaning products, printing inks and in extractive processes. Green chemistry encourages the replacement of organic solvents with aqueous solvents along with supercritical fluids, ionic liquids or by using solvent free processes. (IPC = C08F2/10)	3 347
Selected white biotech	This falls into the white biotechnology/catalysis area and involves the preparation of oxygen containing compounds using fermentation (or similar). (IPC = C12P7)	31 959
TCF bleaching technologies	Totally chlorine free bleaching technologies used in the pulp paper industry removes dioxins found in both paper products and wastewater when using pre-existing technologies. TCF technologies involve no chlorine compounds and remove all but naturally present Adsorbable Organic Halides (AOX), dioxins and furans. (IPC = D21C9/153 or D21C9/16)	4 176
Green plastics	Unlike the other categories which use IPC codes to identify patents, Green Plastics applications have been identified using key word searches on titles. Specifically, this involves looking for polylactide, polylactic acid, PLA, polyhydroxybutyrate, PHB, polycaprolactone and PCL in application titles in relevant areas as defined broadly using IPC codes. These are biodegradable polymers that are also derived from renewable feedstocks in the case of PLA and PHB. This search was restricted to patents with English titles.[3] Due to varying quality of data from different patent offices and the fragile nature of key word searches, the Green plastics figure should be treated with care.	508

1. Technical descriptions of IPC codes can be found on the WIPO website: *www.wipo.int/ipc8earlypub/ipcpub/index.php?lang=en&menulang=EN*. To look at patent applications corresponding to certain IPC codes, please refer to the Esp@cenet website: *http://ep.espacenet.com/advancedSearch?locale=en_EP*.
2. The Biochemical Fuel cell and the Selected White Biotech categories were defined with the help of Pr. James Clark at York University.
3. In the future we hope to improve this search by ensuring all family members are included even when they fail to have a title with the correct key words.

In addition, a related project has examined innovation in climate change mitigation technologies (see Haščič *et al.*, 2010). Some of the fields examined as part of this work relate to green chemistry, including carbon capture and storage (CCS) (*e.g.* by chemical separation or adsorption), solar photovoltaic cells (*e.g.* dye-sensitised solar cells, microcrystalline solar

PV cells) and cellulosic ethanol. The search algorithms for these areas were developed by patent examiners at the European Patent Office.

Major trends in selected green chemistry inventive activity

Patent counts by inventor country

Figure 5.7 shows general invention trends in selected green chemistry areas by looking at application counts (CP + SING) by year as indexed on the year 2000. Since patenting activity in general has increased over time, the *ALL_SECTORS* indicator is included for purposes of comparison, as well as the *ALL_CHEMISTRY* indicator which encompasses all chemistry patents. Note that the rate of applications for chemistry has followed a similar pattern to that for *ALL_SECTORS*, with approximately 50% more applications in the 2000s than in 1988. However, *ALL_SECTORS* has increased nearly 20% since 2000 while *ALL_CHEMISTRY* has remained static.

Patents for *biochemical fuel cells* have shown rapid growth since 1988 when compared to the other areas, but note that the counts for this category are relatively low, with approximately 600 applications (including duplicates) in the 1970-2007 period. Similarly, *green plastics* patents have shown rapid growth, but again have relatively small counts. Furthermore, the *green plastics* comparison is imprecise as the applications have been selected from those with English titles, and preferably the comparison groups would also be derived from the same population.

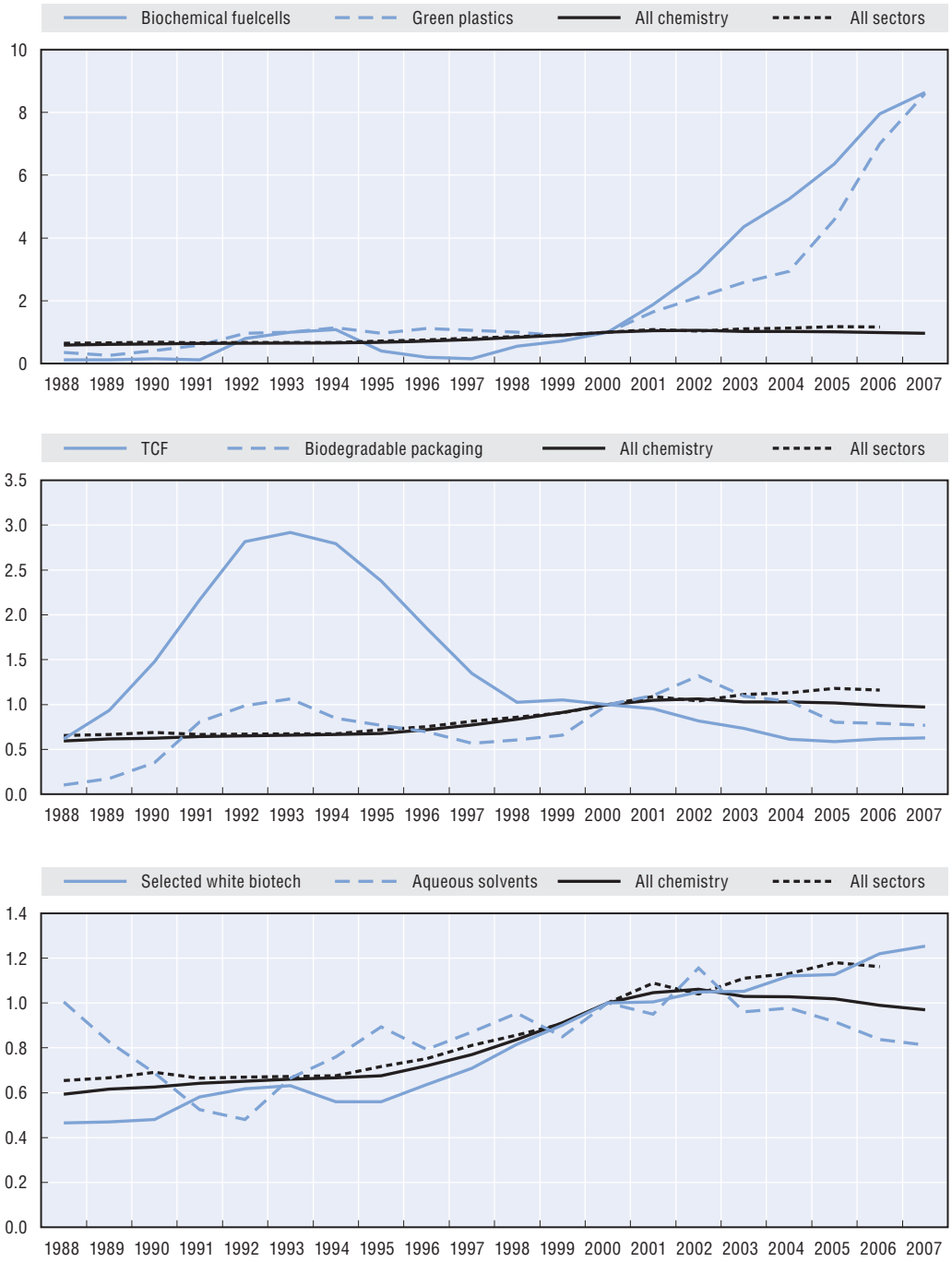
Patents for *biodegradable packaging* show two peaks, first in the early 1990s and then later in 2002. Since 2002, rates have fallen slightly. Patents for *totally chlorine free* (TCF) bleaching peaked in 1993 at nearly 3 times the 2000 level. In 2007 TCF applications were at same level as they were in 1988. The counts for *selected white biotech* have increased steadily since 1988. In 2007 it was more than 20% higher than in 2000 however it is in line with the *ALL_SECTOR* application trend. Invention in the *aqueous solvents* area has stagnated since 1988 and has not kept pace with the overall growth in patent applications.

Figure 5.8 shows the proportion of applications (claimed priorities and singulars) by inventor country over the 1988-2007 period. The United States dominate the counts for *biochemical fuel cells* with approximately 35% of the applications, the next biggest inventor countries are Japan, Korea, Germany and China. In terms of *biodegradable packaging*, the top five inventor countries are the United States, Germany, Great Britain, Japan and China. The *aqueous solvent* area is dominated by Japan, Germany and the United States. *Selected white biotech* is a large area with a number of inventor countries, the top five being the United States, Japan, Germany, China and the Netherlands. The main inventor in the *TCF* area is the United States, the next four largest are Sweden, Canada, Finland and Germany. For *green plastics*, Japan and China account for over half of patents, the United States, Germany and Korea are the next largest. The result for the *green plastics* area is likely to be biased due to the key word selection criterion.

Patent counts by patent office

Protection of intellectual property must be obtained from the patent office of each country where protection is sought. Looking at the data in term of the offices in which applications are deposited (CP, DUPL and SING) allows us to determine the markets where protection is sought, rather than the origin of the invention. This can be useful, for

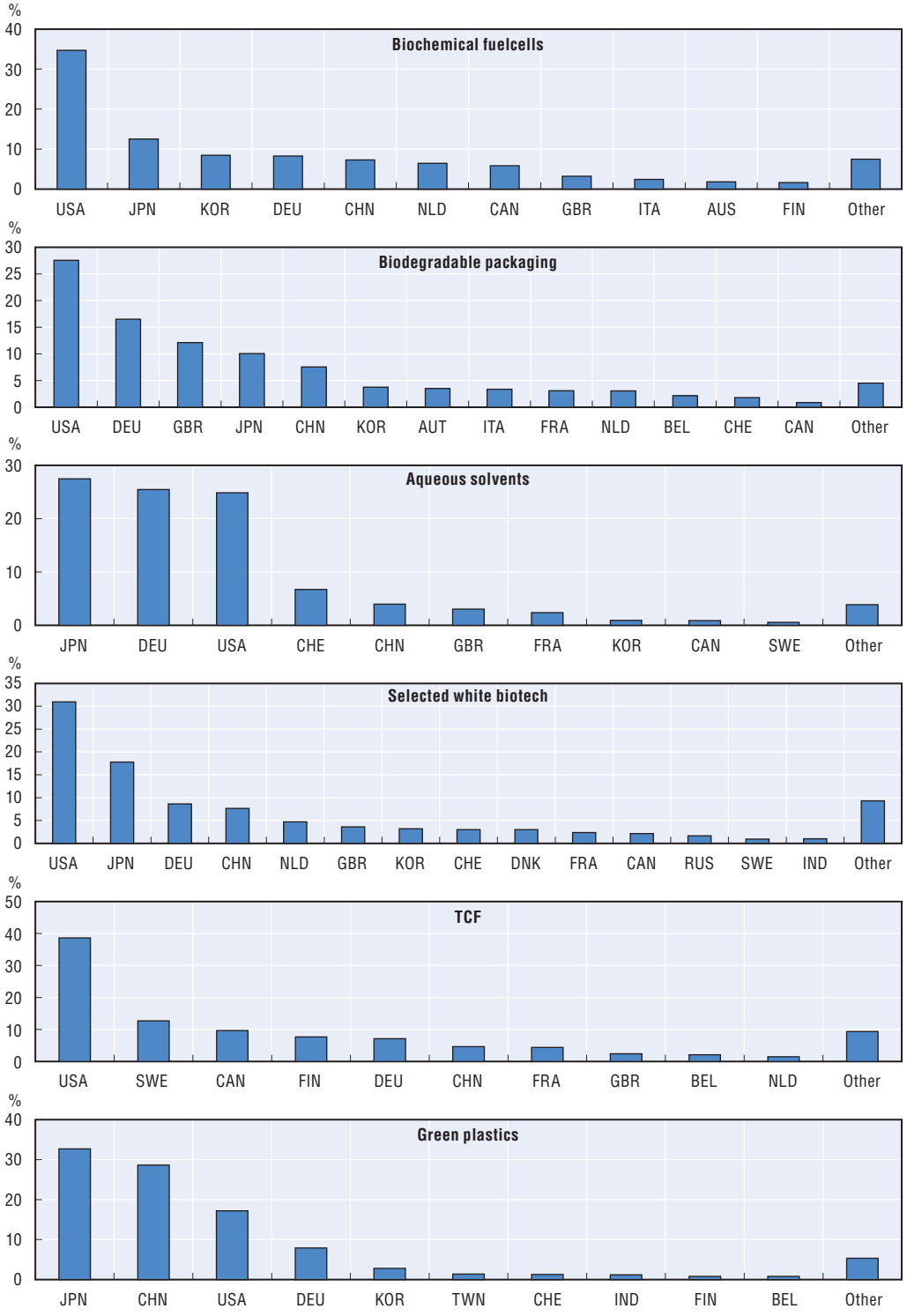
Figure 5.7. **Growth rate of selected green chemistry area (count of CPs and SINGs worldwide, 3-year moving average, indexed on 2000 = 1)**



instance, when assessing the impacts of environmental regulations on local production practices.

However, care must be taken when interpreting such data. Patent offices have different procedures which can bias the results. For instance, the scope of claims may vary widely – a single patent application submitted to the European Patent Office may require

Figure 5.8. **Share of world wide patenting by inventor country – CP + SING, 1988-2007**



coverage by two different applications in the Japanese Patent Office due to different practices relating to the scope of claims.

Box 5.2. **Increasing share of invention by China**

Figure 5.9 shows the share of invention in China in the 1988-97 and 1998-2007 periods. In the 1988-97 period China had proportionately very few or no patents in these areas of green chemistry. However, in the 1998-2007 period, invention in China notably increased in all of these categories. For instance in the 1988-97 period, China accounted for less than one per cent of *TCF* patents, this increased to 15% in 1998-2007 period. The rate of increase for *Green Plastics* was even more dramatic, but needs to be treated with caution due to the key word selection criterion.

Figure 5.9. **Share of invention by China 1988-2007**

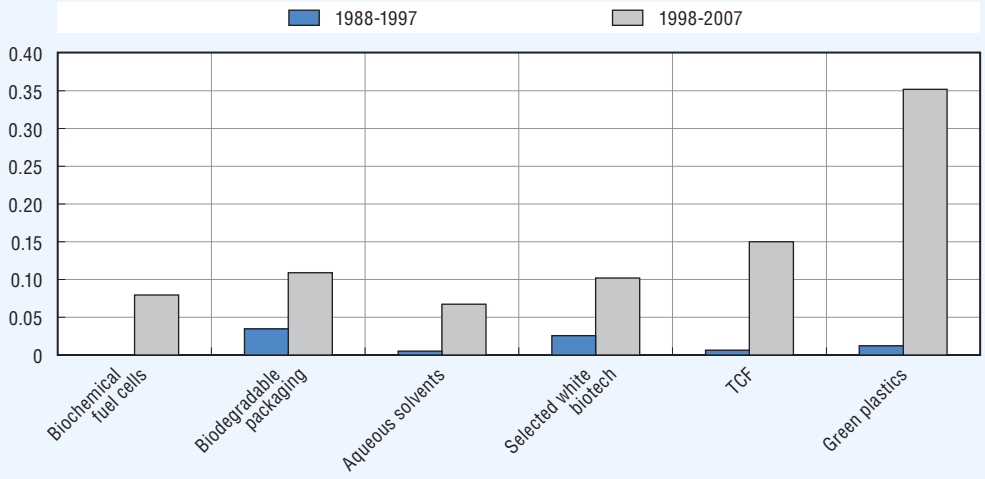


Table 5.2 shows three types of information for the different fields: *i)* the number of offices receiving at least one application; *ii)* the offices receiving the most applications; and *iii)* the proportion of all patents that are found in the top 10 offices. Firstly, the number of offices receiving applications varies widely by type, but this is partly a function of the overall number of applications. For instance, *selected white biotech* applications have been

Table 5.2. **Patent application offices for all patents 1988-2007**

	Biochemical fuel cells	Biodegradable packaging	Selected white biotech	TCF	Aqueous solvent	Green plastics
Number of patent application offices	32	57	73	59	54	21
Top 10 patent application offices						
1	JP	JP	JP	JP	JP	CN
2	US	EP	US	CA	EP	US
3	EP	US	EP	EP	US	EP
4	CN	DE	CN	US	DE	JP
5	AU	AU	AU	AU	CA	CA
6	CA	CA	CA	FI	CN	KR
7	KR	CN	DE	DE	AU	MX
8	DE	AT	AT	BR	AT	DE
9	ES	ES	BR	SE	ES	NZ
10	GB	GB	KR	AT	BR	TW
% of patents in top 10 offices	89	78	80	74	81	95

deposited in the most patent offices (73) when compared to other areas. However, they also have the greatest number of patents.

The Japanese, the United States and European patent offices commonly have the most applications, with the exceptions of *TCF*, where Canada is prominent and *green plastics* where the Chinese Intellectual Property Office leads. Again, the *green plastics* area must be treated with caution as it is hard to determine the extent to which this is an artefact of the data. For instance, care has been taken to provide clear English titles for Chinese patents in the *PATSTAT Database*, where as for countries such as Germany, the titles will be in German and so will not be picked up by the key word selection criterion.

International technology co-operation

This section looks at the level of international technology co-operation in the green chemistry area. Co-operation is measure as "co-invention" of patented inventions. Figure 5.10 shows the proportion of patents that have been invented by researchers from more than one country. The overall rate of international co-operation found in *ALL_CHEMISTRY* applications is 9%. Rates for *biochemical fuel cells* and *selected white biotech* are both about 10%. Co-invention for *totally chlorine free (TCF)* bleaching has the highest rate at 17% followed by biodegradable packaging at 12%. Aqueous solvents have a lower rate of co-invention (6%) than the *ALL_CHEMISTRY* area. *Green plastics* have the lowest rate of co-invention, but this may be due to the nature of the data extraction method.

Figure 5.10. **Proportion of patent applications involving international co-operation 1988-2007**

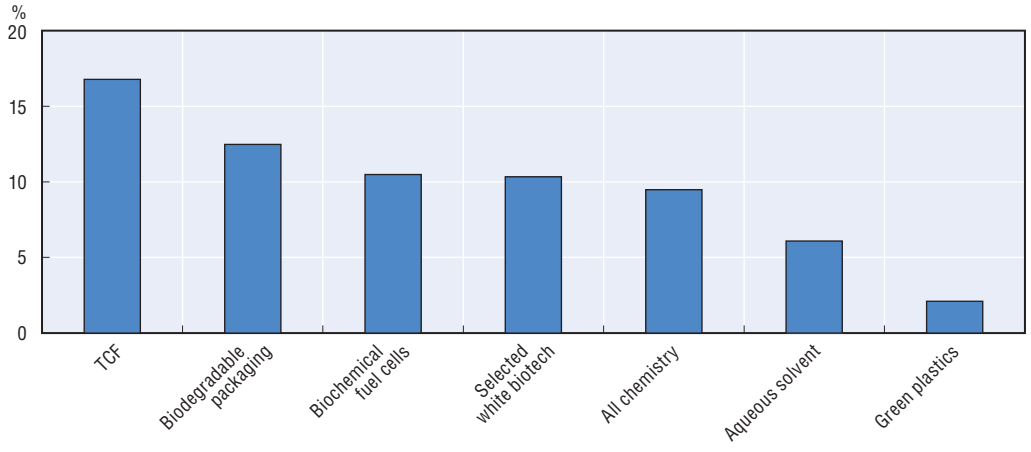


Table 5.3 shows the top five countries involved in international technology co-operation. The United States has co-operated most often in the five green chemistry areas. Note however, that they are also a prominent inventor, being top in all these areas with the exception of *aqueous solvents*. Although Japan is also a significant inventor in many of these areas, they have low involvement in international invention co-operation. Looking at *ALL_CHEMISTRY* patents, the United States co-invents the most, followed by Germany, Great Britain, France and Switzerland.

Table 5.4 presents data on the percentage of top inventor countries co-operating internationally by technology area. Asian countries such as Japan, China and Korea tend to

Table 5.3. **Top 5 co-invention countries 1988-2007**

	Biochemical fuel cells	Biodegradable packaging	Selected white biotech	TCF	Aqueous solvent	*ALL CHEMISTRY*
1	US	US	US	US	US	US
2	KR	GB	DE	CA	DE	DE
3	DE	DE	CH	SE	JP	GB
4	ES	FR	NL	FI	SE	FR
5	CA/AU	BE	GB	FR	FR	CH

Table 5.4. **Proportion of selected top inventor countries co-operating internationally**

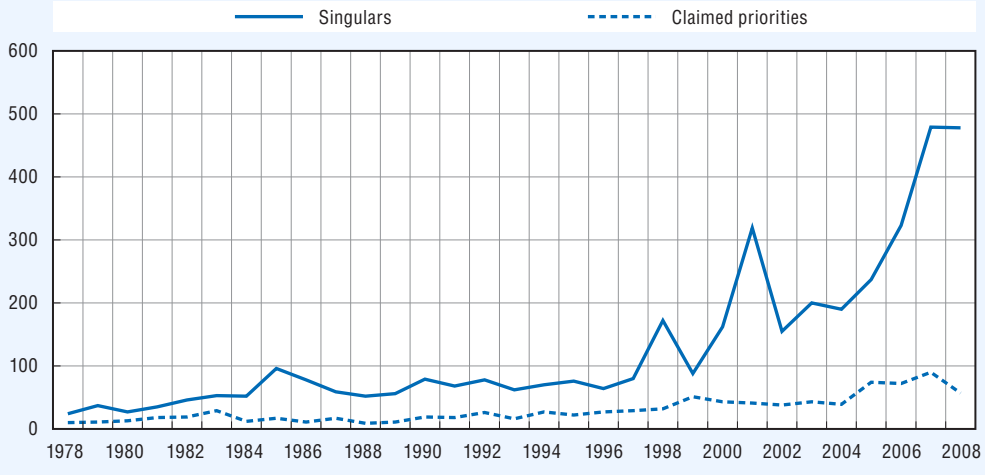
TCF (%)		Biodegradable packaging (%)		Biochemical fuel cells (%)		Selected white biotech (%)		Aqueous solvents (%)		ALL CHEMISTRY (%)	
US	29	US	23	US	14	US	16	JP	3	US	15
SE	25	DE	23	JP	0	JP	6	DE	10	JP	6
CA	56	GB	49	KR	48	DE	43	US	14	DE	29
FI	39	JP	1	DE	34	CN	4	CH	9	CN	5
DE	21	CN	7	CN	11	NL	40	CN	16	KR	6
CN	9	KR	2			GB	50				
						KR	10				
						CH	63				
						DK	46				
						FR	48				

Box 5.3. **Carbon capture and storage**

Patent applications were identified that relate to CO_2 capture using absorption, adsorption, biological, chemical, membrane diffusion, and rectification and condensation processes, and those that relate to CO_2 storage. Approximately 20% of the applications are CPs. The data clearly suggest an increasing trend, however the volume of patenting activity in CCS storage remains low. In terms of all priority docs (CP + SING), the US, Japan, Germany but also Canada and the Netherlands were the top inventor countries in CCS during this period. Other significant inventors include France, the UK, and Norway, followed by China, Australia and Italy. Since the late 1990s, Korea, South Africa, Denmark, Switzerland and the Russian Federation started to be more active.

