Patents as a measure for eco-innovation

Vanessa Oltra*, René Kemp** and Frans de Vries***

*University of Bordeaux, **UNU-MERIT and ***University of Stirling

Report for MEI project

Deliverable 9

Final version of June 3, 2008

MEI is a project for DG Research of the European Commission (Call FP6-2005-SSP-5A, Area B, 1.6, Task 1) about measuring eco-innovation. The project is done in collaboration with Eurostat, the European Environment Agency (EEA) and the Joint Research Center (JRC) of the European Commission. MEI offers a conceptual clarification of eco-innovation (developing a typology) and discusses possible indicators, leading to proposals for eco-innovation measurement.

Project Title: **Measuring eco-innovation**
Project acronym: **MEI**
Proposal contract No: 044513

Instrument: STREP
Project Call: Call FP6-2005-SSP-5A, Area B, 1.6, Task 1

1. Using patents as an indicator of technological innovation

1.1 Definition and introduction

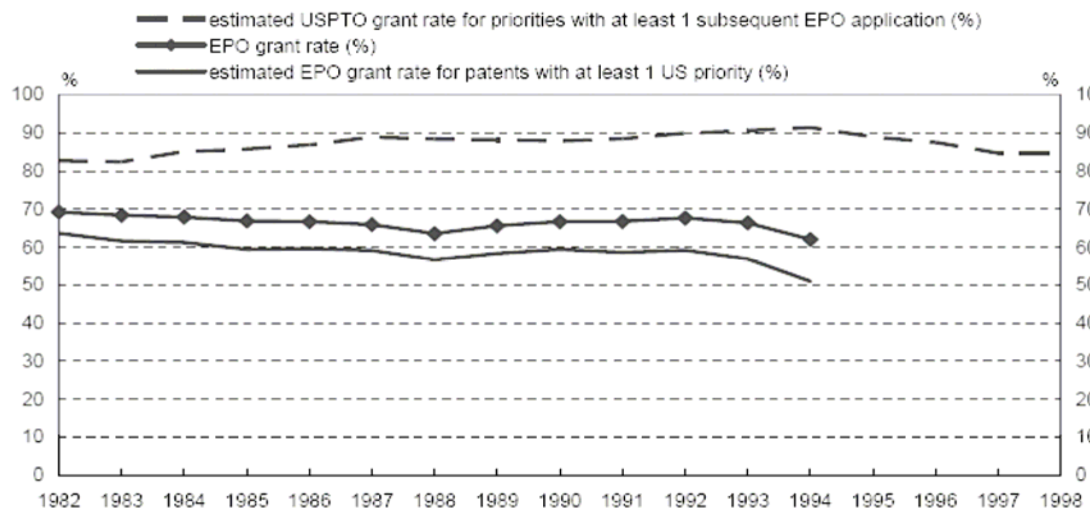
What is a patent? A patent is an exclusive right to exploit (make, use, sell, or import) an invention over a limited period of time (20 years from filing) within the country where the application is made. Patents are granted for inventions which are novel, inventive (non-obvious) and have an industrial application (useful). There are other types of exclusive rights over intangible assets, notably copyright, design protection and trademarks, but patents provide a broader protection that extends beyond the specific expression of an invention to the invention itself. Due to this control over the technology, the patent holder is in a position to set a higher-than-competitive price for the corresponding good or service, which allows recovery of innovation costs. In return, the applicant must disclose the invention in the text of the application, which is published 18 months after application (From OECD report Patents and Innovation: Trends and challenges, 2004, p.8).

As a patent is valid only within the country in which it is granted, it is subject to national laws and litigation settled in national courts. The forthcoming community patent in Europe will be an exception, as it will provide protection in all EU member countries, and litigation will be centralised in a specialised court. International agreements such as the agreement on Trade Related Aspects of Intellectual Property Rights (TRIPS), signed in 1994 and overseen by the World Trade Organisation (WTO), tend to place restrictions on what national laws and policies can do. TRIPS introduced intellectual property rules into the multilateral trading system for the first time, in an attempt to guarantee the same minimum standards of protection across countries. (From OECD report Patents and Innovation: Trends and challenges, 2004, p.8).

The right embedded in the patent can be assigned by the inventor to somebody else, usually to his employer, a corporation, and/or sold to or licensed for use by somebody else; this right can be enforced only by the potential threat of or an actual suit in the courts for infringement damages (Griliches, 1990, p. 1661-1662). The standard of novelty and utility imposed on the granting of such a right is not very high (Griliches, 1990, p. 1663). In Europe, the EPO grants about 70% of the patents applications. In the US more than 80% of the patents applications are granted.

Figure 7. USPTO and EPO estimated grant rates

Priority years: 1982-98

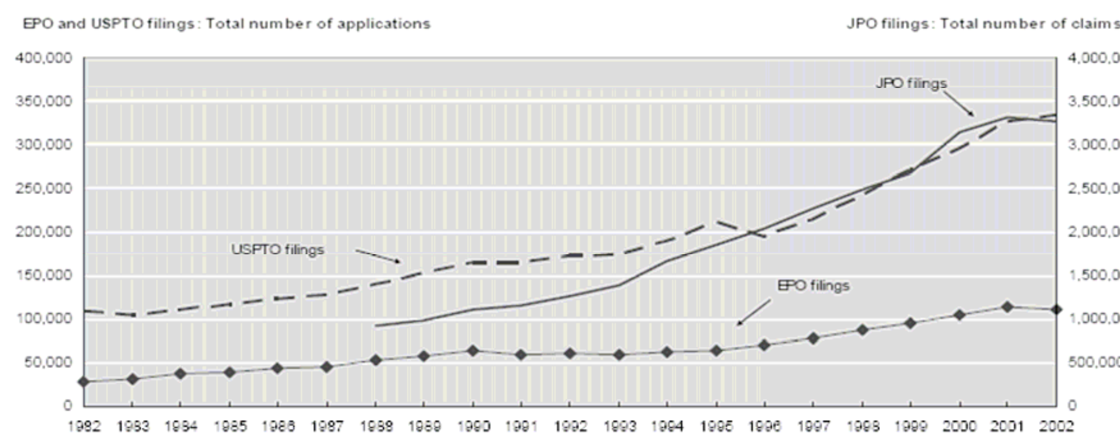


Note: EPO grant rates are defined as number of applications with grant date divided by total number of applications, sorted by year of priority (data on EPO grants is still partial for recent years). The methodology to estimate the grant rate at USPTO for US priorities also applied at EPO consists of the following steps: 1. Select all EPO applications with at least one US priority in the EPO database; 2. Track the corresponding patent number in the USPTO database on grants; 3. Divide the number of US priorities in EPO applications with a grant date at USPTO by the total number of US priorities in EPO applications, sorted by year of priority. Priority year corresponds to the initial date of filing of a patent application worldwide, regardless of subsequent filings in other countries; it normally corresponds to the date of filing in the applicant's domestic patent office.
Source: OECD Patent Database, November 2003.

Patenting behaviour has increased the last 20 years. More than 850,000 patent applications were filed in Europe, Japan and the United States in 2002, against about 600,000 in 1992 (OECD, 2004).

Figure 1. Patent filings at EPO, USPTO and JPO[1]

Filing years: 1982-2002



1. EPO and USPTO filings correspond to total number of applications. JPO filings correspond to total number of claims (number of claims per application multiplied by total number of applications) to account for the effect of the 1988 law reform allowing more than one claim per patent application at JPO.
Source: OECD Patent Database and USPTO, EPO and JPO Annual reports. JPO figures for 2001 and 2002 are OECD estimates.

Three factors are generally viewed to lie behind an increase in the value of IPRs: 1) changes in legislation to strengthen patents, 2) changes in business IPR strategies, and 3) a shift in innovative activities from mechanical engineering towards knowledge-based activities such as information technology, software and biotechnology. It is hard to say which of these is the most important factor (Arundel, 2000?)

New international agreements on the use of IPRs, as illustrated by WIPO or the EPO, have improved the ability of firms to extend IPRs to a larger number of jurisdictions. Also, the establishment, in 1982, of a Federal Court of Appeals for patents has made it easier for firms to protect their patents from infringement in the United States. This could be one factor behind the rise in patent applications in the United States after 1987, although Kortum and Lerner's (1997) analyses indicate that the main factor is a shift to more applied research, which has increased the number of inventions (Arundel, 2000)

1.2 Strengths and limits of patent data

The question of the measurement of technological innovation has long preoccupied economists. R&D and patent data have emerged as relevant indicators of the innovativeness of an economy. R&D expenditures provide an input measure of innovative activity, while patent data are considered to be an output indicator. The main advantage of patents is that they are publicly available for rather long time series and provide detailed technological information. The long time series make patents unique among innovation indicators. Using patent data, it is possible for researchers to collect data in highly disaggregated forms and to subject this to statistical analysis. In terms of costs, the cost of processing patents data is lower than survey-based data.

Patents measure inventive output and may be used as measure for innovation, but there are important caveats for use, discussed below. As a measure of invention patents have a close (if not perfect) link to invention. There are very few examples of major inventions that were not patented in the last two centuries. Patents cover a broad range of techniques, extending now to biotechnology and software, with first extensions towards services-related inventions (so-called "business methods"). Invention is not the same as innovation. Innovation

1.2.1 What can we measure with patent data?

The use of patent data enables researchers to study and to assess different features of innovative processes. On the basis of the huge literature on patents, we can emphasize five attributes of innovative activities that can be evaluated through patent data.

- **The level of inventive activity:** Given that patent applications are usually filed early in the research process (Griliches, 1990), they are not only a measure of innovative output, but also an indicator of the level of innovative activity itself (Popp, 2005).[1] Cohen et al. (2000) emphasize that there is a mutual causation between R&D and patents, and that patenting tends to stimulate R&D. Lanjouw and Mody found a strong positive correlation between patents and R&D in alternative energy for the US.