Figure 5.11. **Patenting activity in CCS**

Count of singulars and claimed priorities worldwide



Box 5.3. **Carbon capture and storage** *(cont.)*

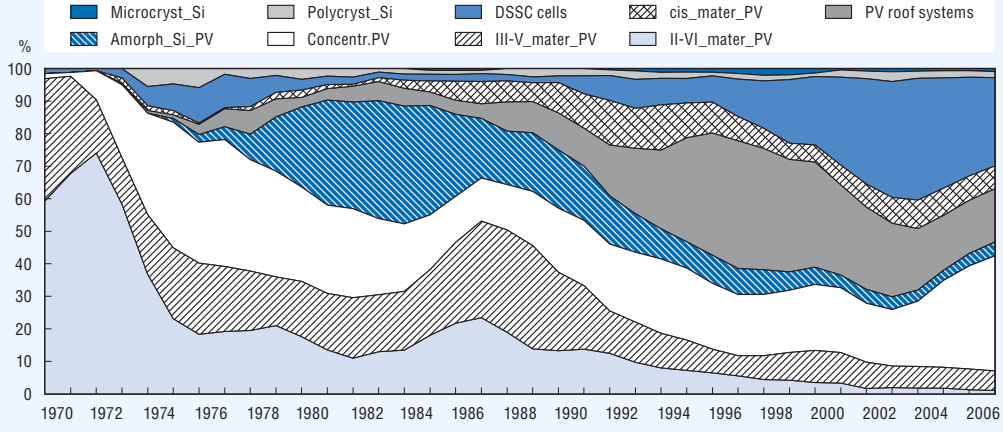
Finally, our data suggest that CCS differs from other mitigation technologies in several respects. First, inventive activity in CO_2 storage and, to a lesser extent, in CO_2 capture is concentrated in hands of a small number of patent applicants (assignees) relative to renewable energy fields. Second, the "propensity to patent abroad" is significantly higher in CCS than in other renewable energy fields.

co-operate less often than European countries and the United States. In the *ALL CHEMISTRY* area, Germany co-invents for 29% of their inventions compared to 15% for the United States, 6% for Japan and Korea and 5% for China. In the selected green chemistry areas, Japan co-invents the least often, while Korea and China have high co-invention rates for some areas such as *biochemical fuel cells* for Korea at 48% and *aqueous solvents* for China at 16%.

Box 5.4. **Trends of photovoltaic cells**

Invention in Solar Photovoltaic cells has grown rapidly in the last decades and is an important innovation area amongst climate mitigating technologies. The Figure 5.12 shows the relative share of various PV technologies. Since 1990, DSSC cells (Dye Sensitised Solar Cells) have become prominent in patent applications.

Figure 5.12. **Inventive activity in solar PV technologies 1970-2007, relative share of selected PV technologies, 3-year moving average**



The institutional characteristics of assignees

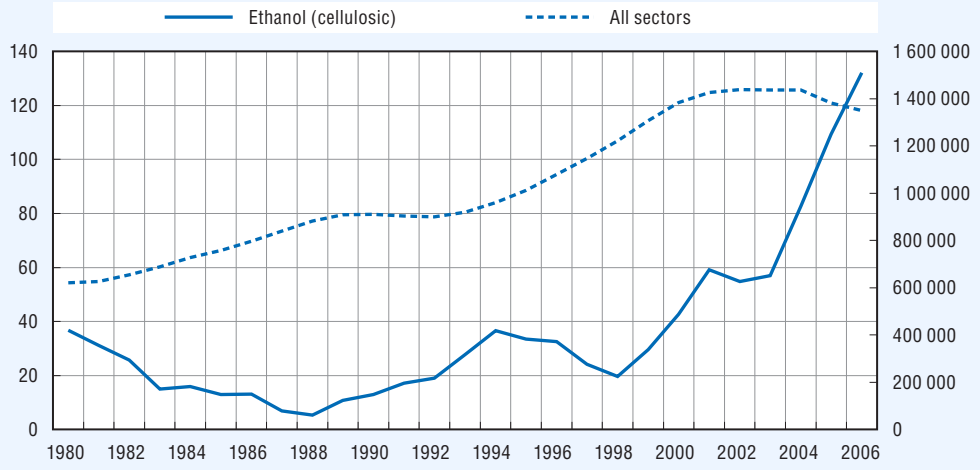
Patent databases include information on assignees who apply for patent protection and, if successful, are the owners of patents. The assignee can be an individual, but typically it is the company, university or research centre where the invention took place. By looking at assignees we can look at which companies are involved in invention.

The proportion of inventors from "public" bodies has increased over time for chemical patents. This increase has been largely driven by universities, in 1988 there was approximately an even split between government, universities and private-non-profit,

Box 5.5. **Trends in cellulosic ethanol**

Cellulosic ethanol is produced from low value plant matter such as wood, grass and non-edible parts of crops, The main advantage of cellulosic ethanol over traditional biofuels made from crops such as corn or starch, is that it can be made from a wide range of inputs including wastes from crops. Furthermore it has lower Green House Gas emissions than traditional biofuels. However cellulosic ethanol does require more processing. The Figure 5.13 shows that the patent application rate for *Ethanol (cellulosic)* has grown much faster than *ALL SECTORS*, furthermore, it has risen sharply since 1998.

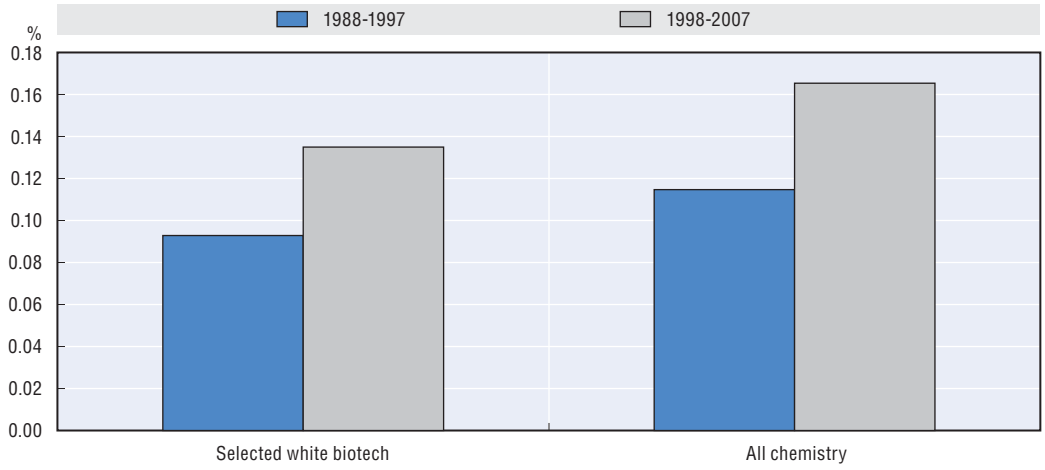
Figure 5.13. **Patent applications (CP, SING + DUPL) for cellulosic ethanol 1980-2006**



by 2007 university inventors accounted for over 11% of patents, private-non-profit at 5% and government at 3%. Green chemistry technologies have a higher proportion of public inventors when compared to all chemistry patents and new technologies more so than mature ones (see Figure 5.14).

For *selected white biotech* large broad-based chemical companies such as Du Pont, BASF and DSM are the top assignees. However, more specialised biotech companies such as Novozymes, a producer of industrial enzymes, also have a strong presence. In the *aqueous solvents* area, large chemical companies again predominate: Nippon Shokubai, BASF, Dow and Mitsubishi Chemicals. Pulp and paper companies, major chemical companies and other large companies such as in the mechanical equipment sector are major assignees in the *totally chlorine free* area. They inclue Mitsubishi, *OJI Paper*, Weyerhaeuser and Cargill Incorporated. Consumer goods companies such as Proctor and Gamble and Reckitt Benckiser feature in the *biodegradable packaging* area, along with other companies including Mitsubishi. In the *biochemical fuel cell* area large corporations such as Sony, Ebara and Canon feature along with a number of Universities including St Louis, Michigan State, Western Ontario and Konkuk. In the *green plastics* area, predominant assignees include Toray Industries from Japan, Samyang for Korea and Donghua University.

Figure 5.14. **Proportion of patents with public inventors 1988-2007 by selected technologies**



The effect of public policy on green chemistry innovation

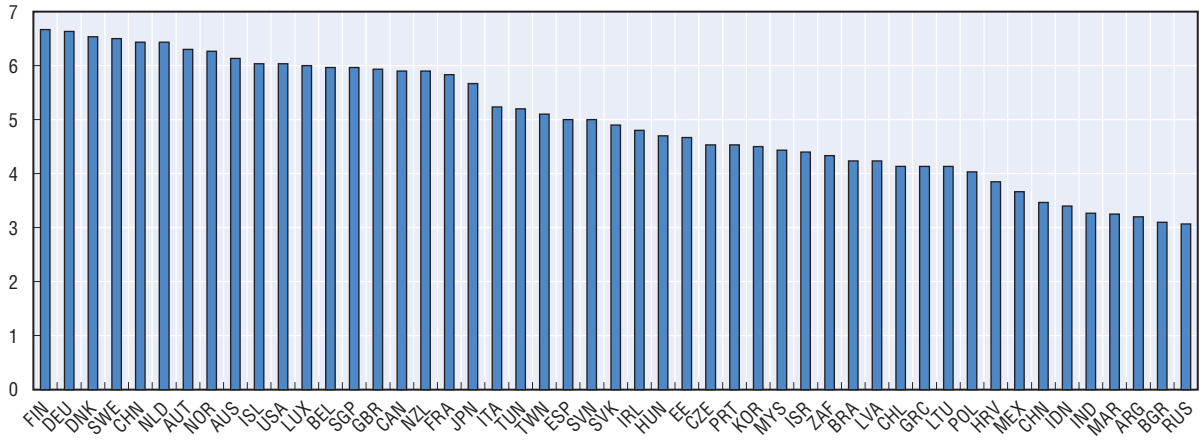
Previous work undertaken at the OECD has shown that public policy can be an important inducement to innovation. In particular it is found that policy stringency, predictability, and flexibility have a significant impact on the number of "high-value" patents for environmental technologies deposited. (See *www.olis.oecd.org/olis/2009doc.nsf/linkto/ENV-EPOC-WPNEP(2009)2-final*.)

Given the breadth of "green chemistry" it is particularly difficult to come up with commensurable measures of the policy frameworks in place in different countries. In the aforementioned study, data from the *World Economic Forum*'s "Executive Opinion Survey" is used to measure policy stringency. The survey was implemented by the WEF's partner institutes in over 100 countries, which include departments of economics at leading universities and research departments of business associations. The means of survey implementation varied by country and included postal, telephone, Internet and face-to-face survey. In most years, there were responses from between 8 000 and 10 000 firms (see WEF, 2008 for a description of the sampling strategy).

Respondents are asked a number of questions related to environmental policy design. Unfortunately, none of them relate directly to "green chemistry". However, the degree of perceived stringency of a country's chemical waste policy was assessed on a Likert scale, with 1 = lax compared with that of most other countries, and 7 = among the world's most stringent. Mean responses for selected countries are provided in Figure 5.15. The most important patenting countries are also generally those with the most stringent regimes. However, it must be noted that the focus of the question is much narrower than the objectives of green chemistry.

While it is true that some of the countries with the most stringent chemicals waste policy are also the countries with the highest rates of innovation, such a measure only covers a small sub-set of the areas in which the benefits of green chemistry are likely to arise.

Figure 5.15. **Stringency of chemical waste policies (mean WEF value 2001-04)**



Instrument types

In this section we consider more specific examples of public policies, and how they may have had an influence on green chemistry. Relevant policy instruments can be broadly classified as:

- Negative instruments – provide incentives for innovation in "green" technologies by concentrating on identifying, assessing and then controlling polluting and dangerous chemicals. By reducing negative environmental and health impacts these instruments can broadly encourage green chemistry innovations. These instruments include: risk assessments, regulations (*i.e.* limits, and bans) and taxes (including the purchasing of pollution permits).
- Positive policies – aim to stimulate green chemistry by concentrating on encouraging the good technologies: support for R&D, adoption and training of industry, public procurement, labelling and awards.

Negative instruments

Risk assessment plays a central role in basic chemical legislation in many OECD countries, and can be considered as a precondition for the implementation all other instrument types. The recent EU REACH legislation and the US Toxic Substance Control Act 1976 (TSCA) are both policies where assessment of risk plays a large part. Both policies aim to address the problem that in the past chemicals were introduced to the market without comprehensive safety testing and consequently there are many substances on the market that may or may not be safe.

The US treats existing and new chemicals differently under the TSCA (Toxic Substances Control Act) of 1976. Existing chemicals are defined as those prior to December 1979 (approximately 62 000 chemicals). In order to impose limits on existing chemicals the EPA (Environmental Protection Agency) must prove that they pose an unreasonable risk and that the benefits of regulation outweigh the costs to industry. For new chemicals, the TSCA registration process requires chemical manufacturers to provide any available test data, but in practice only 15% of pre-manufacturing notices submitted to the EPA contain any health or safety test data; this data gap has been attributed to cost and time disincentives faced by chemical companies (US GAO, 2009)

Consequently only five chemicals out of more than 83,000 now used in commerce have faced restrictions since the inception of TSCA. As part of assessment procedures for new chemicals, the EPA has developed a number of tools to help tackle the problems associated with knowledge gaps – specifically whether chemicals are safe or not. The EPA also operates a programme called "Design for the Environment" that aims to identify chemicals that are "best in class" according to health and safety metrics for a variety of industrial and consumer applications, but does not have clear authority to establish safety standards based on the findings. In 2009 the EPA announced "Essential Principles for Reform of Chemicals Management Legislation", calling for data and testing burdens to be shifted to industry, consistent funding for safety assessments, and greater transparency and public access to chemical information. The principles also specifically state that green chemistry should be encouraged to lower risk and improve energy efficiency and sustainability (*www.epa.gov/opptintr/existingchemicals/pubs/principles.html*).

The European Union introduced the REACH (Registration, Evaluation and Authorisation of Chemicals) (see *http://ec.europa.eu/environment/chemicals/reach/pdf/2007_02_reach_in_brief.pdf*) regulation in June 2007, to be phased in over 11 years. REACH legislation pushes the burden of proof onto industry to prove that products are safe, whereas under past legislation the burden was on the government to prove the chemical was not safe. Prior to REACH, the EU had different safety testing for "new" and "existing" chemicals. Existing chemicals, those in the market before 1981 were not automatically required to meet the testing requirements of new chemicals. As existing chemicals are the majority of those used, this resulted in a knowledge gap where the health and environmental effects of these chemicals is unknown.

This provides an implicit disincentive on innovation, providing a market "rent" to existing chemicals and the manufacturers of these chemicals (Farber, 2008). REACH was designed to address this anomaly by requiring all chemicals to be assessed. Furthermore, the burden of testing has been shifted from the state to industry. Other aspects of REACH include the phasing out and substitution of the most dangerous chemicals. The safety data on chemicals will be publically available on a database managed by the European Chemical Agency. Other important EU legislation includes the Regulation for Classification, Labelling and Packaging of Substances and Mixtures (CLP Regulation, January 2009). This requires internally agreed classification and labelling so that hazards are transparent to the entire supply chain that may use or distribute the chemical, including consumers. It is based on the UN GHS Globally Harmonised System of Classification and Labelling of Chemicals, which aims to provide a clear, worldwide standard for classifying chemicals according to various hazards such as acute toxicity or flammability. By focusing on the intrinsic properties of the chemical and communicating the resulting hazards, the CLP regulation is line with the green chemistry approach to risk, which focuses on inherent hazard instead of the circumstances of chemical exposures.

In Japan, the "Law Concerning the Examination and Regulation of Manufacture of Chemical Substances" was passed in 1973, and subsequently revised in 1986. This was primarily concerned with identifying (and regulating) the adverse effects from chemical substances. In 1999 the "Law Concerning Reporting and Release to the Environment of Specific Chemical Substances and Promoting Improvements in Their Management" was passed. This stressed the disclosure of information on the use and impacts of chemical substances.

Canada announced the Chemicals Management Plan in 2006 which proposes to assess all chemicals by 2020 (*www.chemicalsubstanceschimiques.gc.ca/plan/index-eng.php*). More

recently, the Californian "Green Chemistry Initiative" is working towards a comprehensive system specifically aimed at encouraging green chemistry. To date, legislation passed in 2008 has initiated a web-based *Database Toxics Information Clearinghouse* with information on toxicity and hazards of chemicals (*http://californiagreenchemistry.squarespace.com/*).

As noted above, risk assessments are a necessary precursor to regulation. For instance, the California Department of Toxic Substances Control (DTSC) has been given authority to develop processes to identify chemicals of concern and subsequently to impose restrictions or bans. In September 2010 DTSC released a Proposed Regulation for Safer Consumer Products. Under these rules, the DTSC will prioritise chemicals and products according to both hazard and exposure traits, considering volumes and effects on sensitive sub-populations. Manufacturers will be required to submit alternatives assessments, which will be reviewed by DTSC. DTSC will have a range of regulatory options including labelling requirements, usage restrictions, and outright bans (*www.dtsc.ca.gov/PollutionPrevention/GreenChemistryInitiative/Proposed-Regulation.cfm*).

Positive instruments

Significant gains can be made by providing positive support to help industry adopt greener technologies. A number of governments provide financial support (grants and tax preferences) for R&D expenditures which related to green chemistry. While, in the United States the proposed "Green Chemistry Research and Development Act" was never passed, grants are provided under the EPA/NSF programme on "Technology for Sustainable Development" (*www.epa.gov/greenchemistry/pubs/grants.html#TSE*).

In Japan, the National Institute of Advanced Industrial Science and Technology (AIST) undertakes a considerable amount of research on green and green chemistry, particularly in the areas of catalysis, membranes, supercritical fluids and renewable resources. In addition, the Ministry of Economy, Trade and Industry provides support for research in the following areas (see *www.chugoku.meti.go.jp/mailing/ouen/59-2.pdf*):

- Chemicals risk reduction technology.
- Technology for supercritical fluid utilisation.
- Development of transgenic plants for production of industrial materials.
- Development of technological infrastructure for industrial bioprocesses.
- Bio-catalysis.

Incentives for the adoption of green chemistry products are an important driver for innovation. This is particularly relevant for small-to-medium enterprises which typically spend fewer resources process improvements and product development than large companies. The Massachusetts Toxics Use Reduction Act (TURA) 1989 is of particular interest as it requires firms to look at ways to use alternatives and reduce waste of some 900 industrial chemicals. TURA created a state Office of Technical Assistance and Technology (OTA) that consults with users of toxic substances to implement pollution prevention and reduction strategies and promote innovative, less toxic technologies. The legislation also created a Toxics Use Reduction Institute (TURI) that sponsors programmes in research, education, and information dissemination related to cleaner, safer products.

Over 1,000 firms have participated since 1990, and the programme has resulted in major reduction of toxic and hazardous waste (Tickner *et al.*, 2005; Koch *et al.*, 2006). It has been estimated that TURA filers have decreased their toxic chemical use by 14% from

the 2000 base year to 2007. Using the same method of adjustment, TURA filers are generating 34% less by-products or waste per unit of product and have reduced releases of TRI reported on-site chemicals by 44%.

Many OECD countries have introduced green public purchasing policies to reduce the environmentally damaging effects of their procurement of goods and services. The government is a significant purchaser of goods and services and therefore such procurement preferences can act as an incentive to industry to develop more environmentally friendly products. Also, if there is sufficient government demand this can serve as a signal ("demonstration") to private purchasers, giving the greener technology the competitive advantage, thus encouraging innovation. Furthermore, the government demand may allow economies of scale thus reducing the cost and encouraging wider use of these technologies.

One prominent example of the use of environmental criteria for public purchasing decisions which may have encouraged "green chemistry" would be the requirement that paper meets chlorine-free standards. Austria's "Check It!" green purchasing criteria accords a preference for TCF (totally chlorine-free) over ECF (environmentally chlorine-free) paper because of reduced pollution. Support for alternative-fuelled vehicles, and purchase of alternative-fuelled vehicles is seen for example in the United States, where the Energy Policy Act of 1992 mandated that certain federal and state government fleets acquire AFVs (*www1.eere.energy.gov/vehiclesandfuels/epact/*).

Awards have proven to be a successful means of inducing innovation in a number of areas, including health and energy technologies (see, for example, Newell and Wilson 2005). They have raised the profile of Green Chemistry and encouraged research. The US presidential Green Chemistry Challenge Awards have been granted in the following areas (for a list of past award winners see *www.epa.gov/opptintr/greenchemistry/pubs/pgcc/technology.html*):

- Biotechnology – general.
- Biotechnology – genetic engineering.
- Biotechnology – use of isolated enzymes.
- Polymers – chemical polymers.
- Polymers – biopolymers.
- Renewable resources.
- Safer chemical products.
- Solvents – CO_2.
- Solvents- solvent-free processes.
- Solvents – water.
- Solvents – other.
- Synthetic processes.
- Chemical catalysts.

There are many other countries which have instituted awards including the European Sustainable Chemistry Award and the Royal Australian Chemical Institute Green Chemistry Challenge awards.[8] In Japan the "Green and Sustainable Chemistry Network Awards" were established in 2002.

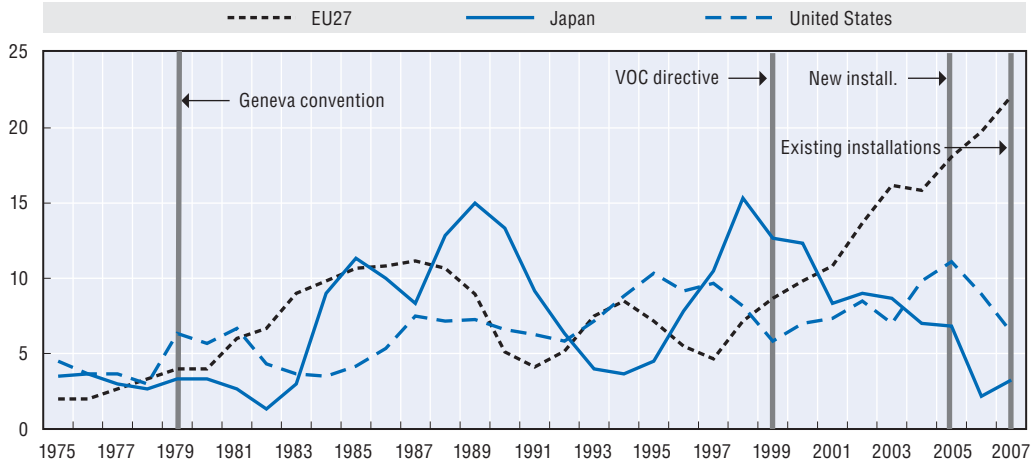
The evidence of innovation impacts

Matching policy data with innovation impacts is complicated by the heterogeneous nature of both "green chemistry" policies and the innovations themselves. As such, in this final sub-section a limited number of technologies and policy measures are examined. It is important to emphasise that the data is presented descriptively and it is not possible to draw firm conclusions from the effects of different policies on innovation. For instance, more general trends in the market may be driving much of the innovation (see Johnstone, Haščič and Popp, 2010, for a discussion in the context of renewable energy technologies).

Aqueous solvents

Figure 5.16 charts the trend in patent counts for aqueous solvents in the EU27, Japan and the United States. Arguably the 1999 Directive affected the trend rate in growth in patents, at least for the EU27. However, there was an earlier peak for both Europe and Japan. This may have been a consequence of the 1979 Geneva Convention on Long-range Transboundary Air Pollution (*www.unece.org/env/lrtap/lrtap_h1.htm*). As part of the Convention a Protocol was signed by 23 European countries on VOC emissions (*www.unece.org/env/lrtap/vola_h1.htm*).

Figure 5.16. **EU legislation on VOC and patent counts**



The European Commission's VOC Solvent Emissions Directive (SED) is another example. Passed in 1999, the Directive covers emissions from printing, surface cleaning, painting and coating activities, dry cleaning and manufacture of footwear, and pharmaceutical products. The SED establishes emission limit values for VOCs in waste gases and maximum levels for fugitive emissions for solvents (*http://eur-lex.europa.eu/LexUriServ/site/en/consleg/1999/L/01999L0013-20040430-en.pdf*). The Directive takes the quantity of solvents input and then sets maximum allowances depending on the type of activity and the toxicity of the solvent (see Belis-Bergouigan *et al.*, 2004). New installations had to comply by 2002, while existing installations had until 2007 to do so.

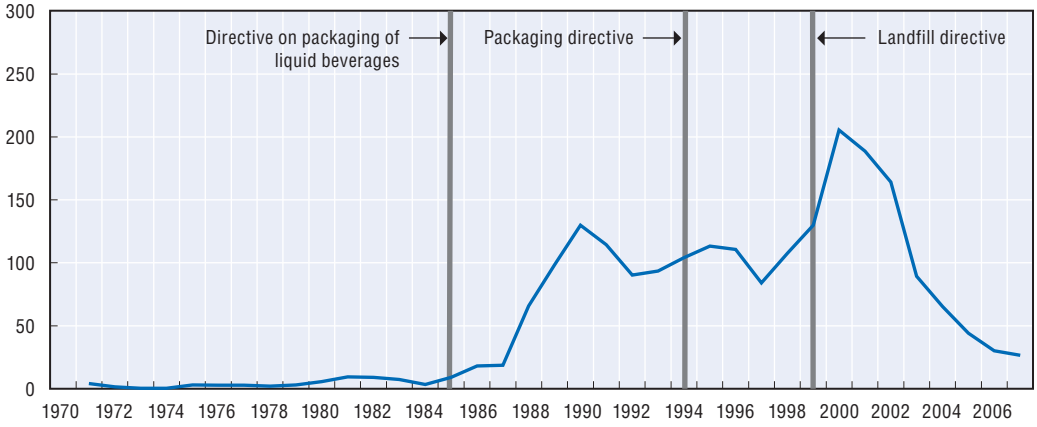
Packaging

Waste has also been subject to stringent regulations which may have given a spur to "green chemistry" innovation. For instance, in Europe the Directive on Packaging of Liquid

Beverage Containers (1985), the Packaging Directive (1994), and the Landfill Directive (1999) (*http://europa.eu/legislation_summaries/environment/waste_management/l21207_en.htm*) may have lead to innovation in the area of biodegradable packaging and "green" plastics. While there was clearly a sudden increase in the late 1980s and late 1990s in European countries, the link with specific policy initiatives is less clear.

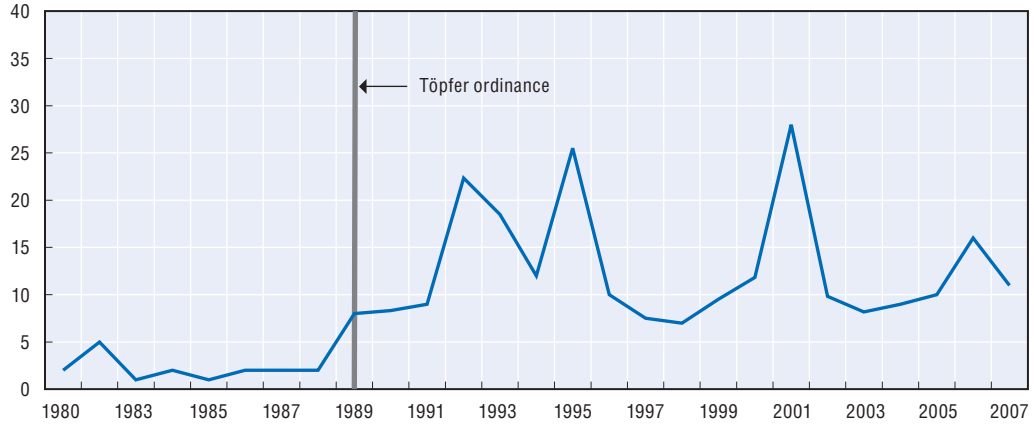
Figure 5.17. **EU packaging directives and European inventor country patents for biodegradable packaging**

CP's and singulars – 3-year moving average



However, if we look at the case of Germany, the effect of the Töpfer Ordinance is more revealing. There was a discernible impact on innovation in biodegradable packaging patent counts in the years following the introduction of the law.

Figure 5.18. **The Töpfer law and German inventor country patents for biodegradable packaging**



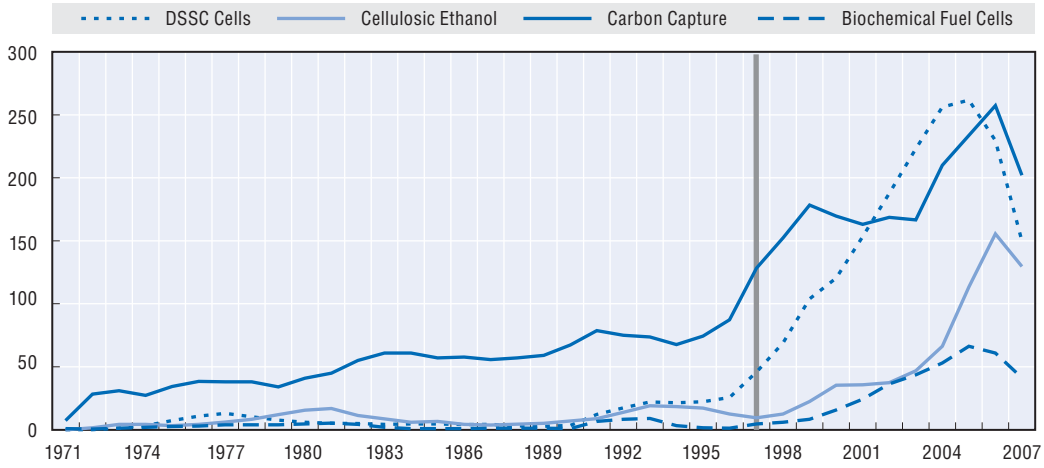
CCM technologies

Dechezleprêtre *et al.* (2011) have looked at the effect of the Kyoto Protocol on climate change mitigation technologies. Using a more refined search strategy developed by patent examiners from the European Patent Office it is possible to identify specific "green chemistry" innovations which serve to mitigate climate change. As can be seen in

Figure 5.19, the rate of innovation for many of these – particularly dye-sensitised silicon crystal cells – increased markedly in the period following the signing of the Protocol.

Figure 5.19. **Kyoto Protocol and selected CCM green chemistry technologies**

Global CPs and singulars – 3-year moving average



Chlorine-free bleaching technologies

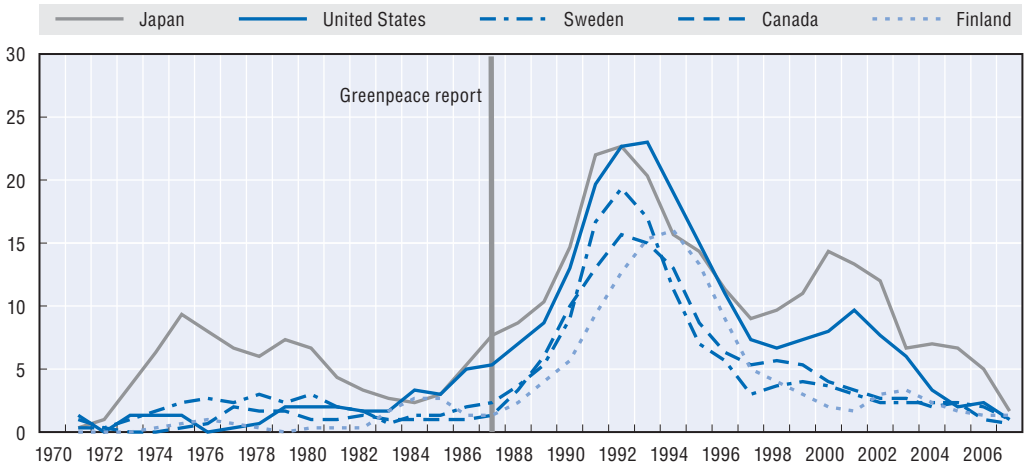
The main regulations related to emissions of AOX in the bleaching of pulp are summarised in Table 5.5 (see OECD, 2008). It is important to note that some of these regulations could be met through the use of elemental chlorine-free bleaching rather than totally-chlorine free bleaching. However, the standards passed in Sweden and later Finland and some Canadian provinces would have been a spur to the use of TCF.

Table 5.5. **Summary of key regulations for the pulp and paper sector**

Sweden	
1991	Environmental legislation establishes strict guidelines for AOX (**0.1-0.2 kg/t**). Enforcement is through plant-by-plant permitting.
Finland	
1987	Issues first guidelines for AOX (**1.4 kg/ADT**), to be met by 1994. Enforcement is through plant-by-plant permitting.
1993	Accepts Nordic Working Group performance standards for AOX (**0.2-0.4 kg/t**). Enforcement is through plant-by-plant permitting.
Canada	
1990	British Columbia sets AOX limits of **1.5 kg/ADt**, to be met by 1995. Since lowered to **0.6 kg/ADt**.
1992	Quebec passes AOX limits that are phased in gradually. AOX limit of **0.8 kg/ADt** by 2000. New mills limited to **0.25 kg/ADt**.
1993	Ontario passes AOX limits that are phased in gradually. AOX limit of **0.8 kg/ADt** by 2000.
United States	
1993	Proposed Cluster Rule suggests TCF as best available technology. Never took effect.
1997	Revised Cluster Rule limits monthly average AOX releases to **0.62 kg/t** pulp for existing sources, and **0.27 kg/t** pulp for new sources. Mills have until 2001 to comply.
Japan	
1991	Pulp and paper industry proposes voluntary AOX limit of **1.5 kg/metric tonne** by end of 1993.
2000	First law limiting dioxins in wastewater (1 pg/l). No specific limit for AOX or for the pulp and paper industry.

However, as can be seen in Figure 5.20 innovation in TCF technologies in the main pulp-producing countries preceded the introduction of these regulations. Popp *et al.* (2008) argue that this was a consequence of consumer pressure, with regulatory measures

Figure 5.20. **Totally chlorine free bleaching patents**



following afterward as a response. In particular, the release of a Greenpeace report, highlighting the environmental and health implications of bleaching technologies seemed to have played a role. This is quite different from the other cases discussed, and may be related to the fact that there were direct health concerns associated with the use of bleached paper. Indeed, it has been argued that the discharge limits adopted by the Nordic States became redundant because green market demand had surpassed those limits for more stringent measures (Smith and Rajotte, 2001).

Conclusions

This paper has provided a review of the development of green chemistry. While there is significant evidence of institutional activity, it is important to determine whether this has been translated into concrete innovations. Descriptive analysis of trends in green chemistry innovation was undertaken using patent data. Unfortunately, due to the nature of the patent classification system it was impossible to identify all green chemistry patents. However we looked at a number of important green chemistry areas.

Of the green chemistry technologies surveyed, biochemical fuel cells and green plastics were the two areas that have shown the most growth. Other areas were past their peak: notably totally chlorine free pulp and paper technology and biodegradable packaging. For TCF technology the peak was in the early 1990s while the trend for biodegradable packaging has been less obvious, with a peak at 1992 and in 2002. The trends in selected white biotechnology are interesting in that this is a key area for green chemistry and it is hoped that many future green technologies will emerge from this area. Although this area has increased, it has not increased more than the general chemistry or all-sector indicator.

Some tentative conclusions have been drawn on the role of public policy in inducing innovation in selected areas. In some cases, like TCF pulping, it appears that public pressures on the market led to changes in technology before regulations took effect. In other cases, for example biodegradable packaging in Germany, the effect of policy on innovation is less ambiguous. There are, however, some more "qualitative" conclusions that can be drawn from the review of country experience.

Perhaps most significantly it is important that regulations which implicitly favour "incumbent" (or "existing") chemical products are likely to slow the rate of innovation. This

will grant a rent to existing chemicals. In some cases this may discourage both the "exit" of environmentally-damaging chemicals and the "entry" of less-damaging possible substitutes. Rectifying this disincentive was part of the motivation for the introduction EC's REACH Directive.

It has been noted, that there is an increasing role of public inventors, particularly universities, in green technologies. Policymakers who seek to support innovation in green chemistry should be aware of this change in the patenting landscape. There are a number of models that policy makers can look to in developing programmes that support efficient partnerships between industry, academia and government. One example is the Design for the Environment (DfE) programme at the US EPA. This programme brings together industry, academia and government to assess alternatives to particular chemicals, has instituted a labelling programme, and has defined and disseminated best practices for chemical use in particular sectors. Work at DfE has included flame retardants, cleaning products, car-care, de-icers and odour removal. DfE is popular with industry, which is able to take advantage of the programme's expertise with LCA, alternatives analysis, and other evaluation tools. They benefit from both the label, as well as from the development of best practices that protect their own employees as well as their customers.

In China, governments at the provincial and municipal level are providing incentives for green chemistry R&D Centres by providing matching funds to academic institutions that are able to secure funding from an industrial partner. Government at these levels is also acting as a matchmaker, disseminating requests for proposals (RFP's) to academic researchers around the country. These RFP's are usually focused on key green chemistry challenges faced by local industry, and are considered of strategic economic importance for a local area. By working with academics throughout the country, the government and industry have access to a broader range of expertise than might be available locally.

Most partnership programmes are focused on key technology platforms or areas that are attractive to a number of firms and academics. If well-designed there are benefits for all of the parties. The combination of partners has several advantages- it helps industry co-ordinate with academia on areas of research that are important, but whose pre-competitive nature makes it difficult and inefficient to perform within a single firm. It also provides a route for academic R&D to become commercialised. And effectiveness is also aided by the ability of government to act as a convenor or matchmaker to bring together more interdisciplinary groups.

From a policy standpoint, it would of course be desirable to avoid funding projects industry would undertake, even in the absence of government support (the problem of "moral hazard"). However, government support, if provided intelligently, can either speed along existing R&D efforts, or make new initiatives more attractive. One strategy is to fund areas in which companies tend to under-invest. There are many developments in green chemistry that are considered to be pre-competitive research, but which would benefit many firms. In the case of the pharmaceutical industry, the members of the *ACS-GCI Pharmaceutical Roundtable* have contributed to a series of yearly grants on particular green chemistry challenges that are common to all of the members. This has included specific transformations or reactions, but could also be powerful in areas such as solvent systems, catalysis, and alternative reaction conditions which have a broad impact- and thus very little incentive for any one firm to develop on their own.

Another strategy is to develop a more detailed picture of where green chemistry technologies have the greatest barriers in moving from laboratory to full commercialisation. There are certain steps in the process that can be particularly risky-such as moving into pilot scale, or building (or changing over) large production facilities based on a new, largely unproven technology. In biotech and pharmaceuticals, these problem areas have been addressed in some cases by partnerships between smaller innovators, who conduct novel research, with larger pharmaceutical companies who have the financial capital and other resources required for clinical trials, production and marketing.

Policies could be used to help remove some risks/uncertainties in order to encourage firms to invest themselves. For small and medium sized companies, that could involve providing expertise and assistance, or helping to create partnership with larger firms at key stages in the commercialisation process. Some examples of incentives include access to less expensive capital, in the form of rotating capital funds or low-interest loans linked to specific projects that require applications, business plans, and demonstration of how government investment would make otherwise unfeasible projects possible. Other potentially useful policies include beneficial regulatory timelines and more tax credits for particular R&D on green chemistry in order to stimulate firms to invest. It is probably impossible to prevent some firms who would have invested in the absence of policy from benefiting. However, even these firms are providing some level of public benefit through their actions, so some government support for their actions is not completely unjustified.

In many cases, governments are not always best qualified to target specific innovations. Rather than just focusing on one or two particular "hot" areas, policy makers can adopt different approaches. One strategy is to identify key chemicals of concern for which alternatives do not exist. This is the approach being considered in the latest draft of the Safer Chemicals Act of 2010 in the US. In this case, the advantage is that the problem is already identified, and there is less uncertainty about a market for green chemistry products. If the government funds a variety of projects in a particular area, at least some of them will be successes, although some funding will inevitably go to less successful innovations.

Another approach is to fund key pre-competitive areas of basic research (see above), such as important transformations or solvent systems. Once again, for any given project, it is hard to anticipate success. But certain areas are of a high level of industrial importance, and government funding can help direct academic efforts into these areas. Furthermore, it encourages the development of more basic scientific knowledge and understanding, which is important in the long-run when new and difficult challenges requiring alternatives arise.

In terms of the individual projects which are supported, the best strategy is most likely to be one in which the government adopts a portfolio approach. The government usually funds a number of projects in any particular area, with the expectation that the combination of markets and the science will render some successful and others not. The goal for policy makers should be that overall their investment is yielding progress in key areas.

It is well-established that innovators do not like regulatory uncertainty. It makes what are already technically challenging and uncertain projects subject to yet another kind of risk. Several things can be done to give innovators a long and clear enough policy horizon to make risky, but important investments. The first is to have a comprehensive chemicals

policy. Situations in the United States, where different states are legislating regulations on a chemical-by-chemical basis increase the level of risk and uncertainty, and make it hard to anticipate what markets will be in the longer term for particular green chemistry technologies. While the US' Toxic Substances Control Act (TSCA) has been criticised on many aspects, firms appreciated its predictability, and the ability to interact with regulators relatively early in the regulatory process for new chemicals. The expectations were generally clear. While REACH and proposed TSCA reform will mean large changes in the chemical regulation process, once they have been fully implemented, firms will know what to expect, and will better be able to invest in the long-term.

The other policy that helps firm invest is to have incentives that are also stable. Small Business Innovation Research (SBIR) grants in the US frequently do this by having smaller, initial grants. These can be followed, if firms are able to demonstrate success in the first round, by larger grants in the second round. The sum total is a long enough time frame for firms to make investment decisions, while still allowing the government an "out" for projects that are not performing. Additionally, wherever possible, incentive programmes, such as tax credits, should be available for multiple year periods, to prevent some of the problems in the US with wind energy subsidies, whose tenuousness hurt the willingness of investors to put their funds into wind projects.

Notes

1. For the purposes of this report "green" and "sustainable" chemistry are used interchangeably.
2. *www.oecd.org/dataoecd/16/25/29361016.pdf*. The OECD started working in the area of green chemistry in 1998 with the aim of providing guidance to member and non-member countries in the development of national programmes. An OECD workshop in 1998 identified what work was being done in the field of sustainable chemistry and what could further its development and use. An "Issues Team" was established in 1999 with 10 OECD countries represented. The Sustainable Chemistry Platform was started in 2007 to assist information exchange, to monitor new developments and to investigate the drivers of sustainable development.
3. Two Nobel Prises were awarded for catalysis during the past decade: in 2001 for hydrogenation, and in 2005 for olefin metathesis.
4. The figure for the chemical industry have been calculated using Table A.1 and includes 2400 Chemicals, n.e.c., 2411 Basic Chemicals, 2413 Plastic Resins, 2423 Drugs and 2429 Miscellaneous Chemicals. The rate of patenting varied across these categories, with 2423 Drugs having the highest product patent rate at 95.5% and 2400 Chemicals n.e.c. having the highest process patenting rate at 61.49%. Note that when the 2423 Drugs category is removed, the product and process patenting rates are still above average.
5. Part of the reason behind the importance of licensing is the role that SEFs (specialised engineering firms) have played in the chemical industry. SEFs specialise in process innovations and by licensing their technology have spread the latest technologies throughout the world.
6. Figure from 2008 *Annual Report*, *www.dow.com/financial/pdfs/161-00720.pdf*.
7. Version SEP 2009.
8. *http://portal.acs.org/portal/acs/corg/content?_nfpb=true&_pageLabel=PP_TRANSITIONMAIN&node_id=1316&use_sec=false&sec_url_var=region1&__uuid=ff85c816-f628-407c-aa2e-cc040f58c64b*; *www.gscn.net/awardsE/index.html*; *www.euchems.org/ESCA/* and *www.raci.org.au/national/awards/greenchemistry.html*.

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Chapter 6

Policy Conclusions

In this book the potential impacts of environmental policy on innovation have been analysed in a wide variety of fields (*i.e.* motor vehicles, solid waste, regional air pollutants, green chemistry). The research presented draws upon a worldwide database of patent applications and introduces an indicator of innovation in technologies related to the mitigation of environmental impacts. A number of key conclusions emerge from the different chapters.

It has been found that policy stringency plays a significant role in inducing innovation. More specifically, based on evidence from a broad cross-section of countries it is found that the perceived stringency of environmental policy has a positive impact on the likelihood of developing innovative means of mitigating air and water pollution and managing solid waste. A more "stringent" policy will provide greater incentives for polluters to search for ways to avoid the costs imposed by the policy. This finding is largely confirmed by the research presented on the more specific policy measures and technology fields assessed in this volume.

All environmental policies attach a price to polluting, whether they are taxes, subsidies, regulations, or even information measures. However, it is not just the "level" of the price of polluting which matters. Predictability and credibility of the price over the longer term are also important. Price signals that are difficult to predict encourage investors to postpone investments, including the risky investments which lead to innovation. In the face of unpredictability there is an advantage to "waiting" until the policy dust settles. By adding to the risk which investors face in the market, an "unpredictable" policy regime can serve as a "brake" on innovation, both in terms of technology invention and adoption. Frequently changing policy conditions come at a cost, and such instability should be avoided.

In addition, the more "flexible" – or technology-neutral – a policy regime, the more innovation takes place. This implies that rather than prescribing certain abatement strategies (such as technology-based standards), governments should, wherever possible, give firms stronger incentives to seek out the best means to meet a given environmental objective. Since future trajectories of technological change cannot be foreseen, it is important to give innovators the incentive to search across a wider "space" to identify potential means of complying with regulations. Flexibility "unleashes" the search for new innovations, some of which may be only improvements on existing technologies.

Research in other fields has identified technology transfer (embodied and disembodied) as an important means of bringing about improved welfare. This is particularly true in the case of environmental technologies where many negative impacts cross borders. Two environmental policy factors appear to have an influence on the flow of technologies across borders: A) the degree of flexibility of the domestic policy framework; and B) the degree of international policy co-ordination. If environmental policy is prescriptive and unco-ordinated this can result in fragmented technology markets, with the potential market for the innovations induced split across different policy jurisdictions.