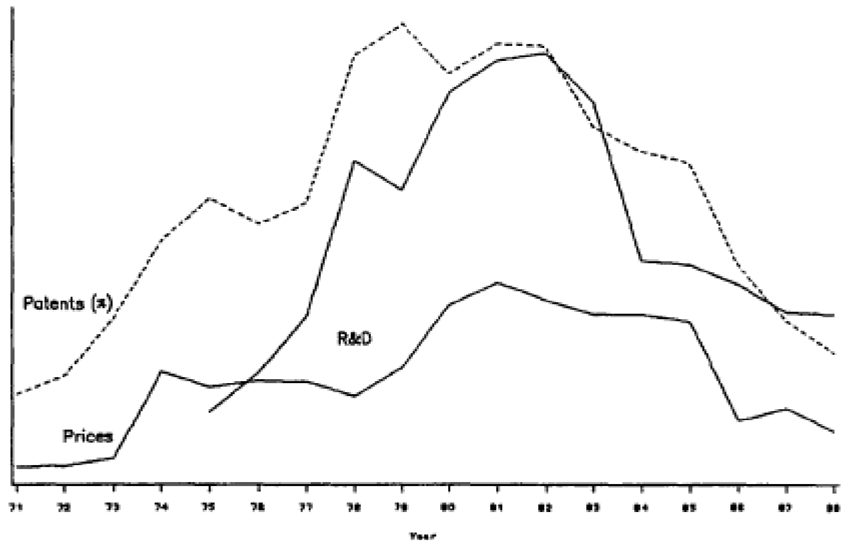


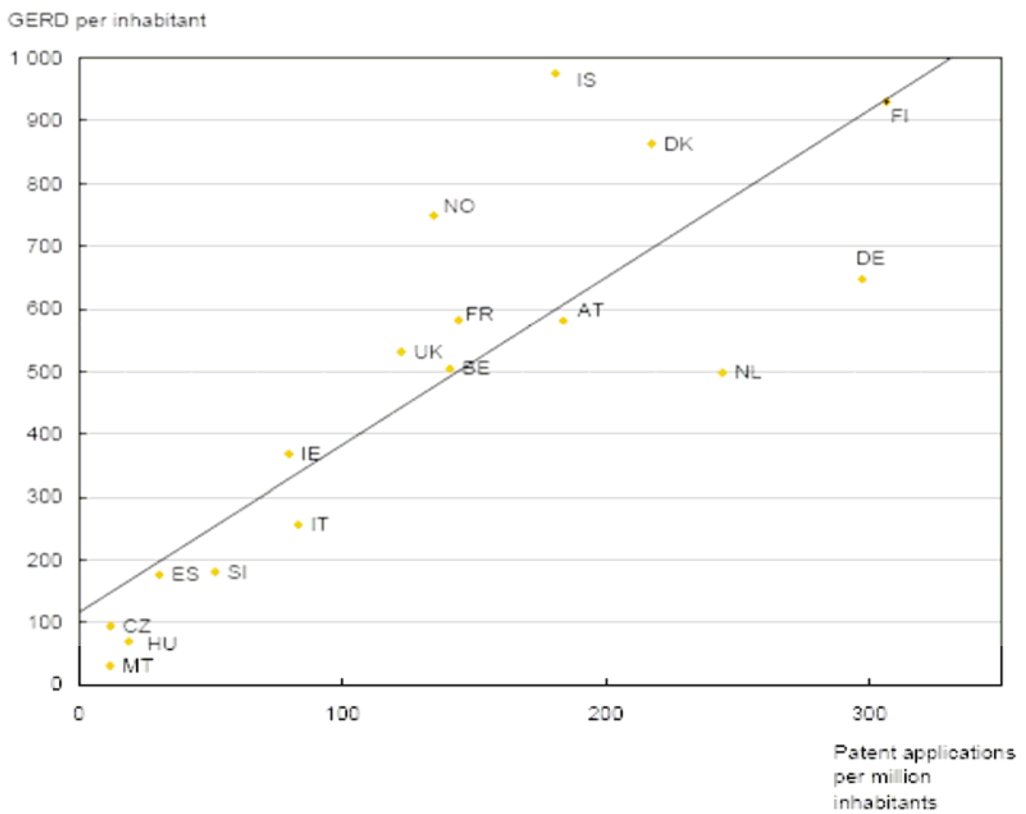
Fig. 4. Alternative energy. Patents, energy prices, R&D. Note: patents (%) is alternative energy patents / total U.S. patents. Sources: R&D funding. Chemical and Engineering News (various February issues).

Source Lanjouw and Mody (1996, p. 560)

If we look across countries we also observe that countries with high levels of R&D per capital tend to have more patents per capita. The Netherlands and Germany have the high levels of patents applications per GERD.[2]

[1] It is better to talk about *inventive* activity instead of *innovative* activity, as they are different things. Innovative activity involves far more than the development and use of an invention. Innovation involves production, design and marketing. An innovation project need not be based on an invention.

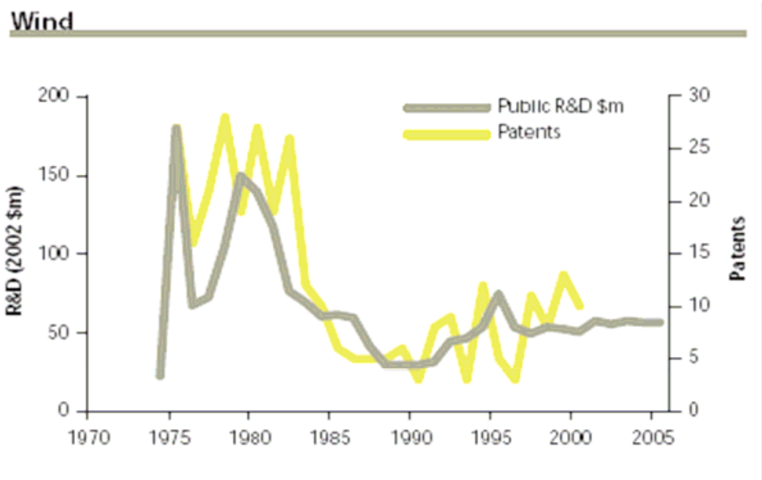
[2] Gross domestic expenditure on R&D (GERD) is total intramural expenditure on R&D performed on the national territory during a given period. It includes R&D performed within a country and funded from abroad but excludes payments made abroad for R&D.

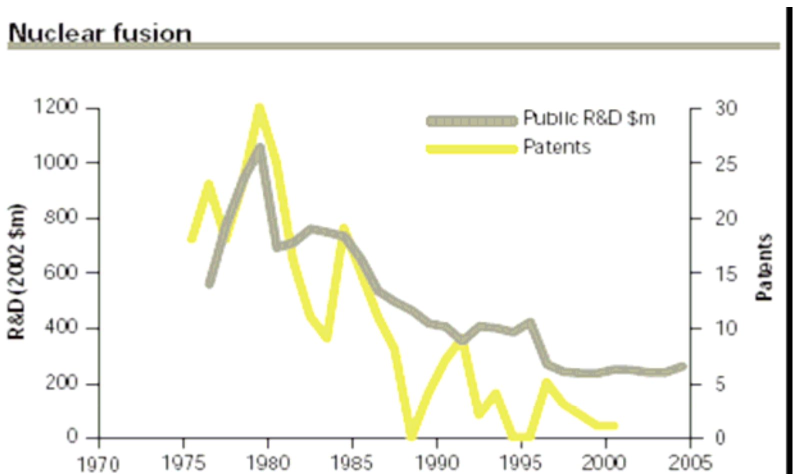


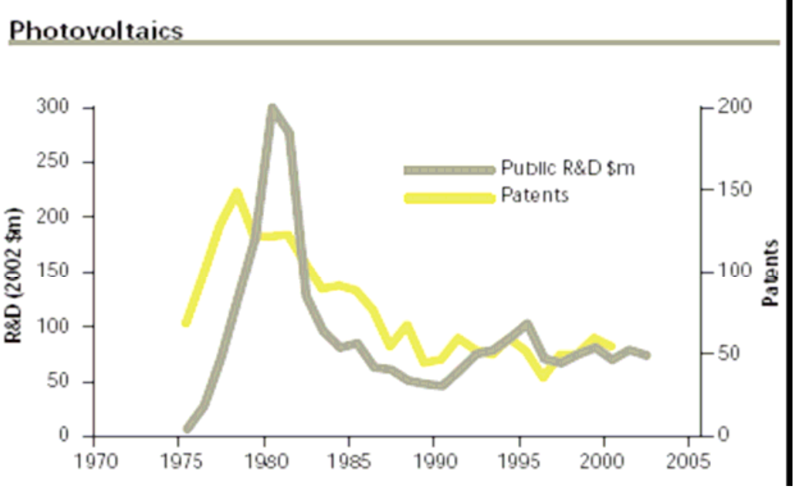
Source: Eurostat (2006)

Patent data are correlated with R&D. The advantage of patent data is that they are available for technologies whereas R&D data are usually not. For broad technology classes such as alternative energy technologies information on public R&D is available. Information on private R&D on specific technologies is usually not available, as companies do not want to report this and also are requested to do so by statistical agencies.

Looking at the correlation between public R&D and patents for alternative energy technologies we can see that they tend to be correlated but this is not always so.

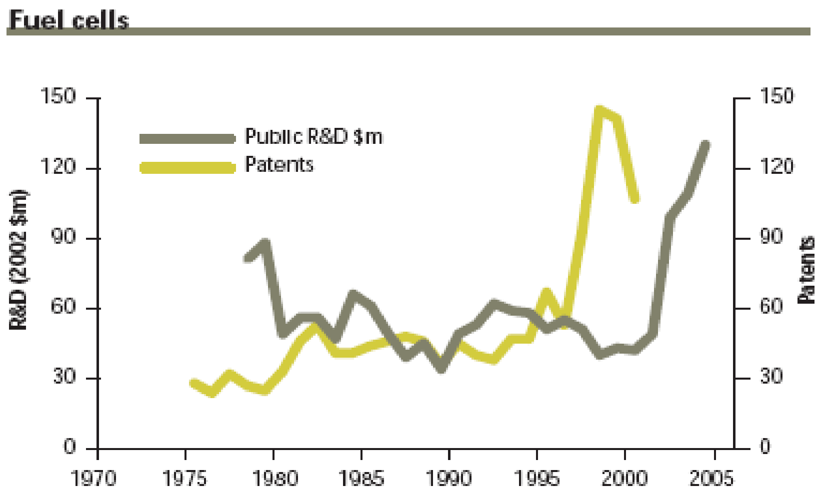






Source: Kammen and Nemet (2005, p. 86)

In the case of fuel cells there is not really a correlation between public research and patents, probably for the reason that private R&D is very important.