In this book, both of these aspects have been examined. The effect of the flexibility of domestic policy regimes on the international diffusion of environmental technologies has been assessed. The results confirm that flexibility of policy regimes not only increases domestic rates of innovation but it also ensures that markets are not fragmented across different countries. Given the risks associated with expenditures on research and development, and the economies of scale required to recover such expenditures, it is important that regulatory regimes in "source" countries not constrain the potential markets for any induced innovations. In addition, flexible policy regimes in "host" countries allow potential adopters of innovations to access a much wider range of technologies available on international markets.

We also assessed the role of international policy co-ordination through adherence to multilateral environmental agreements. More specifically, we examined whether adherence to a series of international agreements on SO_X and NO_X emissions abatement (the LRTAP) has induced the transfer of technologies across signatories. We hypothesised that transfer of technology between signatories can be a way of encouraging adherence, providing an inducement for upwind countries to participate. Some descriptive evidence of the plausibility of such an assumption is provided, but more formal analysis might be addressed in future work.

However, the primary focus of the research presented has been an assessment of whether the Protocols arising out of the LRTAP have encouraged the transfer of technologies between signatories. Indeed, the major finding is that there is a positive effect on technology transfer between pairs of countries which have both joined the LRTAP Protocols. It must be emphasised, however, that while the Protocols place emphasis on co-operation across signatories, there are few explicit incentives. The finding presented may be due to the simple sharing of information on available abatement technologies through intensive co-operation – *i.e.* through regular conferences and sharing of documentation.

While general policy conditions are clearly important determinants of the development and international diffusion of environmental technologies, a more precise assessment of the effects of policy on innovation necessitates an analysis of the effects of specific policy instruments. Moreover, in many cases different instruments are introduced in combination, sometimes with different but related environmental objectives. In this vein, work has been undertaken in the area of alternative-fuel vehicles (AFVs) and waste recycling technologies.

In the case of AFVs, the relative importance of fleet-level fuel efficiency performance standards, post-tax fuel prices, and public support for R&D were assessed. Based on precise characterisations of the policy instruments implemented in different countries, the results indicate that relatively minor changes in a technology standard or automotive fuel prices would yield effects that are equivalent to a much greater increase in public R&D budgets. However, there are significant differences between electric and hybrid vehicles. For example, in the case of electric vehicles the role of post-tax fuel prices is insignificant, but standards play an important role. Conversely, for hybrid vehicles it is post-tax fuel prices which are significant and not standards.

The results may indicate the importance of sequencing of policy measures. Relative prices may have less a role of a play than ambitious performance standards the further a technology is from being directly competitive with the incumbent technology (petrol- and diesel-driven cars). While in theory, a price sufficient to induce an equal level of innovation

could be introduced, such a measure would likely be politically infeasible in practice. Moreover, even if introduced it may not be perceived as credible over the longer-term by potential innovators.

The study of waste recycling innovations has been conducted through a descriptive analysis of the correlation between the introduction of important policy measures and patent counts for different waste streams. The results provide an indication that the first wave of policies (end of the 1980s, beginning of the 1990s) may have produced a technological shock in the system, but the effect of more recent measures is less pronounced. This result is especially underlined in the analysis of specific waste streams (end-of-life vehicles, packaging, composting), where there seems to be a strong and positive link between policy action and innovation performance at the beginning of the 1990s, but this link is less clear in the last fifteen years.

One possible explanation for this finding could be that the sector is technologically mature relative to other areas of environmental innovation, a point which is reflected in the data presented in the first chapter. Rates of innovation in waste management have been declining, with the exception of some emerging economies. However, even there the rates are lower than for innovation overall. For mature sectors responses to environmental policy shocks may be reflected in behavioural and organisational innovations, rather than in terms of technological inventions. Such a hypothesis remains to be tested.

In most of the fields examined in this volume, it has been possible to establish a clear link between environmental policy "shocks" and innovation, even if the measures introduced were not the most important factors. However, the case of "sustainable" (or "green") chemistry is different insofar as the nature of the patent classification system did not allow for the identification of the "population" of green chemistry patents. The scope of innovation is too broad, and the causal factors at play too diverse. However, some specific fields were identified.

Biochemical fuel cells and green plastics were the two areas that have shown the highest growth. Other areas are past their peak: notably, totally chlorine-free pulp and paper technology and biodegradable packaging. The trends in selected white biotechnology are interesting in that this is a key area for green chemistry and it is hoped that many future green technologies will emerge from this area. Although patenting activity in this area has increased, it has not increased more than the general chemistry or all-sector indicator.

Qualitative review of the role of public policy indicates that it is important to remove biases in existing regulations which implicitly favour market incumbents relative to new entrants, whether they be firms or specific products. In addition, innovation in "green" chemistry requires efficient partnerships between industry, government and academia. This is perhaps due to the mix of both "basic" and "applied" research required in order to bring innovations to market. And finally, the "positive" nature (R&D support, public procurement, grants, awards) of many of the policy measures introduced to support innovation in this area means that policymakers face a delicate task in supporting particular innovations or activities in the face of imperfect information and uncertainty over future trajectories.

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ANNEX A

Methodological Issues in the Development of Indicators of Innovation and Transfer in Environmental Technologies

by
Nick Johnstone, Ivan Haščič and Fleur Watson (OECD Environment Directorate)

Introduction[1]

This book presents analyses of the determinants of environment-related innovation – assessing the relative importance of different factors (policy measures, market conditions, scientific capacity, etc.) on the rate and pattern of innovation and the diffusion of these inventions in the world economy. Both of these strands of work depend on the availability of appropriate indicators. This annex reviews the methodological aspects of development of such indicators. It is intended to serve as a reference document for papers arising out of this work.

The indicators of innovation in environment-related technologies (ENV-tech) thus complement those indicators which have earlier been developed by the OECD Science, Technology and Industry Directorate in the areas of Information and Communications Technologies, Biotechnology, or Nanotechnology (see OECD *Patent Statistics Manual*, 2009).[2]

The annex is organised as follows. The next section reviews the different indicators commonly used to measure innovation. This is followed by a review of alternative indicators of technology transfer. In both cases it is argued that in the context of environment-related technologies, patent data offer a good alternative to the existing measures. The final section then presents the methodology of the development of indicators of innovation and transfer based on patent data.

Indicators of innovation in environmental technologies

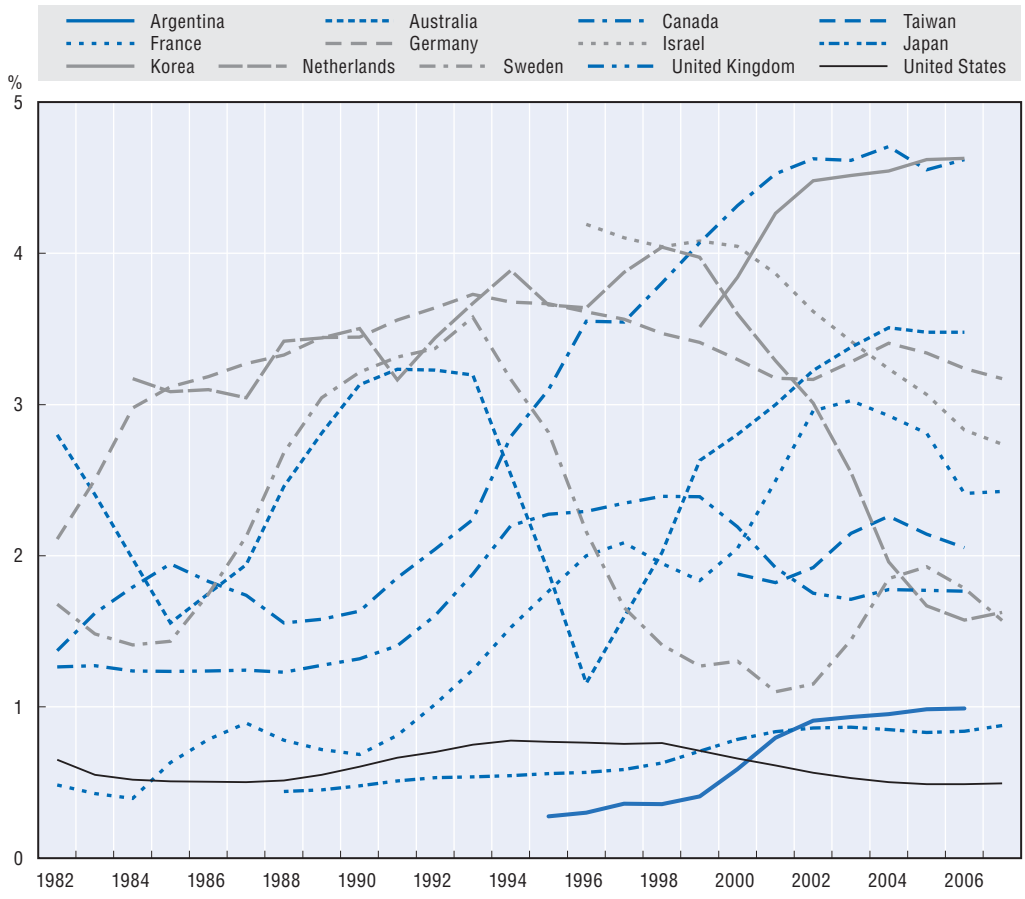
There are a number of candidates for the measurement of innovation (see OECD *Main Science and Technology Indicators*, 2008a). Most commonly, ***R&D expenditures or the number of scientific personnel*** in different sectors are frequently used as indicators. However, a sub-set of OECD and non-OECD countries have also begun to collect data on *government budget appropriations and outlays for R&D* (GBAORD) by socio-economic objective, including "control and care for the environment".[3] Figure A.1 provides some evidence for countries for which this data is relatively complete in recent years. For most countries, the data indicate that between 0.5% and 4% of GBAORD is specifically targeted at environmental objectives. While in large economies such as Germany, Japan and the US this share has remained relatively stable, there seems to have been a large degree of variation across countries and over time.

However, there has been much greater uniformity among countries in GBAORD expenditures directed at "rational utilisation of energy". For most countries, the data indicate that up to 5% of GBAORD is specifically targeted at energy objectives, although this share was higher in the early 1980s (Figure A.2).

Finally, data are also available on government R&D spending in the energy sector (see *OECD/IEA Energy Technology R&D Statistics*). The data include expenditures directed at energy generation from fossil fuels, nuclear energy, and renewable energy, hydrogen and fuel cells, energy storage, as well as measures directed at improving energy efficiency in industry, residential and commercial uses, and transportation. Figure A.3 gives the proportion of total energy technology R&D directed at renewable energy and energy

Figure A.1. **Percentage of GBAORD expenditures directed at "control and care for the environment"**

3-year moving average



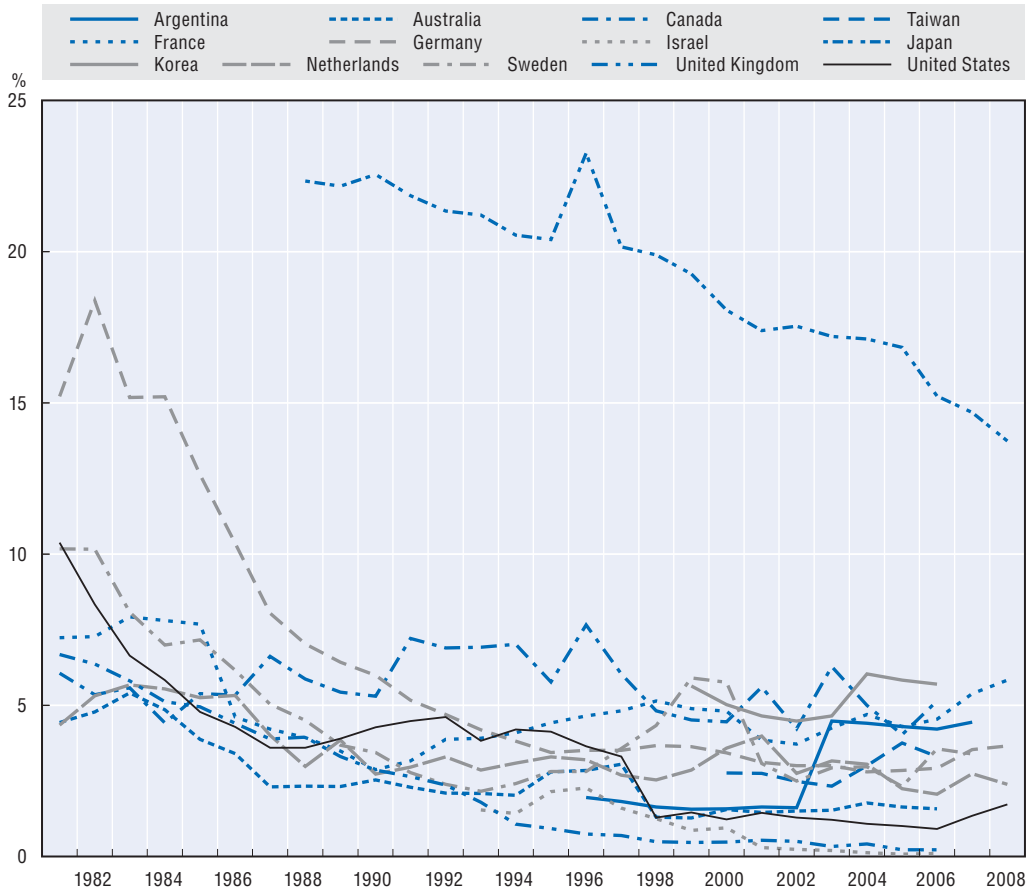
Source: OECD.Stat (*www.oecd.org/statistics*), *Research and Development Statistics*.

efficiency measures. On the one hand, countries such as Finland, Denmark, Sweden, Austria, Ireland and Hungary, devote a relatively high share of their budgets to such aims. On the other hand, this share is much lower for countries such as France, Japan, Germany, Australia, Korea, Canada and the US, often as a consequence of higher levels of spending on nuclear energy sources.

Although such indicators do reflect an important element of the overall innovation system, there are a number of disadvantages associated with their use as indicators of innovation. For example, with respect to private R&D expenditures, the data are incomplete. Further, the data are only available at an aggregate level and (with the exception of the energy sector) they cannot be broken down by technology group. Moreover, there is no source of data for private R&D expenditures by socio-economic objective that is comparable to that used for GBAORD. Perhaps most significantly, R&D expenditures are measures of inputs to the innovation process, whereas an "output" measure of innovation would be broadly preferable.

Given the general lack of data in this area, several ***micro-level data*** collection efforts have, therefore, been undertaken which have sought to measure innovation outputs. For instance, in the European Union, a small number of "environment-related" questions have

Figure A.2. **Percentage of GBAORD expenditures directed at "rational utilisation of energy"**



Source: OECD.Stat (*www.oecd.org/statistics*), *Research and Development Statistics*.

been applied as part of the *Community Innovation Survey*. Figure A.4 gives the respondents' perceptions from that *Survey* of the importance of the effects of their innovation efforts. It is noticeable that "environmental" factors rank at the bottom of this list.

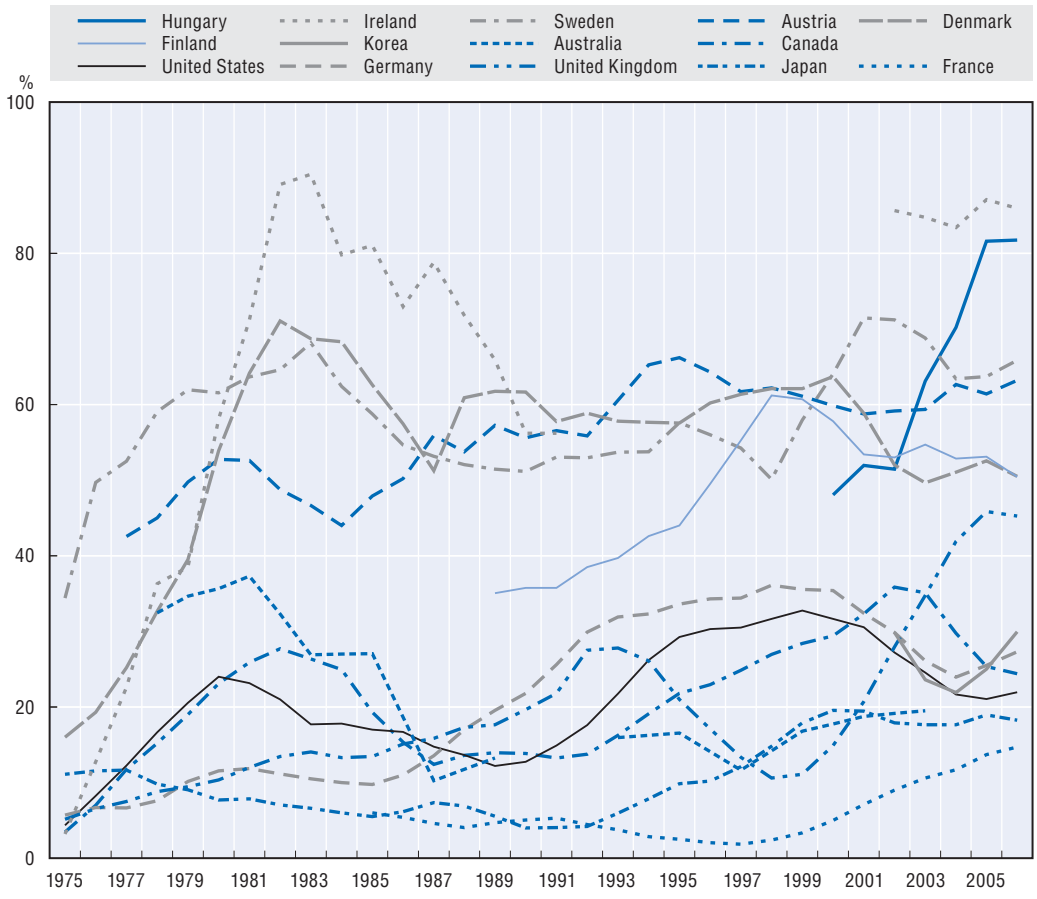
While "environmental" concerns were only addressed tangentially in previous rounds of the CIS, considerable effort has gone into the design of the most recent CIS survey questionnaire, in order to ensure that environmental concerns are addressed in a much more systematic manner in the future (see Box A.1).

Several of the researchers involved in the design of the environmental components of the CIS questionnaire were also involved in the (2006) OECD project on "Environmental Policy and Firm-Level Management" (Johnstone, 2007). In this latter project, data was collected on *input* measures of "environmental innovation", such as expenditures on environment-related R&D, as well as on *output* measures such as "clean production" and "product design". For illustration, Figure A.5 provides data on the percentage of firms in that project (by industrial sector) which reported having taken environmental factors into account in *product design*.

The main shortcoming with such exercises is their cost. A dedicated industrial survey which addresses environmental concerns on a periodic basis would be prohibitively

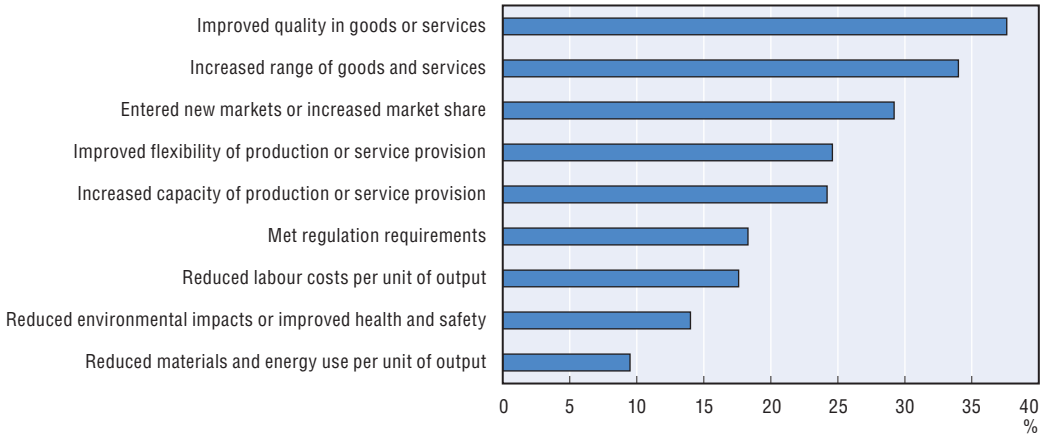
Figure A.3. **Percentage of energy technology R&D expenditures directed towards "renewable energy" and "energy efficiency" measures**

3-year moving average



Source: OECD.Stat (*www.oecd.org/statistics*), *Energy Technology R&D Statistics*.

Figure A.4. **Motivations identified as highly important for innovation activities (CIS 4-EU27)**



Source: *http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-SF-07-113/EN/KS-SF-07-113-EN.PDF*.

Box A.1. **"Environmental" section of CIS 5**

Innovations with environmental benefits

An environmental innovation is a new or significantly improved product (good or service), process, organisational method or marketing method that creates environmental benefits compared to alternatives.

- The environmental benefits can be the primary objective of the innovation or the result of other innovation objectives.
- The environmental benefits of an innovation can occur during the production of a good or service, or during the after sales use of a good or service by the customer.

1. During the three years 2006 to 2008, did your enterprise introduce a product (good or service), process, organisational or marketing innovation with any of the following environmental benefits?

Environmental benefits from the production of goods or services within your enterprise:

Reduced material use per unit output	❒ Yes ❒ No
Reduced energy use per unit output	❒ Yes ❒ No
Reduced CO_2 footprint for your enterprise	❒ Yes ❒ No
Replaced materials with less polluting or hazardous substitutes	❒ Yes ❒ No
Reduced soil, water, or air pollution	❒ Yes ❒ No
Recycled waste, water, or materials	❒ Yes ❒ No

Environmental benefits from the after sales use of a good or service by the customer:

Reduced energy use	❒ Yes ❒ No
Reduced air, water, soil or noise pollution	❒ Yes ❒ No
Improved recycling of product after use	❒ Yes ❒ No

2. During 2006-08, did your enterprise introduce an environmental innovation in response to:

Need to comply with existing environmental regulations	❒ Yes ❒ No
Environmental regulations that you expected to be introduced in the future	❒ Yes ❒ No
Availability of government grants, subsidies or other financial incentives for environmental innovation	❒ Yes ❒ No
Market demand from your customers for environmental innovations	❒ Yes ❒ No
Voluntary codes for environmental good practice within your sector	❒ Yes ❒ No

3. Does your enterprise have procedures in place to regularly identify and reduce your enterprise's environmental impacts? (For example preparing environmental audits, setting environmental performance goals, ISO 14001 certification, etc.)

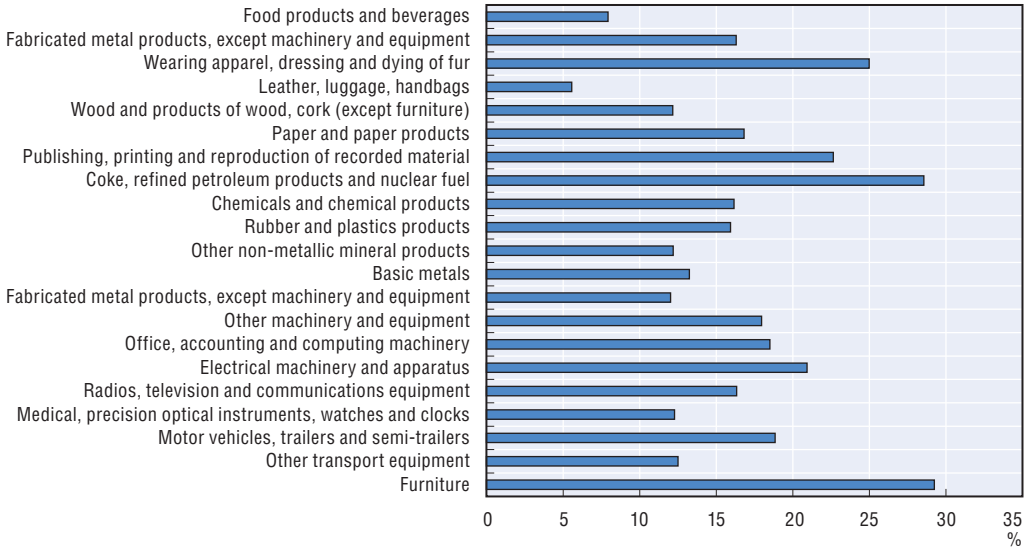
❒ Yes: implemented before January 2006.

❒ Yes: Implemented or significantly improved after January 2006.

❒ No.

expensive. While some countries do have "environmental" components in their standard industrial censuses or innovation surveys (*for example*, Canada, Norway, Japan), these data are not comparable across countries, and therefore cannot be used to develop indicators across countries.

Figure A.5. **Percentage of firms which report having taken environmental factors into account in product design**



Source: Johnstone (2007).

It is therefore necessary to look elsewhere for sources of information/data which can be used to derive indicators. One possibility would, of course, be the development of indicators based upon existing ***sectoral and commodity classifications*** – which have been developed to measure the output of goods and services. To the extent that new technologies are contained in direct (embodied) form in goods and services that are produced, such forms of innovation would be reflected in the base data. However, this would first require identification of sector or commodity classifications which represent "environmental" technologies.

The OECD/Eurostat Informal Working Group on the Environment Industry has developed a Manual (OECD, 1999) which provides a framework for the definition and classification of "environmental industry activities" (see Sinclair-Desgagne, 2008, for a recent discussion). This *Manual* identifies three broad "environmental segments", each of which includes a large range of business activities:

- Pollution management, including goods that help control air pollution, manage wastewater and solid waste, clean up soil, surface water and groundwater, reduce noise and vibrations, and facilitate environmental monitoring, analysis and assessment.
- Cleaner technologies and products, including goods that are intrinsically cleaner or more resource-efficient than available alternatives. For example, a solar photovoltaic power plant is cleaner than a coal-fired one.
- Resource management, including goods used to control indoor pollution, supply water, or help to manage farms, forests or fisheries sustainably. Also included are goods used to conserve energy and goods that help prevent or reduce environmental impacts of natural disasters, such as fire-fighting equipment.

However, and as pointed out in the Manual itself, standard sectoral codes (for example, ISIC, NACE, NAICS) do ***not*** lend themselves to such a breakdown, except in very specific areas such as water supply, wastewater treatment, and solid waste treatment and disposal.

Moreover, such categories relate primarily to "end-of-pipe" solutions to environmental concerns, areas where innovation is likely to be increasingly less beneficial overall.

On the basis of commodity classifications (the Harmonised Commodity Description and Coding System), the OECD has developed an illustrative list of "environmental goods" (see OECD, 2001) – broken down into the following broad headings:

A) **Pollution management:**

- Air pollution control.
- Wastewater management.
- Solid waste management.
- Remediation and clean-up of soil and water.
- Noise and vibration abatement.
- Environmental monitoring analysis and assessment.

B) **Cleaner technologies and products:**

- Cleaner/resource-efficient technologies and processes.
- Cleaner/resource-efficient products.

C) **Resource management group:**

- Indoor air pollution control.
- Water supply.
- Recycled materials.
- Renewable energy plant.
- Heat/energy saving and management.
- Sustainable agriculture and fisheries.
- Sustainable forestry.
- Natural risk management.
- Eco-tourism.

This list has since informed discussions about tariff arrangements related to "environmental goods and services" at the World Trade Organisation (WTO), in the context of the Doha Round of multilateral trade negotiations – which calls *inter alia* for the liberalisation of trade in "environmental goods" (and services).

However, it is important to note that these headings do not feature in the Harmonised System. The commodity codes themselves refer to generic commodity classifications. Indeed, many of the codes included in the list encompass goods and services which have a range of uses besides environmental protection (see OECD 2007 for a discussion of this issue). For instance, the list includes "air compressors mounted on a wheeled chassis for towing" (8414.40) or "articles of cast iron" (7325.10). More significantly, "environmental" goods are often designated as such in relation to a conventional alternative, which may well be included in the very same commodity classification – *i.e.*"parts for spark-ignition internal combustion piston engines" (8409.91).

And finally, classification of a good as being "environmental" does not provide any particular indication of the amount of "innovation" it represents – although production of goods and services is an important determinant and consequence of innovation, clearly

only a small percentage of production can be considered to constitute "technological innovation".

In sum, commodity classifications cannot be used to develop indicators of "environmental innovation", for two key reasons:

- The commodity classifications do not lend themselves to the identification of goods and services with beneficial environmental consequences. In most cases, the classes used are much broader than the intended "target", including goods which have no specific environmental implications. Worse, the classifications are sufficiently broad that they include goods which may well be the "dirty" substitutes for "environmental innovations".
- The commodity classifications do not allow for the distinction between standardised goods and services which have been on the market for some time, and those goods and services which represent real technological innovations.

Fortunately, there are other possible "output" indicators which address both of these concerns: bibliometric data (scientific publications) and technometric data (patent publications). The use of ***bibliometric data*** as a measure of innovation has been given renewed impetus with the growth of the Internet, combined with increasingly efficient search engines. Using keywords and indexing codes, searches of relevant databases (for example, the Science Citation Expanded Index) are typically undertaken here. Data on author, affiliation, date of publication, etc. can be extracted, and counts can be developed to assess the relative innovative activity (see Meyer, 2002).

This kind of indicator is particularly useful for analyzing the diffusion of knowledge among inventors (and between countries), based on co-publications and citations. However, there are also some shortcomings associated with the use of bibliometric data. In particular, while such data is indeed an "output" indicator of innovation, it is only an indirect indicator of a market output. Publication in a peer-reviewed journal reflects a scientific advance, but not necessarily one which has commercial applications. It is therefore difficult to use citations even as an index of quality, let alone of actual economic importance.

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 and OECD, 2009). Patent data provide a wealth of information on the nature of the invention and the applicant, the data is 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 which have not been patented (Dernis *et al.*, 2001).

Most importantly, the application-based nature of the patent classification systems allows for a richer characterisation of relevant technologies. Since the International Patent Classification (IPC) system includes over 70 000 separate classification codes, it is possible to identify very precise technological fields. In the area of "environment-related innovation", some examples of relevant codes include:

- *B60L 7/10: Electrodynamic brake systems for vehicles – dynamic electric regenerative braking for vehicle.*
- *C02F 3/28: Biological treatment of water, waste water or sewage using anaerobic digestion processes.*

- *F03D 3/02: Wind motors with rotation axis substantially at right angle to wind direction – having a plurality of rotors.*

Consequently, patent data ***can be disaggregated to specific technological areas***, as was done in previous OECD work in this area, which examined the cases of renewable energy, wastewater effluent and motor vehicle emissions (OECD 2008b). However, recent developments in the *EPO PATSTAT Database* have enabled the implementation of search strategies which provide broader coverage of the data than those previously available (OECD triadic patent family database and commercial providers). Most significantly, this data allow for the possibility to undertake much more refined and accurate searches of innovations in different spheres.

In the environmental sphere, this allows for the identification of more "integrated" technological innovations (which are virtually impossible to identify using the other data sources discussed earlier). However, it is important to recognise that patents cannot be used to develop a measure of all innovations. First, they are designed only to protect technological inventions. Other IPR regimes exist to protect innovations in other fields – for example, copyrights for literature, trademarks for words or graphic devices which distinguish a product and the registration of designs, and where protection is focussed on the appearance of a produc. In addition, less formal ways (than intellectual property rights) to protect technological inventions also exist – notably industrial secrecy, or purposefully complex technical specifications. Surveys of inventors indicate that the rate at which new innovations are patented varies across industries. A further critique of patent data relates to the fact that not everything that is patented is eventually commercialised and adopted. There are, however, significant fees attached to the examination of a patent application (and to renewal fees, once the patent has been granted). So it is safe to assume that, at least in the expectations of the applicant or patent holder, the prospects for commercialisation and adoption are good. Nonetheless, the economic value of patents varies. For meaningful empirical analyses, it is therefore important to control statistically for differences in the propensity to patent, the scope of the claims, the value of the patent and other factors which vary across countries, time and technology fields.

Indicators of international transfer of environmental technologies

Technology transfer can be either "embodied" or "disembodied", and take place either through market or non-market means. A possible taxonomy might take the following form (see Maskus, 2004):

- Market-mediated transfer:
  - Trade in goods and services.
  - Foreign direct investment.
  - Licensing.
  - Joint ventures.
  - Cross-border movement of personnel.
- Non-market transfer:
  - Imitation and reverse engineering.
  - Employee turnover.
  - Published information (journals, test data, patent applications).

Available empirical evidence strongly supports the finding that the bulk of technology transfer takes place via: **i) *trade;* ii) *foreign direct investment (FDI); and* iii) *licensing*** (Maskus, 2004). Precisely which channel is most important depends in part upon the characteristics of the "recipient country" (*i.e.* domestic research capacity, strength of intellectual property rights regimes, etc.) and the nature of the technology being transferred (*i.e.* the potential for imitation and reverse engineering).

When seeking to assess the spatial patterns and rates of international technology transfer, it is therefore important to focus on measures which reflect potential transfer through these primary channels. Since technologies may be transferred in direct (embodied) form through trade in goods and services, such forms of transfer would be reflected in ***trade*** data. However, this would necessitate the identification of relevant sector or commodity classifications which represent "environmental" technologies.

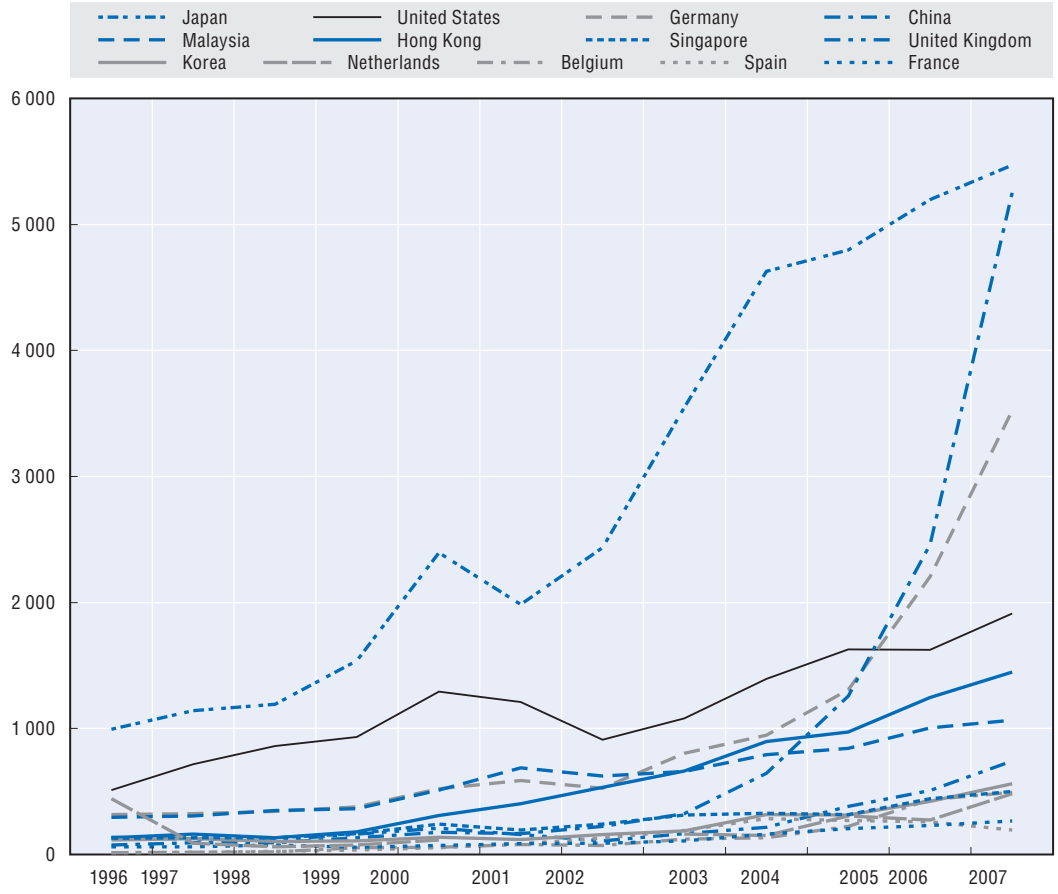
As noted above the OECD has developed an illustrative list of "environmental goods" (see OECD 2001). This list has since informed discussions about environmental goods and services at the World Trade Organisation (WTO), in the context of the Doha Round of multilateral trade negotiations – which calls for the liberalisation of "environmental goods" (and services). In principle, based upon this list, it is possible to examine recent trends in the export of "environmental goods and services".

For instance, according to figures published in OECD *Indicators of Globalisation* in 2006, exports of environmental goods in the OECD area reached USD 370 billion (1% of its GDP and nearly 6% of its merchandise exports). In the same year, BRICS countries (Brazil, the Russian Federation, India, China and South Africa) exported USD 43 billion, which accounted for almost 1% of their GDP and 2.7% of their total merchandise exports. Over the last four years, trade in "environmental goods" also pursued a dynamic pattern of growth, increasing faster than total merchandise trade particularly in the BRICS (where exports have been growing at an annual average rate of 35%). More than 25% of exports of "environmental goods" are for wastewater treatment equipment, which is also the fastest growing segment of the market. This is followed by air pollution control, waste management and environmental monitoring equipment.

However, and as noted above, the list of commodity classes used to extract the data used in these figures – while undoubtedly valuable for negotiating purposes – cannot be used credibly for statistical purposes. This is because a large number of the classes involved are only peripherally related to environmental concerns, and in some cases may even relate primarily to the "brown" substitutes for "green" alternatives (for example, "parts for spark-ignition internal combustion piston engines" – HS 8409.91).

The implications that this has for the assessment of the development of indicators of international technology transfer can be seen with reference to renewable power. HS 8541.40 is proposed as a measure of solar power technologies and Figure A.6 gives the trend in exports for the G7 countries, as well as for China and Spain. The remarkable level and growth rate of exports from China is certainly attributable to the breadth of the definition applied, which includes not only photovoltaic devices but also light-emitting diodes and semiconductor devices. Indeed, Hong Kong, China is the world's fifth largest exporter of this commodity class. Presumably, this is due to a high proportion of re-exports from other countries through Hong Kong, China. However, due to missing data on re-exports for most top exporting countries it is not possible to calculate *net* exports.

Figure A.6. **"Solar power" technology exports (based on COMTRADE data) (million USD)**



And finally, and of even more relevance to *this* paper, trade in an "environmental" good need not actually constitute "technology transfer" – although trade is an important channel of international technology transfer, not all trade can be considered to be technology transfer. In particular, trade in standardised goods and services can hardly be considered technology transfer. For several reasons, therefore, trade data is *not* an appropriate means by which to examine the transfer of environmental technologies.

Technology can also be transferred through ***foreign direct investment***. If a subsidiary of a multinational corporation is established, the parent company may transfer advanced technologies directly to the subsidiary. This may diffuse more widely in the economy by different channels – *for example*, local employees of the subsidiary taking up employment in domestic firms, and carrying knowledge about the technology with them. However, it is even more difficult in this case (than it was in the trade case examined above) to identify potential transfers which are directly relevant to environmental concerns. FDI data is not available at a level of disaggregation that would allow for an assessment of "environment-related" trends.

And finally, technologies can be transferred through ***explicit licensing of specific technologies***. However, data on licensing is very sparse, and to the authors' knowledge, no

effort has yet been made to assess licensing in any sector (or with respect to any particular good or service) which might be considered to be "environmental".

The idea of using ***patent data*** to measure international technology transfers arises from the fact that there will be a partial "trace" of all three of the above-noted channels of transfer in patent applications. If there is any potential for reverse engineering, exporters, investors and licensors will each have an incentive to protect their intellectual property when it goes overseas. Although it cannot capture the full extent of the transfers which eventually take place, patent data *can* provide robust indicators of trends in both the direction and the extent of international transfer. Patent data has already been used extensively for this purpose, although not in the environmental sphere (see Eaton and Kortum, 1996 for the seminal study).

Moreover, relative to measures which rely on commodity and sectoral classifications, patent data has the great advantage that the International Patent Classification system (the IPC) is "technological" by nature. This allows for the identification of very specific "environmental" technologies – *i.e.* a distinction can be drawn between air pollution control devices designed to reduce NO_X emissions and devices designed to control SO_2 emissions (see, for example, Popp 2005). In addition, each application can list multiple codes (unlike commodity or sectoral classifications), which allows for refined searches when innovations are horizontal in nature (*i.e.* the development of fuel cells for mobile uses). And finally, unlike other data, keyword searches can be used to refine the data.

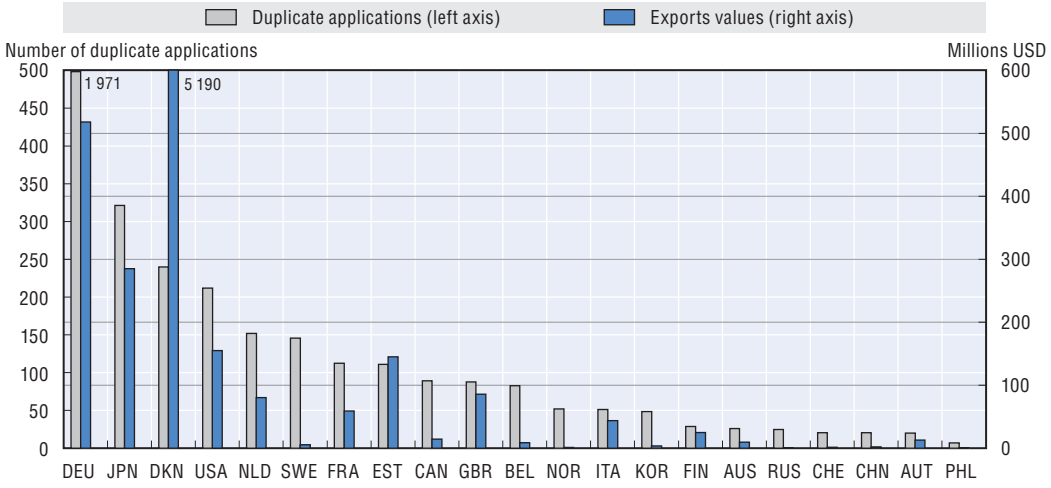
The potential to use patent data as the base from which to develop a proxy measure of technology transfer arises from the fact that protection for the invention may be sought in a number of countries.[4] While the vast majority of inventions are only patented in one country (often that of the inventor, particularly for large countries), 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. For example, evidence on the extent of globalisation of the environmental technology sector can be developed on the basis of extractions of data on "priority" (the first patent office at which an application for a particular invention is filed) and "duplicate" (all subsequent patent offices at which protection for the same invention is sought) applications from the *PATSTAT Database*.

Of course, a patent only gives the applicant protection from potential imitators. It does not reflect actual transfer of technologies. In addition, in some cases inventions may be protected in specific markets for strategic reasons, perhaps even discouraging transfer. Despite these qualifications, there is evidence that patent applications can be used as a measure of transfer (Eaton and Kortum, 1996). Moreover, 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, 2009) also provide more recent data for European Patent Office applications). Evidence indicates that this is true, even within the European patent system. Harhoff *et al.* (2009) find that validation and renewal fees and translation costs affect the likelihood of protecting inventions in multiple markets. If enforcement is weak, the publication of the patent in a local language can also increase vulnerability to imitation (see Eaton and Kortum, 1996; Eaton and Kortum, 1999). As such, inventors are unlikely to apply for patent protection in a

second country unless they are relatively certain of the potential market for the technology that the patent covers.

Next we investigate the robustness of using duplicate patent applications to measure patterns and rates of international technology transfer. This is done through a comparison of particular areas in which trade and patent classifications are similar, including wind power and motor vehicles. Using data from the *UN COMTRADE Database* (*http://comtrade.un.org*), it is possible to compare exports of "wind-powered electric generating equipment" (HS *850231*) with the count of duplicate patent applications by priority office for "wind motors" (IPC *F03D 1-11*). Figure A.7 provides data for the main inventing countries for the period 1996-2003 – the only years for which the trade data is also available.

Figure A.7. **Number of duplicate patent applications and export of wind power technologies**



While the correlation is not perfect, it is positive and significant. Indeed the top four exporters are also the top four priority patenting offices, and the Spearman rank correlation coefficient for the top 30 countries by trade is 0.68. Some of the observed discrepancies between the two data sets may also be attributable to shortcomings in COMTRADE's coverage. For instance, for reasons of commercial confidentiality, trade figures for low-level HS classifications may be significantly downward-biased. This would explain the number of countries with no apparent exports who are known to be active in the field (for example, Sweden, Canada, Norway and Switzerland) (see *http://comtrade.un.org/kb/attachments/1.%20UN%20Comtrade%20Coverage%20and%20Limitations-GUIDbecc0aa5044f44b5a048a8b45bce6d19.pdf*).

Another area in which there is a close "marriage" between IPC and HS classifications relates to the manufacture of motor vehicles. In this case, the correlation between bilateral exports and duplicate patent applications over the period 1988-2005 is approximately 0.74 when a small number of outliers (two of 825 observations) are removed. While this area has little to do with environmental technologies *per se*, it gives a good indication of the value of duplicate patent applications as a measure of transfer.

For this corroboration exercise, road vehicle data has been chosen as it is an area with large numbers of patents, large measurable trade flows, and comparable definitions. Road vehicle patent and trade data has been used to investigate the robustness of using duplicate patent applications to measure technology transfer.

Box A.2. **Patent flow**

Patents have been extracted from the *PATSTAT Database* for road vehicles with an International Patent Classification of B62 "Land vehicles for travelling otherwise than on rail". There are three ways to measure patent flow between countries:

1. Inventor country to priority office.
2. Inventor country to duplicate office.
3. Priority office to duplicate office.

Type three, priority office to duplicate office flow counts, are used in the analysis here.