Source: Kammen and Nemet (2005, p. 86)

The above graphs suggest that patent counting (preferably in combination with R&D expenditures) can be used as a proxy of not just inventive activity but also innovative activity.

- **Types of innovation and technological competencies of organizations:** Each patent provides a detailed description of the invention and is classified according to the International Patent Classification (IPC)[3]. This classification is a hierarchical system in which the whole area of technology is divided into a range of sections, classes, subclasses and groups. This system is indispensable for the retrieval of patent documents in the search for establishing the novelty of an invention or determining the state of the art in a particular area of technology. These data allow for a microeconomic analysis of the patented invention and of the technological competencies of the patenting organizations. More precisely, the description of the technology and the IPC codes can be used to distinguish between different types of technological innovations according to their degree of novelty (radical or incremental) and their technological field. For example, the OST/INPI/ISI classification provides a concordance table between IPC codes and thirty technological fields, which is used to classify patents according to the type of technology. Moreover patents are also a good indicator of the directions of research and of the technological competencies of organizations (public organizations or private firms). The fact that a firm applies for a patent in a given technological field means that such a firm is at, or close to, the technological frontier and has advanced technological competencies in that field. Patent portfolios of firms offer detailed information on the relevant technological areas, which is of particular relevance in order to assess the firms' spectrum

[3] At least one classification code of the IPC is assigned to all patent documents by patent examiners.

of technological activities. Many empirical studies use patent data to analyze firms' technological diversification (see for example, Breschi et al., 2003).

Technology strengths of nations: Patents can be used to determine technology strengths of nations. The US has the highest levels of patents, which is evidence that the US is technologically advanced. Looking at EPO applications in 2002, the United States leads by far with 46 819 patent applications, followed by Germany and Japan with 24 514 and 24 494 patent applications respectively. Eleven of the 20 worldwide leaders are EU-25 Member States. Along with Japan, there are three other Asian countries among the 20 best performing countries: South Korea (8), China (15) and India (20). A further breakdown of patents is needed to determine whether a nation is leading in a sector. A bread down of patents per sector can be found in the "Patent Scorecard" based on information of the 2500 world's top technology firms collected by the American company called Intellectual Property Intelligence Quotient (ipIQ)

Table 9: US patenting activity broken down by industrial sector and world region, as a percentage of 2 500 of the world's top technology firms, 2005

	Industrial sector	North America	Asia	Europe
1	Aerospace and defence	81%	2%	17%
2	Automotive and transportation	29%	44%	27%
3	Biotechnology	90%	-	10%
4	Chemicals	34%	37%	29%
5	Consumer electronics	9%	87%	7%
6	Consumer products	56%	36%	8%
7	Electronics and instruments	53%	42%	5%
8	Energy and environmental	51%	11%	38%
9	Food, beverage, and tobacco	46%	25%	29%
10	Industrial equipment and materials	50%	32%	18%
11	Information technology	42%	57%	-
12	Medical devices	76%	15%	9%
13	Pharmaceuticals	47%	6%	47%
14	Semiconductors	40%	48%	12%
15	Telecommunications	55%	6%	39%

Source: Eurostat based on ipIQ, Patent Scorecard 2006

Europe plays a significant role in US patenting in industrial sectors such as pharmaceuticals (47%), telecommunications (39%), energy and environmental (38%), chemicals (29%), and automotive and transportation (27%). In most sectors the US displays a technological leadership, which is particularly strong in biotechnology, aerospace and defence, and medical devices. Japan is leading in consumer electronics.

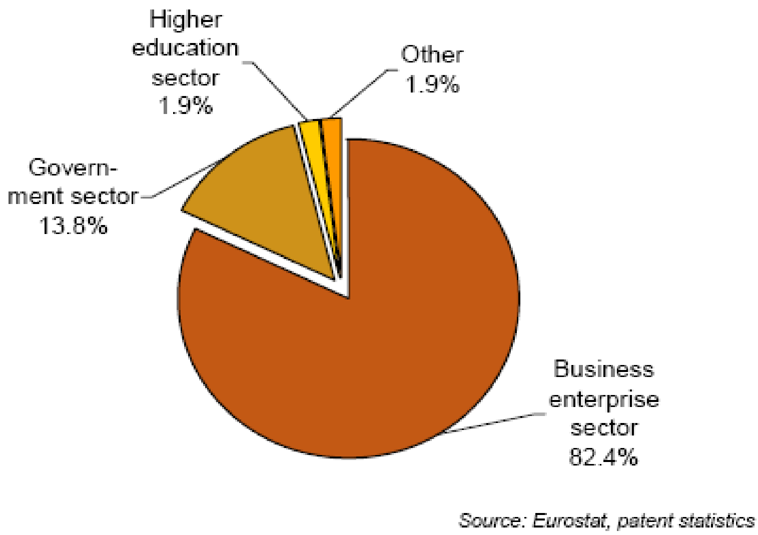
Patents can also be used to determine the technological position of nations in a certain technology area (for example, nanotechnology technology). This is being done by Marinova and McAleer (2003a, 2003b) who analyse the technological position of the top 12 foreign patenting countries in the US in the area of nanotechnology. The non-US countries are Australia, Canada, France, Germany, Great Britain, Italy, Japan, Korea, The Netherlands, Sweden, Switzerland, and Taiwan, using 4 technological strengths indicators based on patent data, which are: i) technological specialization index, ii) patent share, iii) citation rate and iv) rate of assigned patents. The technological specialization index is the quotient of the share of environmental patents in a technological area or sector and the average share; if it is above 1 the nation can be said to be specialized in that area. The patent share is the national share of particular technology in the overall number of patents in the same field, allowing for a ranking of countries. The citation rate gives the mean number of citations per patent from a particular country; it is a measure for the importance of the patents. The rate of assigned patents is the percentage of patents that is assigned; it is indicative for the market relevance. They find that the best performing country in the area of nanotechnology is France, followed by Japan and Canada.

Technology diffusion: Patent data are available from many different countries and so can be used to track patterns of diffusion (Popp, 2005). Because the legal protections granted by a patent only apply in the country in which the patent has been granted, inventors must file patent applications in each country for which they desire protection. In Europe, inventors may choose to file an application through the European Patent Office (EPO), rather than applying to individual patent offices. The applicant designates as many of the 18 EPO member states for protection as is desired. Because EPO applications are more expensive, European inventors typically first file a patent application in their home country, and then apply to the EPO if they desire protection in multiple European countries[4]. Because of the additional costs of filing abroad, only the most valuable inventions are filed in several countries. Filing a patent application in a given country is a signal that the inventor expects the invention to be profitable in that country which is seen as a potential. In that sense, researchers can use these data on multiple filings of patents to track diffusion of technology across countries (Lanjouw and Mody, 1996). Diffusion may be tracked for environmental technology as a whole or subsets. It thus allows for diffusion analysis at a high aggregate level. It does not measure diffusion directly, but only indirectly. For example it does not provide information on the level of diffusion, whether is 1%, 10% or 100%.

- **Source of invention:** From the bibliographic data on a patent, researchers can learn the identity and home country of the inventor and of the assignee (or the applicant). The assignee is the person who has the legal rights to the patent. This information enables researchers to identify the sources of innovation in terms of patenting organizations. By this way, patent data can be used to study the relative role of public and private organizations in the innovative process. For a given technology, or a given IPC section, we can calculate the share of patents filed by private firms, universities and public

[4] These additional filings of the same patent application in different countries are known as *patent families* (Popp, 2005).

laboratories. Businesses applied for most EPO patents (82.4%). Only 17.6% of EPO patent applications are from other institutional sectors (Eurostat, 2006).



Source: Eurostat (2006)

When focusing on private firms, patent data can also be used to study the distribution of patents across sectors and, for example, to emphasize the share of patents filed by component manufacturers.

Some authors concentrate on joint patent application in order to study collaborations and network of innovators. For example, Yarime (2005) analyses university-industry collaboration in the field of photocatalyst technologies. On the basis of joint patent applications, the author maps the networks of innovators and stresses the central role of big Japanese university laboratories. In this type of works, patents are used as an indicator of the relationships between organizations in the innovation process.

- **Technological spillovers and knowledge relatedness:** In recent years there have been various attempts to conceptualize relatedness among technological fields and to find appropriate measures for knowledge spillovers. Various methodologies have been proposed on the basis of patent data: based on Scherer (1982) the 'Yale matrix' is constructed on the data from the Canadian Patent Office, which assigns principal user and producing sectors to each patent, and is used for measuring the spillovers flow from the innovation producing sector to the innovation-using sector; Jaffe (1986, 1989) measure technological relatedness among a sample of US firms by looking at the distribution of their patents across technological fields (each field corresponding to a collection of 12-digit IPC codes); Engelsman and Van Raan (1991, 1994) analyze the co-occurrence of IPC codes assigned to patents to evaluate knowledge links and spillovers; finally Verspagen (1997) evaluates intersectoral technology spillovers by distinguishing between the main classification IPC code and the supplementary codes. Other methodologies use patent citations i.e. references to previous patents. According to Jaffe et al. (1993), a reference to a previous patent indicates that the knowledge in the latter patent was in some way useful for developing the new knowledge described in the citing patent. For a given technology, the set of patents and the citations between can be viewed as a network of ideas and their relatedness. Using this type of interpretation, Verspagen (2005) use patent citations to describe the main paths of knowledge flows in the field of fuel cells and to map the technological trajectories underlying fuel cells development. Such a methodology enables to capture the cumulativeness and the dynamic character of innovation.

• **The novelty of inventions:** The importance of the invention can be assessed through patent analysis. Important patents are cited more often than less important patents. Of course it takes time for a patent to be cited; old patents are likely to be cited more often than new ones. The importance may also be assessed through expert evaluation. The consultation of experts may also be relied upon to identify important inventions not patented.

1.2.2 The limits of patent data indicators

In spite of the wealth of information contained in patents, their use as innovation indicators also present strong weaknesses and biases which researchers should be aware of.