Box A.3. **Trade flow**

Data has been extracted from the *UN COMTRADE Database*. Data was extracted for the period 1988 to 2005, using both the HS and SITC classification systems, SITC = 78 "Road Vehicles" and HS = 87 "Vehicles other than railway or tramway rolling-stock, and parts and accessories thereof". Both exports (gross exports less re-exports) and imports (gross imports less re-imports) were investigated.

Trade and patent transfers between countries are collected for the period from 1988 to 2005. Correlations between patent flows and trade over time and country pairs are shown below. There was trade data and patent transfer counts available for approximately 50 exporting countries and 60 importing countries. Results are presented using all non missing pairs and also with outliers removed, namely flows from Canada to the United States and from Japan to Germany.

Table A.1. **Correlations between trade values and counts of duplicate patent applications**

Correlation between trade flows and duplicate patenting	Full sample	Sub-sample excluding outliers (excl. CA-US and JP-DE flows)
Base dataset – all country pairs and all years (1988-2005), corr; (exports, patents)	0.47 (4 384)	0.69 (4 348)
For each country pair, aggregate over time, corr. (exports, patents)	0.52 (825)	0.74 (823)
For each exporter country, aggregate across partner countries, corr. (exports, outgoing patents)	0.76 (446)	0.87 (446)
For each importer country, aggregate across partner countries, corr. (imports, incoming patents)	0.71 (634)	0.76 (634)

Note: Pearson correlation coefficients; Number of observation in parentheses; When trade data was deflated by the US PPI all correlations improved marginally (by 0.01).

Patent transfer counts between priority office and duplicate office are extracted from the *PATSTAT Database*[5] while trade data between countries comes from the *UN COMTRADE*

Database.[6] Trade and patent transfers are collected for the period from 1988 to 2005 where there is data available for approximately 50 countries.

To substantiate the use of patent data as a measure of technological transfer, we would expect trade and patent flows to be strongly positively correlated as indeed they are found to be. Firstly, each export-import pair (1988-2005) is strongly correlated at 0.69. Aggregating over time for each export-import pair gives a correlation of 0.74. And finally, when aggregating trade and patent data for each exporter (regardless of who imports) gives a correlation of 0.88.[7]

Technological transfer occurs via many channels, though arguably trade, foreign-direct investment and licensing are the most important. Given the lack of suitable data in these areas, in particular with respect to the environmental, patent transfer data which relates to these three channels of international technology transfer, offers a suitable indicator.

Development of indicators of innovation and transfer of environmental technologies based on patent data

Patent classification systems

The International Patent Classification system (IPC, or just IC), developed at the World Intellectual Property Organisation (WIPO), is a hierarchical system classifying inventions into more than 70 000 technological groups and subgroups. It is periodically revised in order to reflect the latest technological advances. Patent offices sometimes use their own classification systems to complement the use of the IPC. For example, the European classification system (ECLA, or just EC) is an extension of the IPC with about twice as many classification codes. EPO examiners also use a further extension of the ECLA referred to as ICO codes (in-computer-only). Other classification systems include the US patent classification (USPC) or the Japanese F-terms. The work presented in this book relies on the use of IPC codes, at times complemented with ECLA codes.

Identification of environment-related technologies using patent data

Since innovation in environment-related technologies (ENV-tech) only represents one small aspect of innovation in general, prior to data retrieval from a patent database a *search strategy* must be developed that identifies the relevant patent documents using alphanumeric codes of the IPC system. For example, all patent documents with the code "*B01D 53/50 – Chemical or biological purification of waste gases; Removing sulfur oxides*" could be categorised as "SO_X end-of-pipe pollution abatement".

Development of a *search strategy* is thus based on identification of relevant patent classes that correspond to the selected "environmental" technology field. As a first step this involves an extensive review of the trade and academic literature which relates to a specific technological field. The relevant IPC classes which correspond to the different fields are then identified in two alternative ways: First, we review closely the descriptions of the classes online to find those which are appropriate (*www.wipo.int/classifications/ipc/ipc8/?lang=en*). Second, using the online world patent search engine maintained by the European Patent Office (*www.espacenet.com*), we search patent titles and abstracts for relevant keywords. The IPC classes corresponding to the patents that emerge are included, provided their description confirms their relevance.

However, in some cases, it may not be possible to identify IPC classes that alone represent the "environmental" field of interest. Possible solutions include: *i)* combining multiple "co-classes" using logical operators (that is, IPC classes whose intersection or negation yields the desired outcome); or *ii)* relevant patent classes may need to be combined with the use of keywords within the search algorithm. As part of the extraction, abstracts of patent documents with the relevant IPC classes would then be searched for the keywords identified. In some cases this would involve the exclusion of patent documents which include a particular word. However, availability of English abstracts limits the practicality of this approach when pooling data from multiple patent offices, unless the propensity to include English abstracts can be corrected for reliably.

When applying the *search strategy*, two possible types of error may arise: irrelevant patents may be included or relevant ones left out. The first error happens if an IPC class includes patents that do not bear the desired "environmental" focus. In order to avoid this problem, we carefully examine a sample of patent abstracts for every IPC class considered for inclusion, and exclude those classes that do not consist only of patents related to "environment". The second error – relevant inventions are left out – is less problematic. We can reasonably assume that all innovation in a given field behaves in a similar way and hence our extracted datasets can be seen at worst as good proxies of innovative activity in the field being considered. However, overall innovative activity may be underestimated, and the totals may be less reliable than trends.

Patent database

Over the last several years, the OECD Directorate for Science, Technology and Industry, jointly with other members of the OECD Patent Statistics Taskforce,[8] have developed a patent database that is suitable for statistical analysis – the *OECD Patent Statistics Database*. Further work has recently been undertaken by the Taskforce members towards developing a world-wide patent database – The *EPO Worldwide Patent Statistical Database (PATSTAT)*. The European Patent Office (EPO) has taken over responsibility for development and management of the database.

The *PATSTAT Database* is drawn directly from the EPO's master database (Rollinson and Lingua, 2007). It has been developed specifically for use by governmental/ intergovernmental organisations and academic institutions, and optimised for use in the statistical analysis of patent data. It has become a primary source of patent data information for statisticians, academics, and policy advisors (Rollinson and Heijnar, 2006).

The *PATSTAT Database* (EPO, 2010) has a world-wide coverage containing data from over 90 patent offices, spanning a time period stretching back to 1880 for some countries. This includes patent documents from the EPO, USPTO, JPO and other national and regional patent offices, as well as international patent applications filed under the Patent Co-operation Treaty (PCT). Overall, over 70 million patent documents are included. The database is updated on a regular basis biannually. Patent documents are categorised using the International Patent Classification (IPC) and some national classification systems (ECLA).In addition to the basic bibliometric and legal data, the database also includes patent descriptions (abstracts), applicant and inventor names, as well as citation data. The *PATSTAT Database* is thus an ideal source of patent data information for the purposes of this report.

Construction of indicators of invention in ENV-tech

Indicators of invention can be constructed as frequency counts of patent applications, disaggregated by:

- *technological field* (based on a patent search strategy, for example using IPC classes);[9]
- *priority date* (based on the first application filing date world-wide);[10]
- *inventor country* (country of residence of the inventor(s),[11] generated as fractional counts;[12])
- application authority (patent office);[13] and possibly also
- *document type* (singular, claimed priority, duplicate – based on patent family data).

Concerning the latter point, using data on patent family the following types of documents are distinguished: *singular* is patent applied for at a single office, with no subsequent applications elsewhere (*i.e.* patent family size = 1); *claimed priority* (CP) is patent application that has subsequently been claimed as priority elsewhere in the world; in other words, these are inventions that have been applied for protection in multiple countries (patent family size > 1); and finally, *duplicates* are the additional applications (sometimes referred to as *equivalents*).

There are several alternative approaches that can be used to construct the statistics:

- Count of all patent applications deposited at a single patent office (for example, at the EPO).
- Count of all patent families world-wide.
- Count of all "high-value" patent families (claimed priorities) world-wide.

In the first case, the indicator provides a count of patent application deposited at a selected patent office – including all three types of patent documents (singulars, claimed priorities, and duplicates).[14] Alternatively, only claimed priorities and duplicates could be included because, other things being equal, these should be the inventions of higher value (see discussion below). Frequently, it is patenting activity at the EPO that is studied because: *a)* the data is most complete and of best quality (within PATSTAT); and *b)* being one of the triadic offices, the statistic should reflect the "global" trends in patenting rather well.

The second indicator reflects the count of all simple patent families (that is, unique patented inventions) deposited at any office world-wide. This is achieved by counting two types of patent documents – singulars and claimed priorities. Since data from multiple patent offices are pooled together, excluding duplicates ensures that inventions are not double-counted. The upside is that this statistic is truly world-wide in its coverage because the entire stock of patent priorities is considered.

The third indicator counts "claimed priorities" (CPs) world-wide.[15] It can be argued that this statistic is the most suitable for the purpose of international comparisons because only the "high-value" priority applications are counted. The reason that claimed priorities can be viewed as representing inventions of higher value is that patenting is costly (*e.g.* translation and maintenance fees). As such, a firm will only go abroad to protect its intellectual property if it expects that the commercial value of its invention justifies it. (For empirical evidence supporting this argument see Guellec and van Pottelsberghe, 2000; Harhoff *et al.*, 2003. Indeed, the use of an indicator which excludes the "one-member" patent families – that is, an indicator based on CPs – justified on the grounds of an

"economic threshold criterion" was advocated already by Faust and Schedl 1983, and Faust, 1990.) Moreover, by excluding priority applications which have never been claimed abroad (one-member families, or singulars) this approach may help contain concerns over strategic patenting. In addition (Faust, 1990), it will thus exclude the large number of exclusively domestic Japanese patent applications with usually only one claim.[16]

It must be noted that the OECD triadic patent family (TPF) indicator has too, been developed with the specific purpose to allow international comparisons. However, in the context of a narrowly-defined technological field – such as environment-related technologies – the TPF indicator is overly restrictive leaving little variation in the data. The less-restrictive CPs thus provide a good alternative.

Care needs to be taken when conducting descriptive and econometric analyses. In particular, comparisons across inventor countries should take into account the potential "home bias" of domestic inventors. In addition, the propensity of inventors to patent, the breadth of invention claims covered by a patent, as well as the scope of patent protection, each vary over time and across countries. In order to account for these differences, the patent counts representing "environmental" innovations should therefore be expressed as shares, or these factors should be controlled for econometrically, using data on patenting activity overall.

Construction of indicators of international transfer of ENV-tech

Indicators of technology transfer can be constructed as frequency counts of:

1. **Patent families, disaggregated by:**
   - *technological field* (based on a patent search strategy);
   - *time* (based on priority date or application date);
   - *source country* (based on inventor country); and
   - *recipient country* (based on application authority – including both the priority and duplication offices).
2. **Duplicate patent applications, disaggregated by:**
   - *technological field* (based on a patent search strategy);
   - *technological field* (based on a patent search strategy);
   - time (based on priority date or application date);
   - source country (based on priority office); and
   - recipient country (based on duplication office).

In sum, in the former case the statistic measures transfer between inventor country and the patent offices included in the corresponding patent family.[17] In the latter case, transfer is to occur from (the country of) the priority office to the duplication office.[18]

Notes

1. This work would not have been possible without collaboration with the Economic Analysis and Statistics Division of the OECD Directorate for Science, Technology and Industry. In addition, much of the groundwork on developing the indicators has benefited from collaboration with researchers at universities and research institutes elsewhere. "Acknowledgement" is provided in the relevant chapters.
2. The data is available for download at *http://stats.oecd.org/Index.aspx?DatasetCode=PATS_IPC*. For metadata and future updates see *www.oecd.org/environment/innovation/indicator*.
3. The distribution of R&D expenditures is set out in the OECD *Frascati Manual*: "The Measurement of Scientific and Technological Activities: Proposed Standard Practice for Surveys on Research and Experimental Development" (OECD, 2002). The definition of the socio-economic objective (SEO) for "control and care for the environment" covers research into the control of pollution, aimed at the identification and analysis of the sources of pollution and their causes, and all pollutants, including their dispersal in the environment and the effects on man, species (fauna, flora, micro-organisms) and the biosphere. Development of monitoring facilities for the measurement of all kinds of pollution is also included. The same is valid for "the elimination and prevention of all forms of pollution in all types of environment".
4. See Dernis *et al.* (2001). Note that the information provided in patent documents can also be used to measure both market (co-invention, co-ownership) and non-market (citation) international knowledge flows. See Guellec and van Pottelsberghe de la Potterie (2000) for a discussion and evidence derived from patent data on the internationalisation of knowledge and technology flows.
5. IPC Code of B62 – Land vehicles for travelling otherwise than on rail.
6. Using both the HS and SITC classification systems, SITC = 78 "Road vehicles" and HS = 87 "Vehicles other than railway or tramway rolling-stock, and parts and accessories thereof".
7. Results are presented using all non missing pairs and also with outliers removed, namely flows from Canada to the United States and from Japan to Germany.
8. Other Taskforce members include the European Patent Office (EPO), the Japan Patent Office (JPO), the United States Patent and Trademark Office (USPTO), the World Intellectual Property Organisation (WIPO), the US National Science Foundation (NSF), Eurostat, and the European Commission Directorate-General for Research.
9. For a list of IPC codes and their definitions see *www.wipo.int/classifications/ipc/ipc8*.
10. "Priority date" indicates the earliest application date worldwide (within a given patent family).
11. For a list of two-letter country codes see *www.wipo.int/standards/en/pdf/03-03-01.pdf*.
12. Generating the counts as "fractional" means that if inventors from two (three, or more) different countries are involved, only a fraction of 0.5 (0.33, etc.) will be counted for a given patent application.
13. See *www.wipo.int/standards/en/pdf/03-03-01.pdf* for a list of two-letter codes of application authorities.
14. For example, this approach was adopted in Johnstone *et al.*, 2010.
15. This is the approach adopted in Chapters 2 and 3.
16. CPs account for a relatively small proportion of the stock of patent applications. For example, in a study focusing on innovation in climate change mitigation technologies Haščič *et al.* (2010) find that only about 11% of the relevant stock of patent applications included in PATSTAT were CPs, with 34% being their duplicates, and 55% being singulars. In other words, in climate change mitigation technologies CPs represent only 16% of the stock of patented inventions (simple patent families), while the large majority (84%) of these inventions were only protected at a single patent office (singulars). It must be noted that there is variation in these proportions across patent offices.
17. For example, this approach was adopted by Dechezleprêtre *et al.* (2011).
18. This is the approach adopted in Chapter 4.

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ANNEX B

Patent Search Strategies

Detailed search strategies are presented for the identification of environment-related technologies using patent data. When applying these search strategies, it is important to keep in mind that:

- The term "environmental" technology is intended to be a reflection of the public consensus on the utility of certain technological approaches in reducing environmental impacts, as compared to available alternatives. Hence, by definition, the notion of which technologies are considered "environmental" evolves over time. This may have implications for the relevance of the search strategies.
- Patent classification systems (such as the IPC, ECLA, etc.) are updated regularly and new "tagging" schemes are being developed. Moreover, availability of patent data (coverage, degree of detail) is improving rapidly. This will have direct implications for the adequacy of the search strategies provided here.

Search strategies for general environmental technologies

Table B.1. **Patent classes for general environmental technologies (AWW)**

	IPC class
1. Air pollution abatement	
Filters or filtering processes specially modified for separating dispersed particles from gases or vapours	B01D46
Separating dispersed particles from gases, air or vapours by liquid as separating agent	B01D47
Separating dispersed particles from gases, air or vapours by other methods	B01D49
Combinations of devices for separating particles from gases or vapours	B01D50
Auxiliary pretreatment of gases or vapours to be cleaned from dispersed particles	B01D51
Chemical or biological purification of waste gases; by catalytic conversion	B01D53/34-36
Chemical or biological purification of waste gases; removing components of defined structure	B01D53/46-72
Separating dispersed particles from gases or vapour, *e.g.* air, by electrostatic effect	B03C3
Use of additives to fuels or fires for particular purposes for reducing smoke development	C10L10/02
Use of additives to fuels or fires for particular purposes for facilitating soot removal	C10L10/06
Blast furnaces; dust arresters	C21B7/22
Manufacture of carbon steel, *e.g.* plain mild steel, medium carbon steel, or cast-steel; removal of waste gases or dust	C21C5/38
Exhaust or silencing apparatus having means for purifying or rendering innocuous	F01N3
Exhaust or silencing apparatus combined or associated with devices profiting by exhaust energy	F01N5
Exhaust or silencing apparatus, or parts thereof	F01N7
Electrical control of exhaust gas treating apparatus	F01N9
Monitoring or diagnostic devices for exhaust-gas treatment apparatus	F01N11
Combustion apparatus characterised by means for returning flue gases to the combustion chamber or to the combustion zone	F23B80
Combustion apparatus characterised by arrangements for returning combustion products or flue gases to the combustion chamber	F23C9
Arrangements of devices for treating smoke or fumes of purifiers, *e.g.* for removing noxious material	F23J15
Shaft or like vertical or substantially vertical furnaces; arrangements of dust collectors	F27B1/18
Alarms responsive to a single specified undesired or abnormal condition and not otherwise provided for, *e.g.* pollution alarms; toxics	G08B21/12-14
Incinerators or other apparatus specially adapted for consuming waste gases or noxious gases	F23G7/06
2. Water pollution abatement	
Arrangements of installations for treating waste-water or sewage	B63J4
Treatment of water, waste water, sewage or sludge	C02F

Table B.1. **Patent classes for general environmental technologies (AWW)** *(cont.)*

	IPC class
Fertilisers from waste water, sewage sludge, sea slime, ooze or similar masses	C05F7
Chemistry; materials for treating liquid pollutants, *e.g.* oil, gasoline, fat	C09K3/32
Devices for cleaning or keeping clear the surface of open water from oil or like floating materials by separating or removing these materials; barriers therefor	E02B15/04-06
Cleaning or keeping clear the surface of open water; devices for removing the material from the surface	E02B15/10
Methods or installations for obtaining or collecting drinking water or tap water; rain, surface or groundwater	E03B3
Plumbing installations for waste water	E03C1/12
Sewers – cesspools	E03F
Fertilisers from waste water, sewage sludge, sea slime, ooze or similar masses	C05F7
3. Solid waste management	
Animal feeding-stuffs from distillers' or brewers' waste; waste products of dairy plant; meat, fish, or bones; from kitchen waste	A23K1/06-10
Footwear made of rubber waste	A43B1/12
Heels or top-pieces made of rubber waste	A43B21/14
Medical or veterinary science; disinfection or sterilising methods specially adapted for refuse	A61L11
Separating solid materials; general arrangement of separating plant specially adapted for refuse	B03B9/06
Disposal of solid waste	B09B
Reclamation of contaminated soil	B09C
Manufacture of articles from scrap or waste metal particles	B22F8
Sawing tools for saw mills, sawing machines, or sawing devices; edge trimming saw blades or tools combined with means to disintegrate waste	B27B33/20
Recovery of plastics or other constituents of waste material containing plastics	B29B17
Preparing material; recycling the material	B29B7/66
Presses specially adapted for consolidating scrap metal or for compacting used cars	B30B9/32
Systematic disassembly of vehicles for recovery of salvageable components, *e.g.* for recycling	B62D67
Transporting; gathering or removal of domestic or like refuse	B65F
Stripping waste material from cores or formers, *e.g.* to permit their re-use	B65H73
Hydraulic cements from oil shales, residues or waste other than slag	C04B7/24-30
Calcium sulfate cements starting from phosphogypsum or from waste, *e.g.* purification products of smoke	C04B11/26
Use of agglomerated or waste materials or refuse as fillers for mortars, concrete or artificial stone; waste materials or refuse	C04B18/04-10
Clay-wares; waste materials or refuse	C04B33/132
Fertilisers from household or town refuse	C05F9
Recovery or working-up of waste materials	C08J11
Luminescent, *e.g.* electroluminescent, chemiluminescent, materials; recovery of luminescent materials	C09K11/01
Production of liquid hydrocarbon mixtures from rubber or rubber waste	C10G1/10
Solid fuels essentially based on materials of non-mineral origin; on sewage, house, or town refuse; on industrial residues or waste materials	C10L5/46-48
Working-up used lubricants to recover useful products	C10M175
Working-up raw materials other than ores, *e.g.* scrap, to produce non-ferrous metals or compounds thereof	C22B7
Obtaining zinc or zinc oxide; from muffle furnace residues; from metallic residues or scraps	C22B19/28-30
Obtaining tin; from scrap, especially tin scrap	C22B25/06
Mechanical treatment of natural fibrous or filamentary material to obtain fibres or filament; arrangements for removing, or disposing of, tow or waste	D01B5/08
Textiles; disintegrating fibre-containing articles to obtain fibres for re-use	D01G11
Textiles; arrangements for removing, or disposing of, noil or waste	D01G19/22
Paper-making; fibrous raw materials or their mechanical treatment; the raw material being waste paper or rags	D21B1/08
Paper-making; fibrous raw materials or their mechanical treatment; defibrating by other means of waste paper	D21B1/32
Paper-making; other processes for obtaining cellulose; working-up waste paper	D21C5/02
Paper-making; pulping; non-fibrous material added to the pulp; waste products	D21H17/01
Street cleaning; apparatus equipped with, or having provisions for equipping with, both elements for removal of refuse or the like and elements for removal of snow or ice	E01H6
Street cleaning; removing undesirable matter, *e.g.* rubbish, from the land, not otherwise provided for	E01H15
Cremation furnaces; incineration of waste; incinerator constructions; details, accessories or control therefor	F23G5
Cremation furnaces; incinerators or other apparatus specially adapted for consuming specific waste or low grade fuels	F23G7

Table B.2. **Patent classes for SO_X/NO_X emission abatement**

	IPC/ECLA
SO_X-specific	
Chemical or biological purification of waste gases, *e.g.* engine exhaust gases, smoke, fumes, flue gases or aerosols:	
Removing sulfur oxides (B01D 53/60 takes precedence)	B01D53/50
By absorption; gases containing acid components; containing only sulfur dioxide or sulfur trioxide	B01D53/14H8
Catalytic processes; removing sulfur oxides	B01D53/86B4
NO_X-specific	
Chemical or biological purification of waste gases, *e.g.* engine exhaust gases, smoke, fumes, flue gases or aerosols:	
Removing nitrogen oxides (B01D 53/60 takes precedence)	B01D53/56
By treating the gases with solids	B01D53/56D
Catalytic processes; removing nitrogen oxides	B01D53/86F2 B01D53/86F2C B01D53/86F2D
Simultaneous SO_X and NO_X	
Chemical or biological purification of waste gases, *e.g.* engine exhaust gases, smoke, fumes, flue gases or aerosols:	
Simultaneously removing sulfur oxides and nitrogen oxides	B01D53/60
Catalytic processes; simultaneously removing sulfur oxides and nitrogen oxides	B01D53/86G

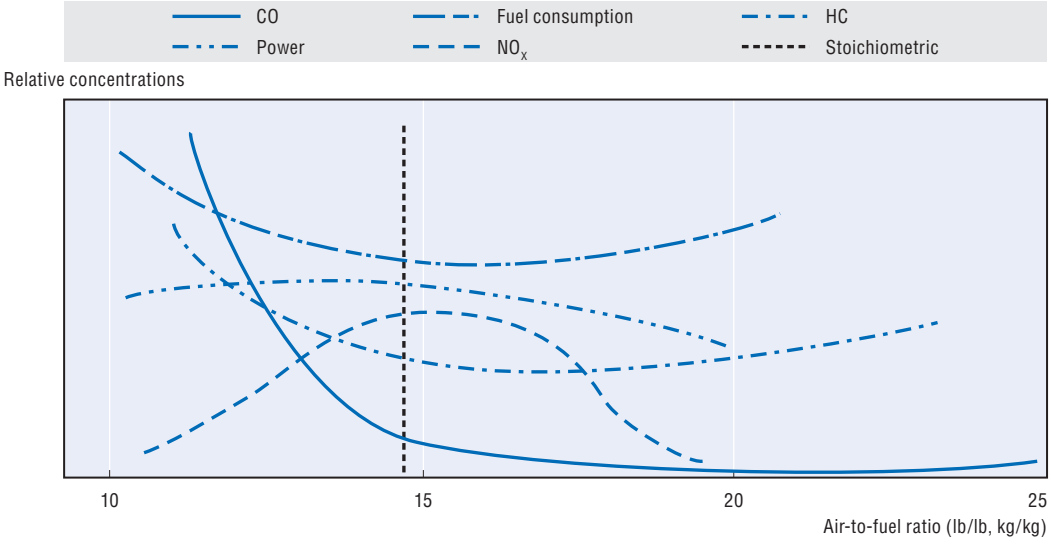
Search strategies for motor vehicle technologies

Technologies to improve fuel efficiency of a conventional engine (improved engine design)

Air-to-fuel ratio

The relative weight of air to fuel in the combustion mixture has important implications for engine power, fuel consumption (CO_2 emissions), as well as pollutant concentration in exhaust gases leaving the combustion chamber. The relationships are complex, as is suggested by Figure B.1. It suggests that maximum power is obtained for a slightly rich mixture, while maximum fuel economy occurs with slightly lean mixture (*i.e.*

Figure B.1. **Effect of air-fuel ratio on emissions, power, and fuel economy (gasoline engines)**



Source: Masters and Ela (2008), p. 408).

more air than the stoichiometric ratio). During the period before emissions regulations were introduced, cars were thus designed to run on slightly rich mixtures for better power and performance (Masters and Ela, 2008).