First of all, patent data do not capture all innovations, but a restricted part of it. As a matter of fact, some innovations are not patentable and, even when they are, patents are not considered by firms to be the most efficient way of protecting and of appropriating innovations. The study of Levin et al. (1987) based on the Yale survey shows that firms consider secrecy, lead time and learning effects as the most efficient way of protecting innovations. The main limits of patents emphasized by the surveyed firms are: the possibility to innovate "around" the patent, the fact that some innovations can only be partly patented, and the detailed description of the patented innovation which is considered to be a source of diffusion of information. As a consequence, patented innovations only represent a small share of the overall set of innovations. According to Crepon et al. (2000), the percentage of patented innovations in the French industrial manufacturing sector is on average 30%. Moreover patent data correspond to a biased sample of innovations since they only concern technological innovations and tend to overestimate product innovations. In general, firms are more likely to patent research that results in new products, rather than research that results in new processes. Because new products will be publicly available in the market, the loss of secrecy that comes with a patent is less of a concern than for an innovative process (Popp, 2005).

Patents, R&D, innovation expenditure are strongly positively correlated, which suggests that they may be used as substitutes. Kleinknecht et al. (2002) undertook a factor analysis to see if the underlying causal structure underlying the values is the same. A first analysis based on absolute values indeed offered suggestions to that effect. However, the apparent correlation between the indicators turned out to be mainly caused by one common factor: firm size. When normalizing the data for firm size, the correlation disappears. This means that the stories behind each of the five relative indicators[5] for innovation really are different (Kleinknecht et al., 2002). For outcomes of innovation studies, it does matter which indicator one uses. One should be aware of the biases of the measures being used.

Propensity to patent

Surveys on patenting firms also indicate that the rate at which new innovations are patented varies across industry (Levin et al., 1987). Table 1 presents the results of the CIS4 survey on the share of innovative firms protecting their innovations with patents.

Industrial sectors (NES 16)	% of firms protecting their innovations with patents
EB: Foods, beverages, tobacco	16,4
EC: Consumption goods	25,1
ED: Motor vehicles	42,5
EE: Equipment goods	33,4
EF: Intermediary goods	30,5
EC à EF: Manufacturing industry (without IAA)	30,5
EG: Energy	29,5
EB à EG: Industry	28,7
EN: Firms services	15,5

Table 1: Share (%) of firms protecting their innovations with patents in the sample of innovative firms over the period [2002-2004] (CIS4, 2004)

At a less aggregated level, the study by Arundel and Kabla (1998), based on the 1993 PACE survey of Europe's largest industrial firms, estimates that the average patent propensity rate varies from a low of 15% in basic metals and steel (ISIC 27) to a high of 74% in pharmaceuticals (ISIC 2423). The patent propensity rate only exceeds 50% in four of twenty sectors: machinery (52%), precision instruments (53%), chemicals (57%), and pharmaceuticals.[6] These significant sectoral differences are linked to the types of innovations and to the characteristics of technological regimes in terms of knowledge bases, cumulativeness of innovation and technological opportunities (Pavitt, 1984; Malerba and Orsenigo, 1996). All the empirical studies show that the propensity to patent is the highest in pharmaceuticals, chemicals and motor vehicles. Thus the relevance of patents as innovation indicators depends on the considered industrial sectors and the differences in patent propensity should be controlled in patent analyses.

[5] The indicators are: logarithm of total number of R&D man years; number of European patent applications; expenditure on innovation; logs of sales of innovative products 'new to the firm'; and logs of sales of innovative products 'new to the market'.

[6] The patent propensity measures the share of *newly developed* innovations that are patented.

According to a study of Brouwer and Kleinknecht (1999), smaller firms have a lower probability to apply for at least one patent. However, given that they do patent, they apply for higher numbers of patents. Apparently, small firms have a threshold problem, the first patent being the most expensive in terms of information costs. Kleinknecht et al. (2002) show that the firms collaborating on R&D patent more intensively than is done by non-collaborators. Seemingly firms wish to protect the most precious parts of their knowledge before engaging into collaboration with a partner.

Value of patents

International comparisons based on patent data raises difficulties since the propensity to patent and the value of patents differ across countries. The characteristics of national patent systems in terms of required degree of novelty, flexibility of legislation and the first-to-file and the first-to-invent system strongly influence the patent propensity. These differences in patents regulations make it difficult to compare patent counts across countries.

Another drawback of international comparison based national patents counts lies in the high heterogeneity in the value of patents. The value of a patent can be roughly defined as the contribution of the invention it protects to the economy: either in technological terms (novelty and fertility of the invention), or in economic terms (return to the patentee). There is broad recognition that the value distribution of patents is very skewed: a few patents have large value, whereas many have very low value. Hence the significance of patents counts is limited, as they put on an equal footing patents of very different values.

Many methodologies have been proposed to evaluate the value of patents. Three sources of data on this topic have been used (Griliches, 1990): results of direct surveys of patent owners about past returns and the potential market value of their rights, the decision whether to pay a fee to renew the patent, a decision that had to be made by European patent holders in the past and is now also facing U.S. patent holders, and finally econometric analyses of the relationship of some other value-denominated variable, such as profits or stock market value, to the number of patents. More recently, many empirical works use patent citations as alternative "indexes" of differential quality of patents. According to Griliches (1990), citations bring us closer to something that might be interpreted as measuring the social rather than just the private returns to these patents. Finally the development of the OECD Triadic Patent Family database is of great interest since it provides a database of "high quality" inventions. The use of *patent families* - i.e. filings of the same patent application (which share the same priority date) in different countries – enables to focus on the most valuable innovations. Indeed, because of the added costs of filing abroad, the less valuable patents are usually filed only in the inventor's home country.

The use of patent data also poses methodological issues. How does one allocate patent data organized by firms or by substantive patent classes into economically relevant industry or product groupings? How can we identify the set of relevant patents dealing with the technologies we want to study? Economists and policymakers are interested in patents counted by economic sector in order to analyse trends across time and across sectors. For example, the propensity to patent, or the inventive productivity of a sector (in terms of patents per unit of R&D), may be useful in determining future sectors for government support. While patent data are now readily available for most nations, these data are still of minimal use for economic analysis due to their mode of presentation. Patents are recorded for administrative purposes using the International Patent Classification (IPC) system, which categorises inventions by product or process. Instead, most economic researchers and analysts are interested in the particular sectors of the economy responsible for the invention or its subsequent use. The OECD Technology Concordance (OTC) presented in Johnson (2002), like its predecessor the Yale Technology Concordance, is a tool allowing researchers to transform IPC-based patent data into patent counts by sector of the economy.

2. Eco-patents

2.1 Measuring eco-innovations with patent data

Patent counts can be used as an indicator of the level of innovative activity in the environmental field. In the same way as for innovation in general, patents of eco-inventions can be used to measure research and invention activities and to study the directions of research in a given technological field.

Patents may also be used for studying eco-innovations – innovations that result, throughout its life cycle, in a reduction of environmental risk, pollution and other negative impacts of resources use (including energy use) compared to relevant alternatives. Whether something is an eco-innovation depends on the environmental effects. To be picked up as an eco-patent, the environmental gain must be described. If the environmental impact is a non-intentional side effect of the innovation, this effect will not appear in the claims and in the description of the patented technology.

In the typology paper we discussed the different types of eco-innovation. Eco-innovation may consist of a new or improved environmental technology, a production innovation, a service innovation, the introduction of an new business method or organizational measure, or a green system innovation. New business methods and organisational innovations are almost never patented, for the reason that it impossible to patent them as there is no clear invention underlying it. For this type of innovaton, patent analysis is not suited. It is also not suited for analyzing service innovation as few services innovations are patented. It is **primarily technological innovations new to the world that are patented**, and it is for these type of innovation that patent analysis may be used. Given that firms are more likely to patent research that results in new products, rather than research that results in new processes, research on environmental innovation that uses patent statistics is likely to focus primarily on product eco-innovations (Popp, 2005). As such, eco-patents tend to cover mostly end of pipe technologies, which are also more easily identifiable. Even if they are patented, clean processes, which are frequently integrated within more general production processes, are difficult to identify as eco-patents on the basis of IPC classifications and/or keywords research. Since changes in production processes and product characteristics are increasingly more prevalent as a means of addressing environmental concerns than end of pipe strategies, this problem is likely to become more acute with time (Frondel et al., 2005).

Patent analysis may be used for green system innovations if they are based on a core technology which is identifiable in the IPC classification. But as system innovation is about a range of interconnected innovations this type of innovation also cannot be really analysed through patent analysis.

In summary, we can say that eco-patents mainly measure inventions that underlie green product innovations and end of pipe technologies, whose environmental impacts are specific aims and motivations of the inventions. For these kinds of innovations it is okay to use patent analysis.

In spite of these limits, eco-patents can provide indicators of environmental innovative activities in specific technological fields. For example using a patent search filter based on IPC codes and keywords, Nameroff et al. (2004) study green chemistry patents, Lanjouw and Mody (1996) count the number of patents in nine environmental fields (including alternative energy), and Johnstone (2005) focuses on renewable energy patents.

In the same way as for innovation in general, eco-patents can be used to analyze the following features of environmental innovative activities:

- **The level of eco-innovation activities and the directions of research in certain environmental fields**: international comparison of eco-patents in specific technological fields, historical evolution of eco-patents in specific fields, technological competition between environmental technologies (for example in the fields of low emission vehicles in Frenken et al. (2004) and in Oltra and Saint Jean (2006) or in the field of renewable energy in Johnsotone (2005).

- **The competencies of organizations in environmental technologies**: eco-patents are used to evaluate technological competencies of private and public organizations in specific environmental fields. For example Frenken et al. (2004) and Oltra and Saint Jean (2006) study the evolution of the patent portfolios of car manufacturers in the field of low emission vehicles.

- **The diffusion of environmental technologies**: international eco-patent data are used to track patterns of diffusion. Lanjouw and Mody (1996) calculate the share of foreign patenting as a proxy of technology transfer and diffusion.

- **The sources of eco-innovations**: The identity and home country of the assignees of eco-patents provide information on the sources of eco-innovation which can be very useful to study the relative role of private firms, universities and public laboratories[7]. Data on co-patenting are also very useful to analyze collaborations in the field of eco-innovations and network of innovators. Empirical works on the sources of eco-innovation and network of innovators can be very relevant to draw policy implications.