However, a rich air-fuel mixture leads to production of relatively large amounts of CO and unburned HC emissions since there is not enough oxygen for complete combustion. A lean mixture (more air than necessary) helps reduce CO and HC emissions unless the mixture becomes so lean that misfiring occurs. Hence, after the first regulations of CO and HC emissions were introduced in 1960s in the US, the initial response of manufacturers to was to redesign cars to run on a less rich mixture (introduction of air-to-fuel ratio devices) (Masters and Ela, 2008).

Production of NO_X is primarily driven by combustion temperature; it is affected by the air-fuel ratio only indirectly, in a bell-shaped manner (Figure B.1). While for rich mixtures, the lack of oxygen lowers combustion temperature thus reducing NO_X emissions, for lean mixtures, more oxygen increases combustion temperature hence increasing NO_X emissions. However, beyond certain point, lean mixtures may have so much excess air that the dilution lowers flame temperatures and lowers NO_X production. Therefore, when also NO_X became regulated (1970 Clean Air Act), modifying the air-fuel ratio was no longer sufficient and manufacturers had to turn to the three-way catalytic converter (Masters and Ela, 2008).

Electronic fuel injection and engine management systems

Introduction of the three-way catalytic converter required the development of precise electronic feedback control systems (*e.g.* OBD) that monitor the composition of exhaust gases and feed that information to a microprocessor-controlled carburettor or fuel-injection system (Masters and Ela, 2008). Development of such "closed-loop" systems with a high degree of control was necessary for the three-way catalytic converters to operate effectively. This is because they must operate within a very narrow band of air-fuel ratios near the stoichiometric value (see Figure B.1).

In diesel engines, electronically controlled fuel injection (such as common rail and unit injectors) was introduced in order to allow flexible injection timing, rate shaping, and higher injection pressures.

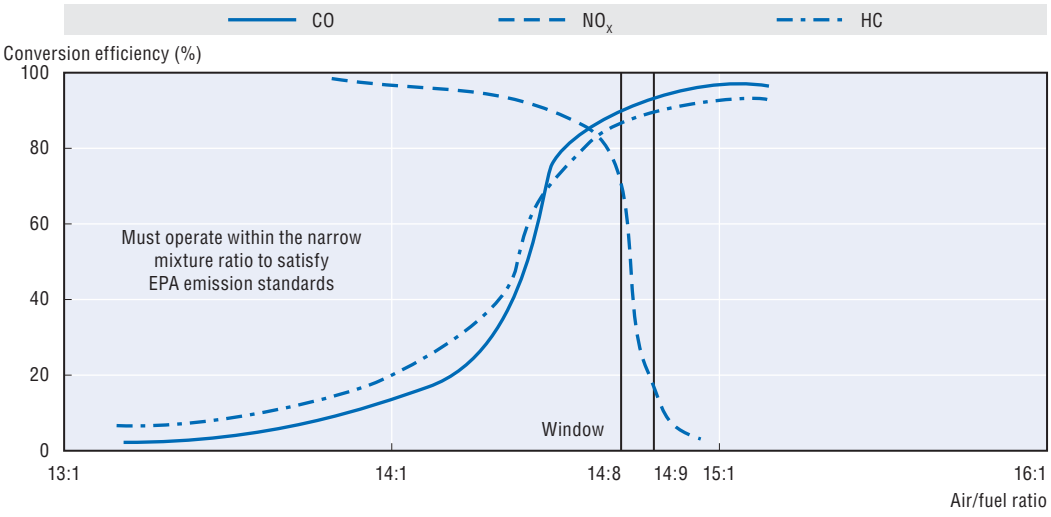
Ignition timing

In addition to controlling the air-fuel mixture, another method for reducing emissions from spark ignition engines is by careful control of ignition timing. Retarding ignition timing from the best efficiency setting reduces HC and NO_X emissions, while excessive retard of ignition increases the output of CO and HC. Increasing engine speed reduces HC emissions, but NO_X emissions increase with load. Increasing coolant temperature tends to reduce HC emissions, but increased temperature leads in turn to higher NO_X emissions.

Other factors related to engine design

Other factors which influence fuel economy and production of pollutants during combustion include variable valve timing, variable compression ratio, combustion chamber geometry, as well as performance during vehicle idling, accelerating, cruising,

Figure B.2. **Effect of air-fuel ratio on conversion efficiency of catalytic converters**



Source: Masters and Ela (2008), p. 411.

and decelerating. See also cold start[1] and start-stop modes (for further info see *e.g.* IEA 2005: 45-46, 65).

Combustion air and fuel conditioning

Recently, fuel conditioning systems have been introduced to improve combustion with the aim of reducing fuel consumption (and hence emissions), *e.g.* by pre-treatment of fuel by chemical, electric, magnetic, or radiation means. The aim (of heating, reforming, or activating) is to increase fuel temperature, increase fuel vaporisation, or change fuel properties, immediately before combustion takes place [citation].

Table B.3. **Patent classifications for improved engine design (IED) technologies**

Air-fuel ratio devices	
Methods of operating engines involving adding non-fuel substances or anti-knock agents to combustion air, fuel, or fuel-air mixtures of engines; the substances including non-airborne oxygen (NB: cases involving exhaust gas are included under EGR)	F02B47/06
Idling devices for preventing flow of idling fuel	F02M3/02-055
Apparatus for adding secondary air to fuel-air mixture.	F02M23
Engine-pertinent apparatus for adding non-fuel substances or small quantities of secondary fuel to combustion-air, main fuel, or fuel-air mixture.	F02M25
Apparatus in which fuel-injection is affected by means of high-pressure gas, the gas carrying the fuel into working cylinders of the engine, *e.g.* air-injection type.	F02M67
Electronic control systems (on-board diagnostics)	
Electrical control of exhaust gas treating apparatus	F01N9
Electrical control of supply of combustible mixture or its constituents	F02D41
Conjoint electrical control of two or more functions, *e.g.* ignition, fuel-air mixture, recirculation, supercharging, exhaust-gas treatment	F02D43
Electrical control of combustion engines not provided for in groups F02D 41/00 to F02D 43/00	F02D45
Sensors	
Monitoring or diagnostic devices for exhaust-gas treatment apparatus	F01N11
Testing of internal-combustion engines by monitoring exhaust gases	G01M15/10

Table B.3. **Patent classifications for improved engine design (IED) technologies** *(cont.)*

Fuel injection systems	
Fuel-injection apparatus	F02M39-71
Ignition timing	
Advancing or retarding ignition; control therefore	F02P5
Devices for fuel heating, reforming, or activation	
Apparatus for treating combustion-air, fuel, or fuel-air mixture, by catalysts, electric means, magnetism, rays, sonic waves, or the like	F02M27
Apparatus for thermally treating combustion-air, fuel, or fuel-air mixture	F02M31/02-18

Anti-knock additives

Changes to fuel characteristics (additives and composition) may also affect fuel efficiency. Anti-knock additives[2] have been used to improve detonation resistance of fuel (gasoline) blends.[3] The original motivation was to improve the combustion potential of fuel (and thus increase engine power and durability). In the past, various lead-containing additives (*e.g.* tetraethyl lead) were used because this was the most cost-effective way of boosting the octane levels (see *e.g.* Kerr and Newell, 2003). However, environmental and health considerations of lead-related air pollutants as well as the incompatibility of lead with the use of catalytic converters, spurred the search for alternatives.[4, 5]

Initially, certain aromatic hydrocarbons (incl. benzene and its derivatives toluene and xylene, or BTX) were introduced as alternative octane-enhancers. However, these volatile hydrocarbons have a high photo-chemical reactivity. As a result, increasing their proportion in gasoline blends also increased evaporative emissions (HC) and the formation of VOCs and photochemical (ozone) smog (Masters and Ela, 2008).[6]

To reduce the volatility of gasoline fuels, many countries introduced limits on gasoline aromatics and substituted them with alternatives, such as ethers (*e.g.* MTBE or ETBE) or alcohols (*e.g.* methanol or ethanol). In the United States, MTBE has been the preferred alternative due to its higher octane ranking and lower cost (USEPA, 2007). Recently, MTBE has started to be phased-out in the United States and replaced by other ethers (*e.g.* ETBE) or alcohols (*e.g.* ethanol).

Table B.4. **Patent classifications for fuel characteristics that improve performance**

Anti-knock additives (octane-enhancers)	
Use of additives to fuels or fires for improving the octane number	C10L 10/10
Use of additives to fuels or fires for improving the cetane number	C10L 10/12

Technologies to address local air pollutant emissions (emissions control)[7]

Post-combustion controls include end-of-pipe measures that capture and/or treat emissions after they have been emitted. Such measures often necessitate complementary measures which must be integrated with engine design, such as sensors, fuel injection, and electronic controls. In addition, some measures have been introduced which relate to fuel characteristics.

Positive crankcase ventilation

During the power and compression strokes, certain amount of combustion gases (HCs) finds their way around the piston into the crankcase. In the past, this "blowby" used to be vented directly into the atmosphere. Positive crankcase ventilation is a method to recycle blowby gases back into the engine air intake system to give it a second chance at being burned and released into the exhaust system, while maintaining the desired air-fuel ratio (Masters and Ela, 2008).

Air injection

An early approach to CO and HC emissions control involved air injection into an enlarged exhaust manifold to encourage continued oxidation after these gases left the combustion chamber. Air injection as a control method has been discontinued (Masters and Ela, 2008).

Exhaust gas recirculation (EGR)

An early approach to NO_X control was to recirculate a portion of the exhaust gas back into the incoming air-fuel mixture, thus decreasing combustion temperature (this relatively inert gas absorbs some of the heat without affecting the air-fuel ratio), and hence reducing the production of NO_X. Controlling NO_X via EGR is becoming less common (Masters and Ela 2008).

Thermal reactor

An early control method, composed of an after-burner that encourages the continued oxidation of CO and HC after these gases have left the combustion chamber.

Catalytic converters

The first-generation of catalytic converters – the two-way catalysts (CO, HC), or "oxidation catalysts" – were later replaced by the second-generation of catalysts that were capable to control also NO_X emissions, hence three-way catalysts (CO, HC, NO_X).

The emission performance of gasoline (spark-ignition) engines is currently based on a closed-loop fuel mixture in combination with a three-way catalytic converter. Control of the fuel mixture is achieved by means of an oxygen sensor in the exhaust system and an electronic control unit (*e.g.* OBD). Based on the signal from the sensor, the air-to-fuel ratio varies around the stoichiometric value, at which a three-way catalytic converter reaches an optimal efficiency (> 99%) (OECD, 2004).

HC adsorbers

Recently, the three-way catalysts have been accompanied with HC adsorbers in order to control emissions when engine runs at rich mixtures (*e.g.* at cold start, during acceleration).

NO_X adsorbers and de-NO_X systems

Diesel engines are characterised by relatively high emissions of NO_X and PM, requiring application of EGR systems (NO_X), recently complemented with additional NO_X adsorbers (NO_X traps) or lean NO_X catalysts (de-NO_X systems, de-NO_X converters).

Since diesel vehicles run on lean fuel mixture, they cannot use the three-way catalytic converters because three-way catalytic converters require stoichiometric (not lean) fuel mixture. Consequently, "one-way" catalysts (known as lean NO_X catalysts, de-NO_X systems, or de-NO_X converters) have been applied instead. These involve passive or active de-NO_X catalysts, selective catalytic reduction (SCR) catalysts, or NO_X storage catalysts.[8]

Particle filters

In diesel vehicles, reducing the emissions of particulate matter (PM) to the level of gasoline engines can only be achieved through the use of particulate filters. They were first introduced on heavy-duty vehicles, with application on light-duty vehicles being delayed since they required introducing solutions which prevent plugging (clogging) of filters due to the relatively low engine loads (and hence low exhaust gas temperatures which prevent automatic regeneration of filters). The technologies include active particulate filters (through after-burning, electric heating, post-injection of fuel, or adding a fuel-borne catalyst) or passive/continuous regenerating filters (continuously regenerating traps – CRTs). The former are very sensitive to the sulphur level in fuel.

Diesel oxidation catalysts

While emissions of CO and HC from diesel engines are relatively low, introduction of strict emissions limits even for diesel cars necessitated the use of oxidation catalysts which can reduce these emissions to near zero levels. However, HC emissions can be significant during cold start conditions.

Table B.5. **Patent classifications for local air pollutant Emissions Control (EMC) technologies**

Crankcase emissions and control	
Crankcase ventilating or breathing	F01M13/02-04
Exhaust gas recirculation	
Exhaust or silencing apparatus combined or associated with devices profiting by exhaust energy	F01N5
Methods of operating engines involving adding non-fuel substances including exhaust gas to combustion air, fuel, or fuel-air mixtures of engines	F02B47/08-10
Controlling engines characterised by their being supplied with non-fuel gas added to combustion-air, such as the exhaust gas of engine, or having secondary air added to fuel-air mixture	F02D21/06-10
Engine-pertinent apparatus for adding exhaust gases to combustion-air, main fuel, or fuel-air mixture	F02M25/07
Oxygen, NO_X and temperature sensors	
Monitoring or diagnostic devices for exhaust-gas treatment apparatus	F01N11
Testing of internal-combustion engines by monitoring exhaust gases	G01M15/10
Thermal reactor	
Exhaust apparatus having means for rendering innocuous, by thermal conversion of noxious components of exhaust; construction of thermal reactors	F01N3/26
Catalytic converters, lean NO_X catalysts, NO_X adsorbers, regeneration	
Processes, apparatus or devices specially adapted for purification of engine exhaust gases	B01D53/92
… by catalytic processes	B01D53/94
Regeneration, reactivation or recycling of reactants	B01D53/96
Catalysts comprising metals or metal oxides or hydroxides; of noble metals; of the platinum group metals	B01J23/38-46
Exhaust or silencing apparatus having means for purifying, rendering innocuous, or otherwise treating exhaust by means of air *e.g.* by mixing exhaust with air.	F01N3/05
Exhaust or silencing apparatus having means for purifying, rendering innocuous, or otherwise treating exhaust; for rendering innocuous by thermal or catalytic conversion of noxious components of exhaust	F01N3/08-34

Table B.5. **Patent classifications for local air pollutant Emissions Control (EMC) technologies** *(cont.)*

Particulate filters and regeneration	
Applications for motor vehicles related to:	
● Regeneration of the filtering material or filter elements outside the filter for liquid or gaseous fluids	(B01D41 or
● Filters or filtering processes specially modified for separating dispersed particles from gases or vapours	B01D46 or
● Exhaust apparatus having means for purifying, rendering innocuous, or otherwise treating exhaust:	F01N3/01 or
❖ By means of electric or electrostatic separators	F01N3/02-035)
❖ For cooling, or for removing solid constituents of, exhaust; by means of filters	and (B60 or B62)

Oxygen-containing additives

Emissions of local air pollutants are also affected by changes to fuel characteristics (additives and composition). In particular, burning "oxygenated" (also known as reformulated) gasoline encourages more complete combustion. The use of oxygen-containing additives is primarily aimed at reducing tailpipe emissions of carbon monoxide (CO) and unburned fuel (HC). Examples of such additives include alcohols (*e.g.* methanol and ethanol) or ethers [*e.g.* methyl tertiary-butyl ether (MTBE), ethyl tertiary-butyl ether (ETBE), tertiary amyl methyl ether (TAME), and diisopropyl ether (DIPE)].

In the United States, MTBE has been used since 1979 initially at low concentrations to replace lead as an octane enhancer. Since 1992 it has been used at higher concentrations to meet the oxygenate requirements set by the 1990 Clean Air Act amendment[9] (USEPA, 2007). Until recently, MTBE has been the most common oxygenate additive, followed by ethanol (Pellegrino *et al.*, 2007). MTBE has been credited for contributing to reducing CO emissions (as oxygenate) and VOC/ozone pollution levels (as oxygenate as well as by replacing aromatics as octane enhancers) (USGS, 2007).

However, due to concerns over drinking water contamination and potential negative health effects, the use of MTBE has become increasingly controversial. Twenty-five US states have mandated reduction or elimination of MTBE (incl. California where it has been banned since 2003) and suppliers have begun replacing it with ethanol. In addition, the Energy Policy Act of 2005 removed the fuel oxygenate requirements (Pellegrino *et al.*, 2007). It is expected that most suppliers will have phased-out MTBE by summer 2006 (EIA, 2006). MTBE is being replaced by ethanol, and to a lesser extent, by the ethanol-derived ETBE.

In sum, some compounds, such as alcohols and ethers, can be used to both, oxygenate the fuel blend (and reduce CO and HC emissions) as well as to increase its octane rating (thus replace VOC and ozone-forming aromatics).

We also note that adding oxygenates to fuel blends may increase fuel combustion. This is because while adding oxygen to fuel blends improves combustion efficiency, it also increases fuel volume without contributing energy. Consequently, adding oxygenate compounds may actually increase fuel combustion for a given power output. Whether this will be the case depends on the relative contribution of improved combustion *versus* lower energy-content of the fuel.

Table B.6. **Patent classifications for fuel characteristics that improve combustion**

Oxygen-containing additives	C10L10/10

Technologies to improve fuel efficiency characteristics of a vehicle (improved vehicle design)[10]

There are a number of other factors, not related to engine design, that have an important effect on vehicle fuel consumption. These include:

- Reduction of tractive force requirements (*i.e.* efficiency with which mechanical energy obtained from fuel combustion is used for vehicle propulsion). These include overcoming or reducing:
  - *Inertia* – during acceleration or deceleration, through light-weighting of materials while maintaining the necessary strength, resistance, and durability (*e.g.* use of synthetic composites and carbon fibres).
  - *Friction* – of moving and/or rotating components (*e.g.* wheels, components of the engine and the gearbox) through the use of low-friction materials, optimised geometry of the combustion chamber and intake/outlet ports and valves.
  - *Air resistance* – improved aerodynamic design through streamlined shape of the vehicle and its frontal area (*e.g.* to reduce aerodynamic drag caused by windows and luggage carriers).
  - *Rolling resistance* – through tire quality and optimised tire pressure.
- Reduction of energy requirements of operating electric components of a vehicle (auxiliary systems and accessories):
  - Lighting.
  - Air-conditioning and heating system.[11]
  - *Other* (*e.g.* power steering, power brakes, automatic transmission, electrically operated window shields, windscreen wipers, movable roofs, audio installations, defrosters, etc.).
- Light-weighting of devices that improve comfort:
  - Passive safety measures.
  - *Sound-deadening material* installed to reduce noise levels in the interior of a vehicle.
- Installation of fuel-saving driver support devices or devices that improve driving style:
  - *Speed control* (cruise control).
  - *Eco-driving* (adaptive cruise control).
- Finally, reduction of non-combustion emissions can improve the life-cycle fuel efficiency of a vehicle:
  - *Vapour recovery systems* that mitigate evaporative emissions of volatile hydrocarbons.
  - *Improved fuel tanks* (their safety and durability) to prevent leakage of fuel.

Table B.7. **Patent classifications for Improved Vehicle Design (IVD) technologies**

Air resistance (aerodynamic design)	
Vehicle bodies characterised by streamlining	B62D 35/00
Stabilising vehicle bodies without controlling suspension arrangements; by aerodynamic means	B62D 37/02
Rolling resistance (tyres)	
Devices for measuring, signalling, controlling, or distributing tyre pressure or temperature, specially adapted for mounting on vehicles; arrangement of tyre inflating devices on vehicles, *e.g.* of pumps, of tanks; tyre cooling arrangements	B60C 23/00

Table B.7. **Patent classifications for Improved Vehicle Design (IVD) technologies** *(cont.)*

Other fuel-efficiency support systems	
Arrangements of braking elements; acting by retarding wheels; by utilising wheel movement for accumulating energy, *e.g.* driving air compressors	B60T 1/10
Resilient suspensions characterised by arrangement, location, or type of vibration-dampers; having dampers accumulating utilisable energy, *e.g.* compressing air	B60G 13/14
Vehicle fittings, acting on a single sub-unit only, for automatically controlling vehicle speed, *i.e.* preventing speed from exceeding an arbitrarily established velocity or maintaining speed at a particular velocity, as selected by the vehicle operator	B60K 31/00
Purposes of road vehicle drive control systems not related to the control of a particular sub-unit, *e.g.* of systems using conjoint control of vehicle sub-units (incl. path keeping, cruise control)	B60W 30/10-20

Alternative fuel vehicle (AFV) technologies

Following the discussion in Table B.8 patent classifications corresponding to selected technologies are presented below.