- **Environmental technology strength of nations**: The strength of nations in the various areas of environmental technology can be analysed on the basis of patent data. It may even be done for environmental technology in general, bearing in mind that such an analysis is heavily skewed towards technical innovations in the end-of-pipe technology and alternative energy technologies. Marinova and McAleer (2003c) analysed the technological position of the top 12 foreign patenting countries in the US in the area of environmental technology, using 4 technological strengths indicators based on patent data, which are: technological specialization index, patent share, citation rate and rate of assigned patents. They find that Germany is the best performing country with a specialization index of 1.34 (second the group of 12 countries), a patent share of 10.5% (first), a rate of assigned patents of 0.83 (second) and a citation rate of 3.18 (fourth). Canada and Japan ranked equal second, but showed significant national differences in their environmental technologies. Canada has a high value of the technological specialisation index (1.34, equal to Germany) but a very low rate of assigned patents. The reverse is true for Japan who has the highest rate of assigned patents and the lowest value for the TSI.

- **Technological spillovers and knowledge flows**: Eco-patent citations are used as a measure of knowledge flows across inventors and across countries. Papers using citation data include Jaffe et al. (1996, 1998), Johnson and Popp (2003) and Popp (2002). As for innovation in general, the methodologies based on patent citations are very useful to apprehend the dynamic character of eco-innovations. For example, it can be very relevant to analyze the relationships and the complementarities between environmental and non-environmental technologies. Verspagen analysed the trajectories of invention for fuel cells, the results of which are shown in Figure 3.

---

[7] Nameroff et al. (2004) determine the relative share of each type of organizations in green chemistry patents and emphasize the major role of universities.

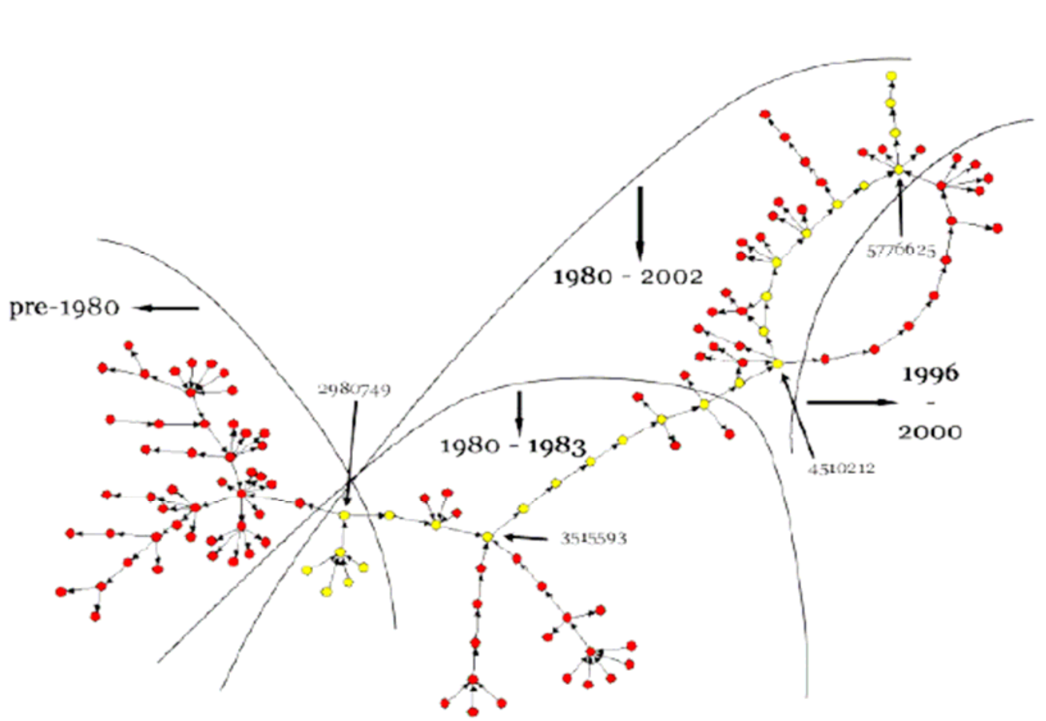


Figure 3. The evolution of main paths over time (network P)

Source: Verspagen (2005)

The analysis shows that in the pre-1980 period there are many different paths, several of which become dead ends. The year 1980 emerges from the analysis as the demarcation year between the phase of exploration and the building up of a cumulative trajectory. The analysis also shows what patents are associated with the establishment of new trajectories.

- **T**he novelty and path-breaking nature of eco-inventions

2.2 Methodological issues: the identification of eco-patents

A particular problem in the environmental sphere is the need to identify those patents which can be said to be 'environmental'. The identification of eco-patents in patent data bases raises methodological issues which should be taken into account when interpreting the results. In the literature two methodologies are used, sometimes in combination: research in specific patent classifications and/or searching for relevant keywords. The problem is that patent classification systems do not provide specific categories which cover environmental patents and there is also no widely accepted agreement in the literature as to what constitutes an environmental technology. The methodology also depends whether the analysis concerns environmental technologies in general or a specific set of technologies.

- Eco-patents on environmental technologies

Lanjouw and Mody (1996) use patent data to investigate the extent of eco-innovations. Relevant patent data were identified on the basis of IPC classifications and keywords. The authors define nine environmental fields[8] and determine the IPC classes which are appropriate to each field. In a second step, relevant keywords are searched[9] and the corresponding IPC classes of the resulting patents considered for inclusion in the analysis.
Example in Lanjouw and Mody (1996) page 570:

Environmental field	Keywords	IPC classifications	Number of US patents	% of patents with at least one keyword
Industrial air pollution	treat, scrub, remove	B01D-53/46	24958	85
		B01D-53/46	7649	53
		C10K-1/3	4088	60
		C10L-3	1166	0
		F23B-5	796	33
		F23J-3	1751	80
		F23J-15	4026	57

By combining IPC classes with keywords, the authors avoid to select too many patents and so to include innovations that bear no relation to environmental fields. With this methodology Lanjouw and Mody (1996) succeed in identifying eco-patents which mainly concerns end of pipe technology in nine environmental fields and alternative energy technologies.

Marinova and McAleer try to evaluate environmental technology strengths of countries on the basis of eco-patent data. In order to identify eco-patents they define the following principle: "When the technology is described in terms of its superior environmental performance, such an invention can be considered to be an environmental patent… A patent is considered to be related to the ecological environment if its abstract or full text contains words such as 'ecology', 'ecological', 'ecologically' or any other word beginning with 'eco-' and 'environmentally'". Such a methodology seems very restricted since these keywords would be included in a patent only if the ecological concerns are at the very core of the aims of the patent. Moreover a lot of patents which directly concern the environment describe the invention in terms of precise technical terms, without including such general expressions as 'ecology or environmental performances'. In order to capture more precisely, eco-patents the search for keywords should be more precise.

The OECD Compendium on statistics (2006) proposes such a methodology which identifies patents related to environmental technology in 6 environmental fields using a combination of IPC classes and keywords (cf. Annex 1). This methodology covers mostly end of pipe technologies which are more easily identifiable.

---

[8] Industrial air pollution, water pollution, vehicle air pollution, solid waste, incineration of waste, alternative energy, oil spills, radioactive waste and recycling and reusing waste.
[9] In the US patent system, a keyword index of terms found in patent document texts is available.

- Eco-patents in specific technological fields

Many empirical studies focus on specific technological fields. In that case the methodology, in particular the definition of keywords can be more precise. Johnstone (2005) studies renewable energy patents by searching relevant keywords in the areas of solar, hydro and wind energy. For each area, a list of IPC classifications was identified as pertinent. Popp (2005) compare the results obtained with different methodologies and different databases in the field of NO_X and SO_2 pollution control technologies. It clearly shows significant differences according to the methodology of research.

Nameroff et al. (2004) present an analysis of the adoption of green chemistry based on US patents. They define a patent research filter using keywords and IPC classifications. Search terms were intended to capture the main concepts of green chemistry and some patent classifications were included either to limit the keyword search to chemically related areas of technology or to exclude subject matter related to pollution remediation and waste treatment. With this methodology, they identify 3235 green chemistry US patents.

De Vries and Withagen (2005) in their study of patents in sulphur dioxide abatement read every patent abstract to determine whether the technology was really related to SO_2 abatement or not (see also below for a more detailed description of their procedure). The number of or rejected patents, including double counts, was 1105 (26%), which is quite high. The non-removal of non-relevant patents may influence the results. When the number of patents is in the ten thousands or hundred thousands one can not really do this kind of screening.

Van den Hoed (2004), Frenken et al. (2004) and Oltra and Saint Jean (2006) use patent data to study eco-innovations in the field of low emission vehicles (LEVs). They mainly use keywords search applied to a sample of patents filled by the main car manufacturers. SO the assignee name and the priority date are also used as search items. With this methodology, they study the evolution of patents in the different alternative engine technologies for LEVs.

- A route on patent data acquisition

In summary, the use of patents to measure eco-innovations raises strong methodological issues. The identification of eco-patents implies time and data consuming methodologies based on IPC classifications and on relevant keywords. In order to be able to define relevant keywords, researchers must have an adequate knowledge of the technologies under consideration. Moreover when the analysis seeks to evaluate eco-patents in general, it is generally restricted to end of pipe technologies. Eco-patent analyses can be broader in terms of types of innovation when it focuses on specific technological fields. When the area of the analysis is more precise, researchers can identify the relevant technologies and define a precise list of keywords. Nevertheless, whatever the methodology, it is difficult to know exactly the characteristics of the distribution of eco-patents, in terms of type of eco-innovation and in terms of their environmental value.

As an example of assembling a workable set of eco-patents, we will outline the procedure that was used in the study by De Vries and Withagen (2005), to study the effect of environmental stringency on innovation in SO_2 abatement technologies. It illustrates many of the problems that were highlighted above and discusses how they were subsequently dealt with.

In general, when an economic agent files for a patent application (the patentee) he submits its application to a patent office, which subsequently determines whether or not the request will be honored in due time. The date of the inventor's initial filing of a patent application to a certain patent office is the so-called *priority date*. If the inventor also wishes to file for patent protection in countries other than the "home country", it can do so within one year of its initial filing. If the home country patent office grants the initial filing, the inventor also has priority over the patent applications he filed in those other countries. As noted before, these are the patent families.