Table B.8. **Patent classifications for Alternative Fuel Vehicle (AFV) technologies**

Electric propulsion	
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
Arrangement or mounting of electrical propulsion units	B60K1
Conjoint control of vehicle sub-units of different type or different function; including control of electric propulsion units, *e.g.* motors or generators	B60W10/08
Hybrid propulsion	
Arrangement or mounting of plural diverse prime-movers for mutual or common propulsion, *e.g.* hybrid propulsion systems comprising electric motors and internal combustion engines	B60K6
Control systems specially adapted for hybrid vehicles, *i.e.* vehicles having two or more prime movers of more than one type, *e.g.* electrical and internal combustion motors, all used for propulsion of the vehicle	B60W20
Electricity storage systems	
Electric circuits for supply of electrical power to vehicle subsystems characterised by the use of electrical cells or batteries	B60R16/033
Arrangement of batteries in vehicles	B60R16/04
Supplying batteries to, or removing batteries from, vehicles	B60S5/06
Conjoint control of vehicle sub-units of different type or different function; including control of energy storage means for electrical energy, *e.g.* batteries or capacitors	B60W10/26
Secondary cells; applications for motor vehicles	H01M10 and (B60 or B62)
Fuel cell systems	
Conjoint control of vehicle sub-units of different type or different function; including control of fuel cells	B60W10/28
Fuel cells; applications for motor vehicles	H01M8 and (B60 or B62)
Gas-fuelled systems (LNG, LPG, hydrogen)	
Applications for motor vehicles related to: • Engines operating on gaseous fuels • Controlling engines working with gaseous fuels • Apparatus for supplying engines with gaseous fuels	(F02B43/10-12 or F02D19/02 or F02M21/02-06) and (B60 or B62)
Power supply from force of nature	
Electric propulsion with power supply from force of nature, *e.g.* sun, wind	B60L8
Arrangements in connection with power supply from force of nature, *e.g.* sun, wind	B60K16

Search strategies for waste management and recycling

Table B.9. **Patent classes for waste management and recycling**

1. End-of-life vehicles (ELVs)	
Systematic disassembly of vehicles for recovery of salvageable components, *e.g.* for recycling	B62D67
Presses specially adapted for particular purposes – for consolidating scrap metal or for compacting used cars	B30B9/32
2. Paper	
Paper-making – Fibrous raw material or their mechanical treatment – using waste paper	D21B1/08-10
Paper-making – Defibrating by other means – of waste paper	D21B1/32
Other processes for obtaining cellulose, *e.g.* cooking cotton linters – working up of waste paper	D21C5/02
3. Plastics	
Recovery of plastics or other constituents of waste material containing plastics (chemical recovery…)	B29B17
Recovery or working-up of waste materials (plastics)	C08J11
4. Material recycling	
Animal feeding stuff from meat, fish, bones or kitchen waste	A23K1/10
Separating solid materials; general arrangement of separating plant specially adapted for refuse	B03B9/06
Recovery of plastics or other constituents of waste material containing plastics (chemical recovery…)	B29B17
Process specially adapted for consolidating scrap metal (cans and bottle)	B30B9/32
Applications of disintegrable, dissolvable or edible materials	B65D65/46
Compacting the glass batches, *e.g.* pelletising	C03B1/02
Glass Batch composition – containing silicates, *e.g.* cullet	C03C6/02
Glass Batch composition – containing pellets or agglomerates	C03C6/08
Preparation of fertilisers characterised by the composting step	C05F17
Fertilisers from household or town refuse	C05F9
recovery luminescent material	C09K11/01
Paper-making – fibrous raw materials or their mechanical treatment – using waste paper	D21B1/08-10
Paper-making – Defibrating by other means – of waste paper	D21B1/32
Other processes for obtaining cellulose, *e.g.* cooking cotton linters – working up of waste paper	D21C5/02
Pulping – Non-fibrous material added to the pulp – waste paper	D21H17/01
5. Landfilling and incineration	
Disposal of solid waste	B09B
Cremation furnaces; incineration of waste, incineration construction	F23G5

Notes

1. Catalytic converters are most efficient when heated up to > 300-350 °C. Consequently, the amount of pollutants emitted at cold start may be very high.
2. Anti-knock (anti-detonation) agents are added to increase octane rating of gasoline and thus improve the smoothness of burning process. In internal combustion engines, the compressed gasoline-air mixtures have a tendency to ignite prematurely rather than burning smoothly. Hence a fuel with higher octane ranking allows higher compression ratio without causing premature detonation (knock). While low auto-ignition resistance is problematic in spark-ignition engines, it is desirable in diesel engines. Resistance of gasoline fuels to auto-ignite or detonate when compressed is measured by the octane number. The tendency of diesel fuels to auto-ignite is measured by the cetane number.
3. Automotive fuel, such as gasoline or diesel blend, consists of a mixture of saturated hydrocarbons (alkanes such as heptanes, iso-octane, cyclohexane) and a smaller amount of unsaturated hydrocarbons (alkenes (olefins), alkynes (acetylene), and arenes (or aromatics such as benzene or toluene)). It is manufactured by fractional distillation of crude oil (yields about 25% of gasoline from a unit of crude oil) which may be complemented with cracking and isomerisation (allow to double the yield of hydrocarbons in the gasoline range). A number of chemical compounds are added to motor fuels to improve performance or to meet various environmental standards.
4. In the United States, lead phase-down began by requiring that new cars after 1974 use unleaded gasoline, and ended with an eventual ban in 1996 (Kerr and Newell, 2003).

5. Isomerisation allows producing high-octane blending components (isomers) and hence represents an alternative approach to adding fuel additives. Isomerisation is a process of altering hydrocarbon molecules to produce compounds (*e.g.* isopentane, isohexane) which have higher octane rating; it does not involve adding or removing any substances (see *e.g.* Pellegrino, 2007). For example, the switch from leaded to unleaded gasoline in the United States was, to a large degree, possible due to the commercialisation of pentane-hexane isomerisation technology which allowed boosting octane levels without using lead additives (Kerr and Newell, 2003).
6. Other alternatives included methylcyclopentadienyl manganese tricarbonyl (known as MMT) used in the United States (until banned in 1977 due to health concerns, and again re-authorised in 1995), and other countries such as Canada and Australia (see *e.g.* Masters and Ela, 2008).
7. Unless indicated otherwise, this section is largely based on OECD (2004).
8. They can be used also with lean-burn gasoline engines instead for catalytic converters.
9. The US Clean Air Act introduced a 2% (by weight) oxygen requirement in fuels used in areas that have high levels of CO pollution (non-attainment zones), starting in 1992. In the United States, higher octane number and lower volatility of MTBE compared to ethanol made it the preferred option.
10. For further details see OECD (2004); IEA (2005).
11. Auxiliary systems may contribute significantly to increased fuel consumption and pollution emissions (see *e.g.* Roujol, 2005). The estimated effect of usage of air-conditioning systems under typical European conditions on fuel consumption varies between less than 1% (Hugruel, 2004 in Roujol, 2005) and 4-8% (ECCP, 2003 in Roujol, 2005).

ANNEX C

Glossary of Relevant Patent and Related Terms

Adoption: The point at which a technology is selected for use by an individual or an organisation.

Applicant: The person or company that applies for the patent and intends to "work" the invention (*i.e.* to manufacture or license the technology). In most countries the inventor(s) does not necessarily have to be the applicant.

Application (or filing) date: The patent application date is the date on which the patent office received the patent application.

Application for a patent: To obtain a patent, an application must be filed with the authorised body (patent office, or application authority) with all the necessary documents and fees. The patent office will conduct an examination to decide whether to grant or reject the application.

Assignee: The person(s) or corporate body to whom all or limited rights under a patent are legally transferred. Assignment of all or limited rights under a patent.

Bibliometrics: Study of the quantitative data of the publication patterns of individual articles, journals, and books in order to analyze trends and make comparisons within a body of literature.

Breadth (or scope): A measure of the extent of the invention covered by a single patent application. For example, one patent application to the EPO would generally include more claims than an application to the JPO.

Citations: They comprise a list of references that are believed to be relevant prior art and which may have contributed to the "narrowing" of the original application. Citations may be made by the examiner or the applicant/inventor.

Claim(s): These define the invention that the applicant wishes to protect. A main claim will define the invention in its broadest form, by including its essential technical features. Further "dependant" claims can then relate to additional features of the invention.

Claimed priority: A priority application that has been duplicated at a foreign patent office at least once. An international patent family with at least two members.

Copyright: The legal right granted to an author, editor or publisher of an article, chapter or complete work. Copyright applies to intellectual property in a variety of artistic fields and attempts to be format-neutral.

Design applications: Designs can be registered for a wide range of products, including computers, telephones, CD-players, textiles, jewellery and watches. Registered designs protect only the appearance of products, for example the look of a computer monitor. Registration of the design does not protect the way in which the product relating to the design works.

Designated countries: Countries in which patent applicants wish to protect their invention. This concept is specific to European patent applications and international patent applications filed under the Patent Co-operation Treaty (PCT).

Diffusion: The extent to which a technology spreads to general use and application in the economy.

Duplicate: A patent that relates to the same invention and shares the same priority as a patent from a different issuing authority. The set of such patents, plus the priority, constitute a "simple" patent family. Also referred to as "equivalents".

ECLA: The European Patent Office's patent classification system. It is based on the IPC Classification System, with greater disaggregation.

Equivalent: See "duplicate".

Esp@cenet: European Patent Office website for searching, displaying and downloading patent documents.

European Patent Convention (EPC): The Convention on the Grant of European Patents (European Patent Convention, EPC) was signed in Munich 1973 and entered into force in 1977. As a result of the EPC, the European Patent Office (EPO) was created to grant European patents.

European Patent Office (EPO): The European Patent Office (a regional patents office) was created by the EPC to grant European patents, based on a centralised examination procedure. By filing a single European patent application in one of the three official languages (English, French and German), it is possible to obtain patent rights in all the EPC member and extension countries by designating the countries in the EPO application. However, translation in local language may be required in order to "validate" the patent in an EPO member country. The EPO is not an institution of the European Union.

European patent: A European patent can be obtained for all the EPC countries by filing a single application at the EPO in one of the three official languages (English, French or German). European patents granted by the EPO have the same legal rights and are subject to the same conditions as national patents (granted by the national patent office). It is important to note that a granted European patent is a "bundle" of national patents, which must be validated at the national patent office for it to be effective in member countries.

Examiner: An employee of a patent office to whom an application is assigned for handling prosecution.

Grant date: The date when the patent office issues a patent to the applicant. On average it takes three years for a patent to be granted at the USPTO and five years at the EPO.

Grant: A temporary right given by the authorised body for a limited time period (normally 20 years) to prevent unauthorised use of the technology outlined in the patent. A patent application does not automatically give the applicant a temporary right against infringement. A patent has to be granted for it to be effective and enforceable against infringement.

Home bias: Propensity for the priority country to be the same as the inventor or applicant country.

Infringement: Unauthorised use of a patented invention.

Innovation: The creation or introduction of something new, especially a new product or a new way of producing something.

Intellectual property rights (IPR): IPR allows people to assert ownership rights on the outcomes of their creativity and innovative activity in the same way that they can own physical property. The four main types of intellectual property rights are: patents, trademarks, design and copyrights.

International patent application: Patent applications filed under the Patent Co-operation Treaty (PCT) are commonly referred to as international patent applications. However, an international patent (PCT) application does not result in the issuance of "international patents", *i.e.* at present, there is no global patent system that is responsible for granting international patents. The decision of whether to grant or reject a patent application filed under the PCT rests with the national or regional (*e.g.* EPO) patent offices.

International Patent Classification (IPC): The International Patent Classification, which is commonly referred to as the IPC, is based on an international multilateral treaty administered by WIPO. The IPC is an internationally recognised patent classification system, which provides a common classification for patents according to technology groups. IPC is periodically revised in order to improve the system and to take account of technical development. The current (eighth) edition of the IPC entered into force on 1 January 2006.

Inventor country: Country of the residence of the inventor, which is frequently used to count patents in order to measure inventive performance.

Inventor: Inventor names are recorded for all patents. These appear in the standard last name-initial(s) format.

Japan Patent Office (JPO): The JPO administers the examination and granting of patent rights in Japan. The JPO is an agency of the Ministry of Economy, Trade and Industry (METI).

Kind Code: The letter, often with a further number, indicating the level of publication of a patent. For example DE-A1 is the German *Offenlegungsschrift* (application laid open for public inspection) while a DE-C1 is the German *Patentschrift* (first publication of the granted patent).

Lapse: The date when a patent is no longer valid in a country or system due to failure to pay renewal (maintenance) fees. Often the patent can be reinstated within a limited period.

Learning by doing: Refers to the improvement in technology that takes place in some industries, early in their history, as they learn by experience, so that average cost falls as accumulated output rises. See infant industry protection, dynamic economies of scale.

Learning curve: Relationship representing either average cost or average product as a function of the accumulated output produced. Usually reflecting learning by doing, the learning curve shows cost falling, or average product rising.

Licence: The means by which the owner of a patent gives permission to another person to carry out an action which, without such permission, would infringe on the patent. A licence can thus allow another person to legitimately manufacture, use or sell an

invention protected by a patent. In return, the patent owner will usually receive royalty payments. A license, which can be exclusive or non-exclusive, does not transfer the ownership of the invention to the licensee.

Novelty: If an application for a patent is to be successful, the invention must be novel (new). The invention must never have been made public in any way, anywhere, before the date on which the application for a patent is filed (or before the priority date).

Obviousness: The concept that the *claims* defining an invention in a patent application must involve an inventive step if, when compared with what is already known (*i.e.prior art*), it would not be obvious to someone skilled in the art.

OECD triadic patent families: The triadic patent families are defined at the OECD as a set of patents taken at the European Patent Office (EPO), the Japan Patent Office (JPO) and the US Patent and Trademark Office (USPTO) that share one or more priorities. Triadic patent families data are consolidated to eliminate double counting of patents filed at different offices (*i.e.* regrouping all the interrelated priorities in EPO, JPO and USPTO patent documents).

Paris Convention: The Paris Convention for the Protection of Industrial Property was established in 1883 and is generally referred to the Paris Convention. The Paris Convention established the system of priority rights. Under the priority rights, applicants have up to 12 months from first filing their patent application (usually in their own country) in which to make further applications in member countries and claim the original priority date.

Patent Co-operation Treaty (PCT): Signed in 1970, the PCT entered into force in 1978. The PCT provides the possibility to seek patent rights in a large number of countries by filing a single international application (PCT application) with a single patent office (receiving office). The PCT procedure consists of two main phases: *a)* an "international phase"; and *b)* a PCT "national/regional phase". PCT applications are administered by the World Intellectual Property Organisation (WIPO).

Patent family: A patent family is a set of individual patents granted by various countries. The patent family is all the equivalent patent applications corresponding to a single invention, covering different geographical regions. Patent family size is a measure of the geographical breadth for which protection of the invention is sought. Several definitions of patent family exist, including "simple" and "extended".

Patent number: A patent number is a unique identifier of a patent. Patent numbers are assigned to each patent document by the patent-issuing authority. The first two letters designate the issuing patent office, *i.e.* EP for EPO patents and the US for USPTO patents

Patent: A patent is an intellectual property right issued by authorised bodies to inventors to make use of, and exploit their inventions for a limited period of time (generally 20 years). The patent holder has the legal authority to exclude others from commercially exploiting the invention (for a limited time period). In return for the ownership rights, the applicant must disclose the invention for which protection is sought. The trade-off between the granting of monopoly rights for a limited period and full disclosure of information is an important aspect of the patenting system.

Patentability: Patentability is the ability of an invention to satisfy the legal requirements for obtaining a patent. The basic conditions of patentability, which an application must meet before a patent is granted, are that the invention must be novel, contain an inventive step (or be non-obvious), be capable of industrial application and not

be in certain excluded fields (*e.g.* scientific theories and mathematical methods are not regarded as inventions and cannot be patented at the EPO).

PATSTAT: The *EPO's Worldwide Patent Statistical Database*.

Prior art: Previously used or published technology that may be referred to in a patent application or examination report: *a)* in a broad sense, technology that is relevant to an invention and was publicly available (*e.g.* described in a publication or offered for sale) at the time an invention was made; and *b)* in a narrow sense, any such technology which would invalidate a patent or limit its scope. The process of prosecuting a patent or interpreting its claims largely consists of identifying relevant prior art and distinguishing the claimed invention from that prior art.

Priority country: Country where the patent is first filed before being (possibly) extended to other countries.

Priority date: The priority date is the first date of filing of a patent application, anywhere in the world (often the applicant's domestic patent office), to protect an invention. The priority date is used to determine the novelty of the invention, which implies that it is an important concept in patent procedures. For statistical purposes, the priority date is the closest date to the date of invention.

Publication lag: In most countries, a patent application is published 18 months after the priority date. For example, all pending EPO and JPO patent applications are published 18 months after the priority date. Prior to a change in rules under the American Inventors Protection Act of 1999, USPTO patent applications were held in confidence until a patent was granted. Patent applications filed at the USPTO on or after 29 November 2000 are to be published 18 months after the priority date, unless requested otherwise by the applicant.

R&D expenditures: The basic measure of R&D expenditures is "intramural expenditures"; *i.e.* all expenditures for R&D performed within a statistical unit or sector of the economy.

R&D: Research and experimental development (R&D) comprises creative work undertaken on a systematic basis in order to increase the stock of knowledge, including knowledge of man, culture and society, and the use of this stock of knowledge to devise new applications.

Renewal fees: Once a patent is granted, annual renewal fees are payable to patent offices to keep the patent in force. In the USPTO these payments are referred to as maintenance fees.

Rent: The premium that the owner of a resource receives over and above its *opportunity cost*.

Reverse engineering: The process of learning how a product is made by taking it apart and examining it.

Revocation: Termination of the protection given to a patent on one or more grounds, *e.g.* lack of novelty.

Scientometrics: The quantitative study of the disciplines of science based on published literature and communications. This could include identifying emerging areas of scientific research, examining the development of research over time, or geographic and organisational distributions of research.

Search report: The search report is a list of citations of all published prior art documents which are relevant to the patent application. The search process, conducted by a patent examiner, seeks to identify patent and non-patent documents constituting the relevant prior art to be taken into account in determining whether the invention is novel and includes an inventive step.

Singular: A priority patent application that has never been duplicated abroad (it has not been "claimed" as a priority). A one-member patent family. Also referred to as "singleton".

Transfer of technology: The communication or transmission of a *technology* from one country to another. This may be accomplished in a variety of ways, ranging from deliberate *licensing* to *reverse engineering*.

Term of patent: The maximum number of years that the monopoly rights conferred by the grant of a patent may last.

Trade-Related Aspects of Intellectual Property Rights (TRIPS): Agreement on Trade-Related Aspects of Intellectual Property Rights requires members to comply with certain minimum standards for the protection of IPR. But members may choose to implement laws which provide more extensive protection than is required in the agreement, so long as the additional protection does not contravene the provisions of the agreement. The WTO's TRIPS agreement, negotiated in the 1986-94 Uruguay round, introduced intellectual property rules into the multilateral trading system for the first time.

United States Patent and Trademark Office (USPTO): The USPTO administers the examination and granting of patent rights in the United States. It falls under the jurisdiction of the US Department of Commerce.

Utility model: Also known as "petty patent", these are available in some countries (*e.g.* Japan). This type of patent involves a simpler inventive step than that in a traditional patent and it is valid for a shorter time period.

World Intellectual Property Organisation (WIPO): An intergovernmental organisation responsible for the negotiation and administration of various multilateral treaties dealing with the legal and administrative aspects of intellectual property. In the patent area, the WIPO is notably in charge of administering the Patent Co-operation Treaty (PCT) and the International Patent Classification system (IPC).

Primary sources

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ANNEX D

Patent Data at OECD.Stat

The OECD.Stat portal provides the possibility to download patent counts on a large number of environment-related technologies (see queries at *http://stats.oecd.org/index.aspx?queryid=29068*). The data can also be accessed through OECDiLibrary (*www.oecdilibrary.org*). Detailed description of the search strategies is provided at *www.oecd.org/environment/innovation/indicator*.

ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT

OECD.StatExtracts

Complete databases available via SourceOECD, OECD's iLibrary

Patents by technology : *Patents in environment-related technologies*

Patents Office & Triadic Patents Families			Patent applications filed under the PCT							
Reference country			Inventor(s)'s country(ies) of residence							
Reference Date			Priority date							
Country			World							
Time			2001	2002	2003	2004	2005	2006	2007	2008
Technology domains & IPC ℹ										
⊐ General Environmental Management (air, water, waste) ℹ			2 065	2 109	2 205	2 245	2 491	2 820	3 010	2 780
General Environmental Management (air, water, waste) ℹ	Air pollution abatement (from stationary sources)		614	681	737	837	956	1 186	1 263	1 149
	Water pollution abatement		892	908	953	915	1 004	1 069	1 143	1 047
	Waste management		600	561	569	547	590	603	666	626
	Soil remediation		91	73	58	49	37	43	50	43
	Environmental monitoring		29	37	44	62	46	47	54	53
⊐ Renewable energy generation			603	685	797	963	1 082	1 572	2 158	2 195
Renewable energy generation	Wind energy		174	188	223	221	232	396	564	572
	Solar thermal energy		107	86	119	123	179	274	383	384
	Solar photovoltaic (PV) energy		277	336	380	491	586	796	1 074	1 107
	Solar thermal-PV hybrids		13	10	18	17	14	24	33	30
	Geothermal energy		13	17	18	31	24	44	61	58
	Marine energy (excluding tidal)		20	28	42	58	55	85	105	104
	Hydro energy - tidal, stream or damless		20	26	31	39	43	70	112	72
	Hydro energy - conventional		58	61	74	106	96	119	155	126
⊐ Emissions abatement and fuel efficiency in transportation			1 480	1 578	1 667	1 697	2 030	2 341	2 624	2 287
Emissions abatement and fuel efficiency in transportation	⊐ Technologies specific to propulsion using internal combustion engine (ICE) (e.g. conventional petrol/diesel vehicle, hybrid vehicle with ICE)		1 187	1 186	1 268	1 270	1 420	1 588	1 733	1 525
	Technologies specific to propulsion using internal combustion engine (ICE) (e.g. conventional petrol/diesel vehicle, hybrid vehicle with ICE)	Integrated emissions control (NOX, CO, HC, PM)	836	816	920	884	947	1 059	1 168	979
		Post-combustion emissions control (NOX, CO, HC, PM)	492	568	558	600	715	796	875	790
	Technologies specific to propulsion using electric motor (e.g. electric vehicle, hybrid vehicle)		135	148	151	171	294	450	542	444
	Technologies specific to hybrid propulsion (e.g. hybrid vehicle propelled by electric motor and internal combustion engine)		74	93	95	176	244	334	415	374
	Fuel efficiency-improving vehicle design (e.g. streamlining)		179	232	244	201	251	241	292	220

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Chapter 5. Innovation in selected areas of green chemistry
Chapter 6. Policy conclusions

Annex A. Methodological issues in the development of indicators of innovation and transfer in environmental technologies
Annex B. Patent search strategies
Annex C. Glossary of relevant patent and related terms
Annex D. Patent data at OECD.Stat

For more information on OECD work on environmental innovation, visit:
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