Each patent has a patent number. At the European Patent Office (EPO), the granted patents are classified according to the European Classification System (ECLA), which is an extension of the IPC system in the sense that the former includes a more detailed coverage of different technological specifications. For example, the ECLA class B01D53 contains patents related to the separation of gases or vapours; recovering vapours of volatile solvents from gases; chemical or biological purification of waste gases (e.g., engine exhaust gases, smoke, fumes, flue gases and aerosols). The class B01D53 is also divided into subclasses. For instance, assuming that a firm invented a new method to control SO_2 emissions, it is likely to be assigned to the class B01D53/50, referring to patents on the chemical or biological processes to reduce SO_2. As one recognizes, the structure of such detailed classification schemes enables researchers to search quite specifically for relevant abatement technologies.

There are basically two routes to access the EPO's database. First, one can search for patents by using their online service *esp@cenet*, which can be entered freely.[10] However, because one can maximally retrieve a number of 500 patents within *esp@cenet*, this on-line service is especially useful for a first initial screening of classes and subclasses, or for a first "rough" search by using keywords. Given the limit number of patents one can download, the EPO was consulted directly by De Vries and Withagen and a search through the EPO's database was established in conjunction with help from experts at the office.

How did the search process work? The essential element of the search process was the use of keywords. This is in line with Lanjouw and Mody (1996), Taylor et al. (2003) and Popp (2006). The search process comprised four stages. First, the search is confined to the pollutant under consideration, i.e. SO_2. Second, keywords – based upon relevant abatement techniques – are applied in order to generate a set of *potentially* relevant patents. Third, the abstract of each single patent as contained in the set generated through the previous stage was screened in order to determine whether it indeed was a relevant

[10] http://www.espacenet.com/

patent. If the patent was not related to a pollution abatement technique, it was eliminated from the set.

This third step was included in order to avoid as much “noise” as possible, thereby improving the quality of the patent set. The drawback of this is that the aggregate number of patent applications may be somewhat understated. This type of error was preferred above the error that would occur if patents that bear no relation to pollution abatement were included, i.e. the total amount of patents would then be overstated. This latter type of error can simply be avoided by being very accurate in judging the patent on the basis of the patent abstract content. However, the former type of error is very difficult to avoid, because it is inherent in proxying innovation by means of patents. Fourth, for every patent judged as relevant the patent families were retrieved. These are the patent applications the inventor filed in the countries other than the home country.

Let us elaborate a bit more on how this overall search structure applies to SO_2. The initial step in the search routine can simply be done by imposing pollutant-related keywords. For example, with regard to SO_2 abatement, the keywords that restrict the search within the database of the EPO were: SO_2, sulfur, and sulphur.[11] Given the pollutant-restricting focus, the second step implied the more “technology-based” search for patents. To do so, first a list of technologies and techniques that are currently available (or are in development stage) to curb the emissions of SO_2 should be established. For example, to reduce or remove SO_2 emissions as a side product of industrial processes, one can use several techniques, such as conventional wet flue gas desulfurization processes or fluidized bed combustion, among others. The technology-based keywords were derived from these technological sources. For the SO_2 example a keyword could be “flue” in combination with “gas” or “combust”.

These two fundamental steps generated a pool of patents that were potentially relevant. Then for every single patent in the pool, the title, the patent and priority number, the EC classification number, the inventor and the patent abstract were generated. To ensure that only patents related to the control of SO_2 were to become included the patent abstract was subject to a thorough screening. Once the irrelevant patents were removed, the families of each patent were retrieved from the database at the EPO, which can be done in a straightforward manner by using the patent number.

2.3 Main indicators and survey of empirical results

Given the huge literature using eco-patent data, we try to summarize the main indicators that one can find in patent analyses and we present a set of empirical results based on these indicators. The following table presents the main indicators calculated on the basis of patent data, with a broad definition and interpretation, and a sample of references using the considered indicator. All these indicators imply a first step of patents counting based on a relevant research methodology using keywords and/or IPC codes.

---

[11] Note that one has to apply both the English and American spelling.

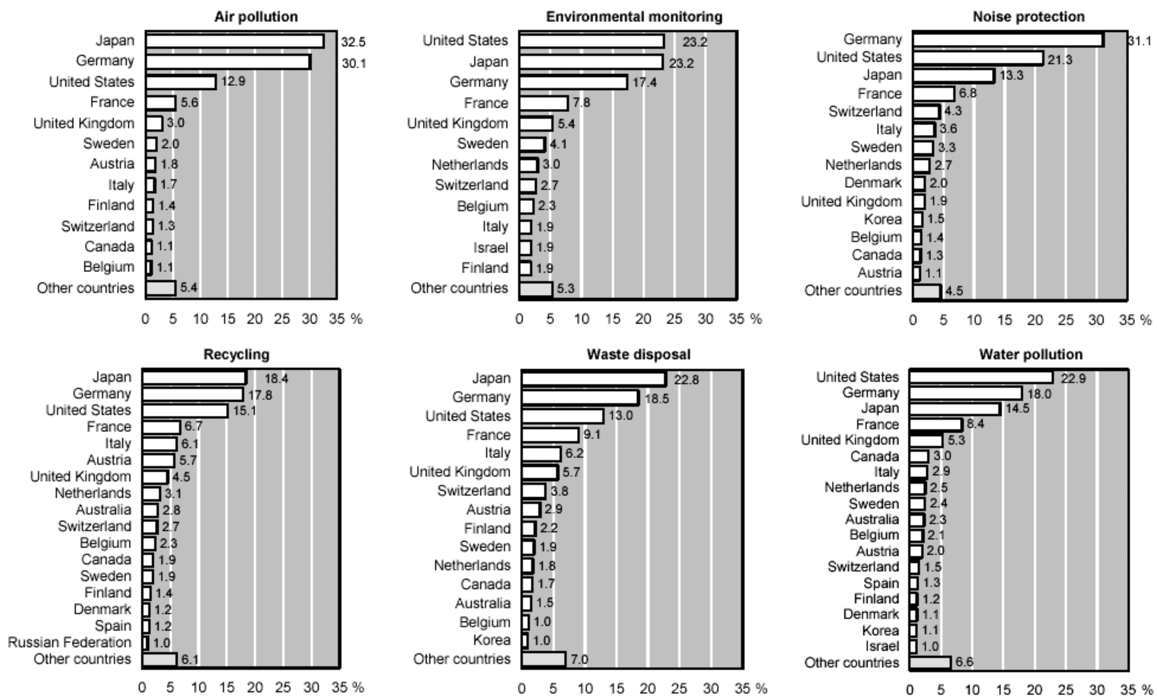
A summary table of indicators

Type of indicators	Definition	Interpretation	References
Eco-patents count	Cumulated number of eco-patents 2 or 3 years moving average of eco-patents number	Evolution through time of eco-patenting	Johnstone (2005) Popp (2005) OECD (2006) Nameroff et al. (2004)
Eco-patents share (%)	Share of eco-patents in total patents National share of eco-patents in the overall number of patents in the same technological field	Evolution through time and across countries of eco-patenting Normalization by total patents to correct the biases linked to differences in propensity to patent across countries or across technological fields	Lanjouw and Mody (1996) OECD (2006) Nameroff et al. (2004) Marinova and McAleer (2003)
Technological specialization index	National share of eco-patents in a particular area divided by the overall share of eco-patents in this area idem for firms	Technological specialization if the ratio is superior to 1	Marinova and McAleer (2003) Oltra and Saint Jean (2006) at firm level
Knowledge and eco-patents value	Citation rate of patents	Knowledge flows as a proxy of patents value	Marinova and McAleer (2003)
Diversification	Entropy $E(X)=\sum p_i.\ln p_i$ with p_i the number of patents in a given technological field	Entropy of a distribution of patents among technologies as a proxy of the technological variety present in the distribution of patents among technologies in a given industry	Frenken et al. (2004) in the case of LEVs
Market	The rate of assigned patents	A proxy of the proximity of patents to commercial exploitation in the market	Marinova and McAleer (2003)
Patent portfolios of firms	Relative share of patents in various technological options in the overall patent portfolios of firms	Eco-patenting strategy of firms and diversification	Oltra and Saint Jean (2006) Van den Hoed (2004) in the case of LEVs

Examples of empirical results:

- OECD (2006)
In the OECD Compendium of Patent statistics the patents linked to environmental technologies are identified in the worldwide EPO database through a list of keywords and IPC classes (see Box 3.3 in Annex1). Such a definition covers mostly end-of-pipe technologies which are more easily identifiable. The environmental technologies identified through patents are classified according to their environmental fields (air, water pollution…). The results show that Germany is among the three most innovative countries, with US and Japan, in the selected environmental fields, and that overall European countries have the largest share of environmental technologies.

3.8.2. Share of countries in EPO patent applications in environmental technologies[1]
1999-2003

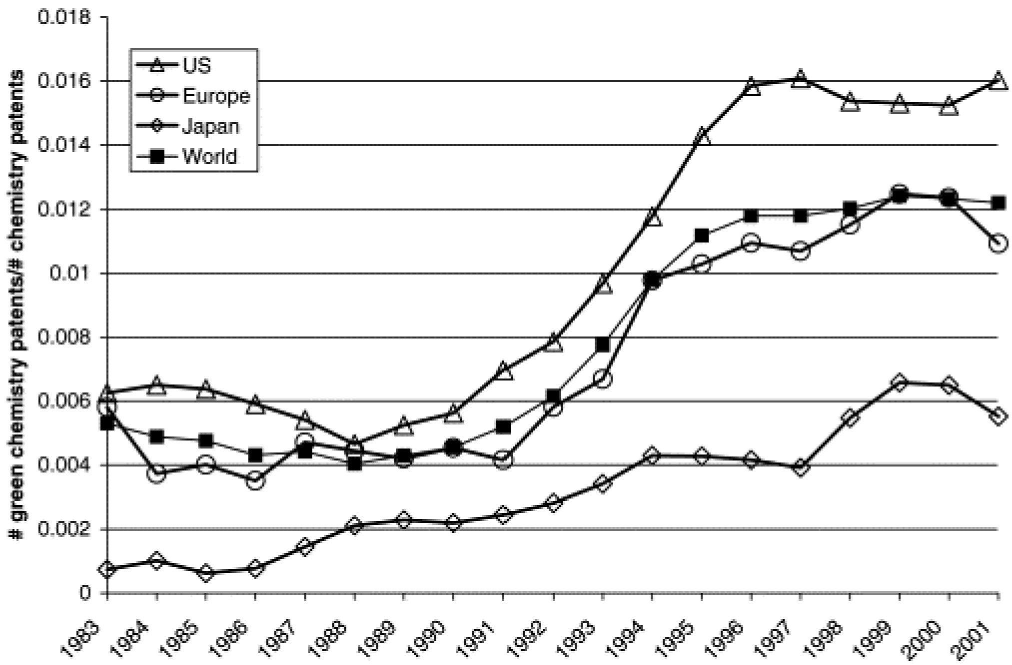


Note: Patent counts are based on the priority date, the inventor's country of residence and fractional counts.
1. The provisional definition of environmental technology patents is presented in the methodological Box 3.3.

Source: OECD, Patent Database, September 2006.

- International comparison of patent activity in green chemistry

Focusing on the case of green chemistry, Nameroff and al. (2004) present a comparison of regional patent activity in green chemistry. On the basis of a 3-year running average, they calculate the share of green chemistry US patents in the total number of patents granted in the chemicals technology, polymer, plastic and rubber patent classifications. The figures show that "the relative emphasis on green chemistry has increased over time in the US, Europe and Japan indicating that the proliferation of green chemistry technology is a worldwide phenomenon" (Nameroff and al., 2004, page 968). However the relative share of green chemistry patents remains low (inferior to 0.02) and the differences among countries suggest that in each region firms may have had different incentives for developing green chemistry technology patents.

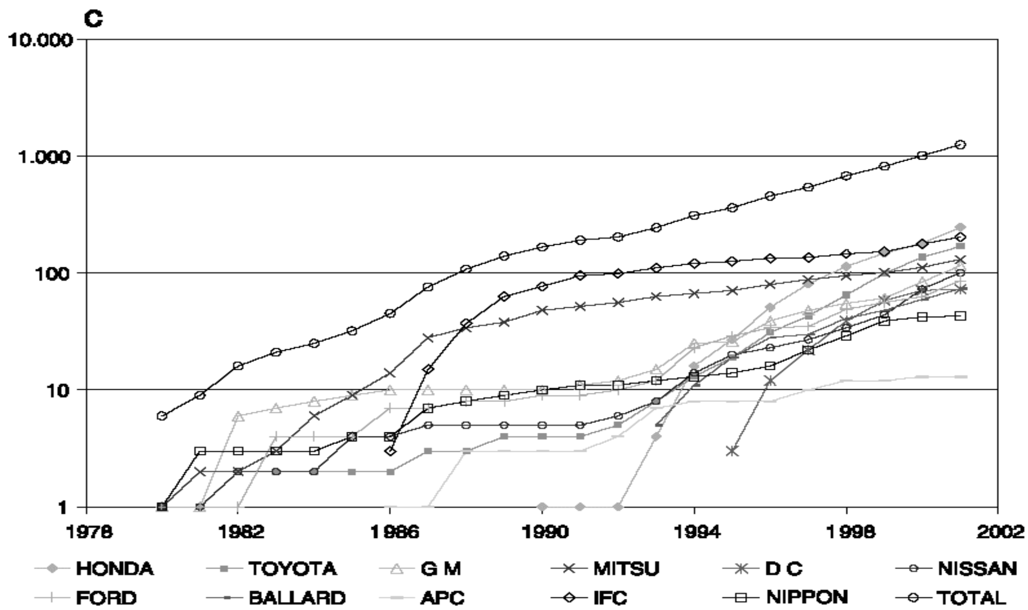


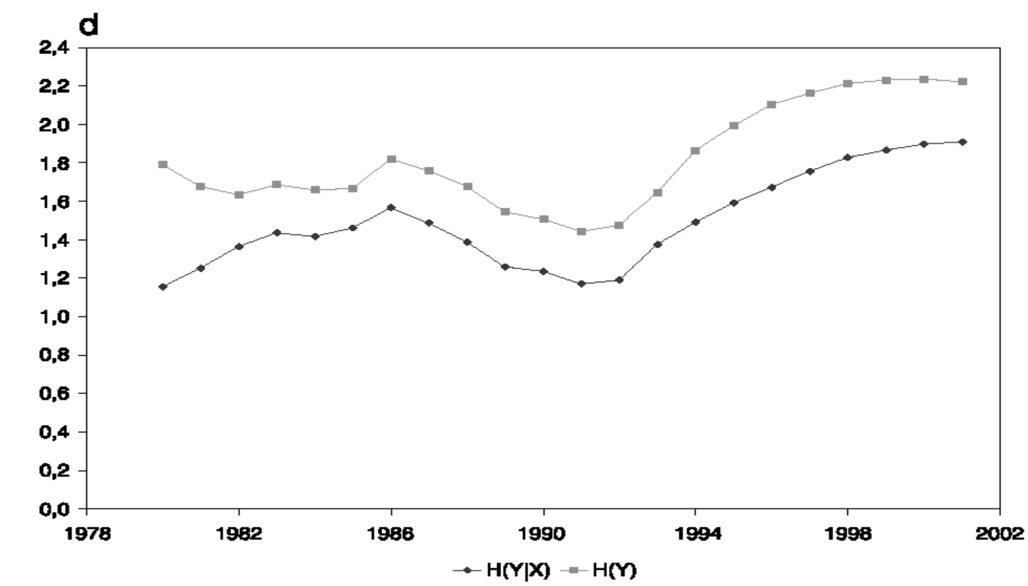
- The case of low emission vehicles (LEVs)

Frenken and al. (2004) analyse patent portfolios (using USPTO database) of a sample of firms (seven car manufacturers, two fuel cell producers, one gas company and one oil company) in LEVs over the period [1980-2001]. The first figure depicts the cumulated number of patents of each firm in the three competing technologies i.e. electric battery vehicle, fuel cell vehicle and hybrid vehicle. Represented on a logarithmic scale, the results emphasize the leading role of two organizations (Mitsubishi and International Fuel Cell) in the 1980s, and the rapid growth of patent activity by Honda and Toyota in the 1990s. Moreover the evolution of the entropy of the distribution of patents among organizations H(Y) and of the average conditional entropy of all technologies H(Y/X) emphasizes that competition is increasing at the level of the industry as a whole and at the level of each individual technology. In other words both technological variety and organizational competition have increased steadily since the early nineties, suggesting that premature lock-in is unlikely to occur.

Cumulative number of patents in all propulsion technologies per firm and entropy statistics (Frenken and al., 2004)

Legend: GM=General Motors; Mitsu =Mitsubishi; DC=DaimlerChrysler; APC = Air Products and Chemicals; IFC = International Fuel Cells). (d) Entropy of firm distribution at the industry and propulsion technology level.





- NOx pollution control technologies (Popp, 2004)

Popp (2004) compare the results obtained with different methodologies of research and different databases. In the following figure, Popp (2004) present four time series for US NOx post-combustion patents:

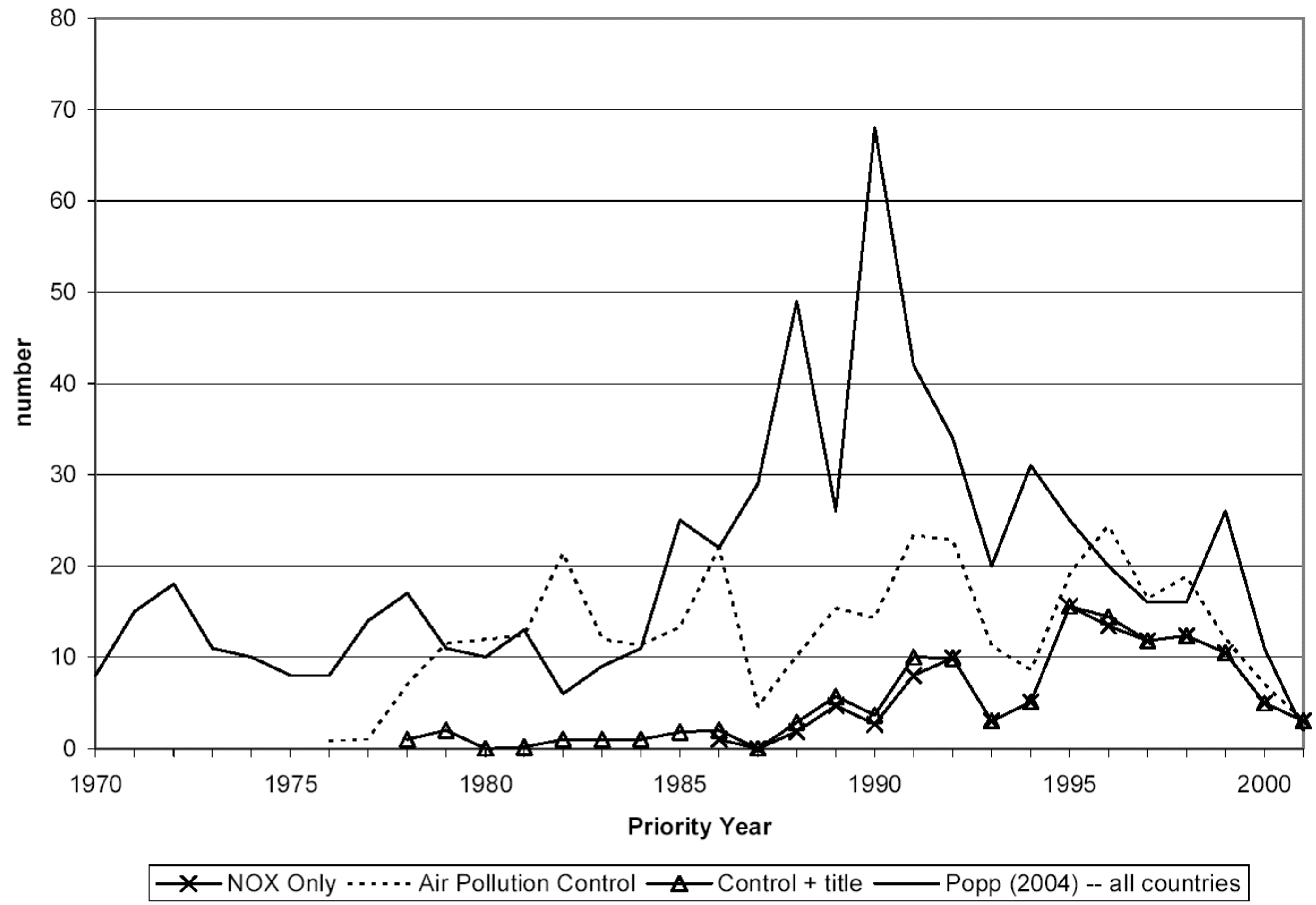
- "NOx only" series include relevant patents taken from the Triadic patent Family database and identified by IPC classifications directcly related to NOx control.
- "Popp (2004)" series include patents identified using ECLA classifications from the EPO's website.
- "Air pollution control" includes in addition to the patents in "NOx only" general air pollution patents.
- "Control + title" includes in addition to "NOx Only"general air pollution patents that also have relevant keywords in the title.

The most striking thing to note is that the counts from a single patent office ("Popp 2004") are nearly always greater than the counts taken from the TPF database. The exception is for the time series including general US air pollution control patents, suggesting that such a search is too broad and erroneously picks up other types of air pollution control patents. We can observe that, even if the general trend is rather similar across series, the choice of the database and the identification strategy of patents strongly determine the results.

- The case of low emission vehicles (Oltra and Saint Jean, 2006)

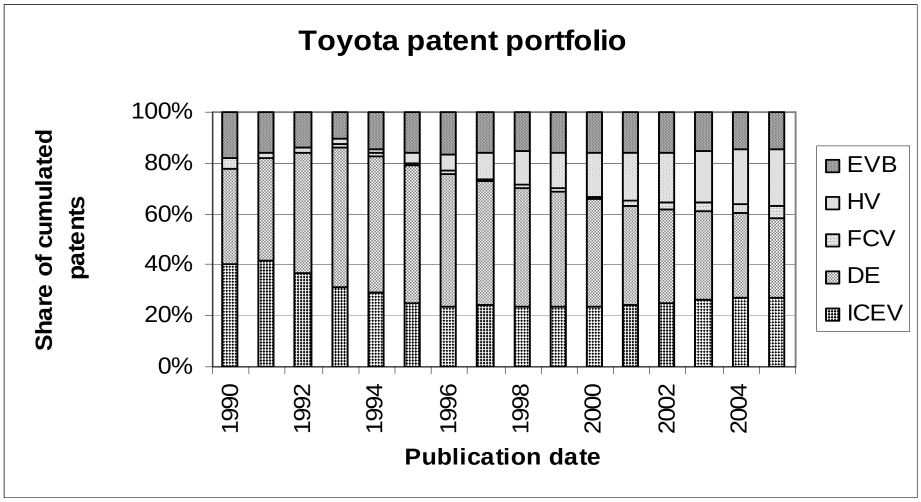
Oltra and Saint Jean (2006) study the evolution of the patent portfolios of car manufacturers in five engine technologies: internal combustion engine, diesel engine, electric battery, fuel cell and hybrid vehicles. For each technology, patent counts give insights on the evolution of firms' strategy of innovation. The results presented on the following figure show a significant diversification of the patent portfolios of the considered firms over the period [1990-2005). However it also shows that the dominant design, that is the internal combustion engine and the diesel technology, still represents the major part of the patenting activity of the three considered car manufacturers. The same result has been observed for the other firms of the sample, which suggests that the conventional engine is far from being played out since it still represents the core of innovative activities of car manufacturers.

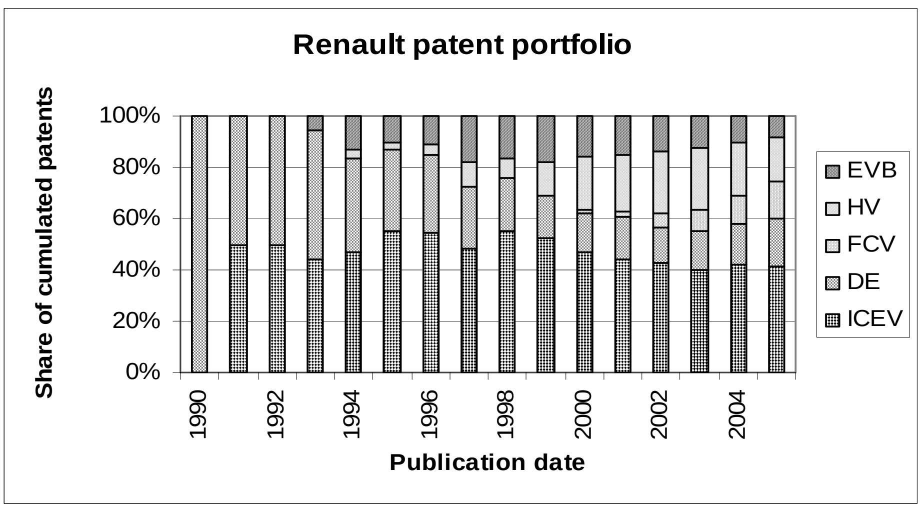
Figure 2 -- US NOX Post-combustion Patents

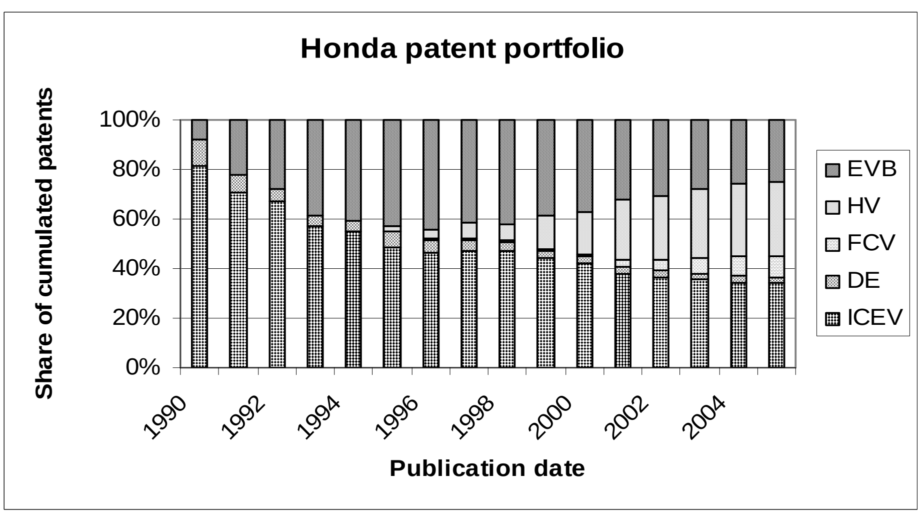


- Patent portfolios of car manufacturers (Oltra and Saint Jean, 2006)

Legend: EVB = Electric Battery vehicle; HV = Hybrid vehicle; FCV = Fuel cell vehicle; DE = diesel engine; ICEV is internal combustion engine vehicle;







Annex 1: Compendium of Patent Statistics, OECD, 2006.

Box 3.3. Identifying patents related to environmental technology

The patent search strategy for environmental technology is built on a combination of IPC codes and search strings. It is divided into six major sub-areas, essentially end-of-pipe technologies, which partly also reflect integrated environmental technologies. For instance, improved engines with reduced energy consumption and reduced emissions of harmful chemicals are considered as integrated technologies. However, specific environmental characteristics are often not directly visible in patent applications.

• ***Waste disposal**:* A62D3 + {"exhaust", "effluent", "flue", "combustion", "waste"} & {"gas", "gases", "smoke", "air"} ; [C02F,B01D53/(34,36)] ; [B09B,B23G] ; G21F9
• ***Recycling**:* {"waste", "refuse", "rubbish", "trash", "garbage", "scrap"} +[B03B7,B23D25/14,C10G1/10] ; [A23J1/16,A23K1/(06,08,10),B02C18/(40,44),B02C19/14,B03B9/(04,06),B05B1/28,B05B15/04,B24B55/12,B27B33/20,B29B17,B30B9/32,B65D(65/46,81/36),B65H73,C04B7/(24,26,28),C04B11/26,C04B18,C05F(5/,7/,9/),C08J(11/,17/),C10L5/(46,48),C10G(19/08,17/10,21/28,25/12),C10M175,C11B13,C11D19,C12F3/(04,08),C12P7/08,(C12S3NOTC12S3/2*),C14C3/32,C22B(7/,19/28,19/30,25/06),C23F1/46,C23G1/36,C25F7/02,C25D21/(16,18,2*),D01C5,D01G11,D01F13,D06L1/10,D06B9/6,D21B1/08,D21B1/(10,32),D21C5/02,D21H(17/01,11/14),B65D90/(24,28,30),B67D5/378,C08L89/(04,06),F17D5/(04,06),G03C11/24
• ***Air cleaning technologies***: [B03C3,A62D3,B01D(45,46,47,49,50,51,53)] + {"flue", "effluent", "exhaust", "combustion", "waste} & {"gas", "gases", "smoke", "air"} ; [B01D53/(34,36),B24B55/(06,08,10)B28B17/04,B28D7/02,B25D17/(14,16,18),B65G69/18,C09K3/22,C10L10/02,D01H11,C21B7/22,C21C5/(38/40),E21F5,F01N3/(08,1*,2*,3*),F02M27/02,F23B5,F23C9/06,F27B1/18,F01N9]
• ***Water cleaning technologies**:*
[B63B(29/16,35/32),B63J4,C09K3/32,C02F(1/,3/,7/,9/,11/),(E02B15 NOT E02B15/02),E03B3
•***Noise protection**:* [B25D17/(11,12),E01F8,E03D9/14,(E04B1/8* NOT E04B1/80),E04B1/90,E04F15/20,E06B5/20,F01N(1/,7/02,7/04),F01B31/16,F02B77/13,F02C7/45,F02M35/(12,14),F42D5/055,G10K11/16,F16L55/033]&{"sound","noise"};[B60R13/08,B64F1/26,E01B19,E01C1,F02K1/(34,44),F42D5/05,F01p11/12,F02C7/(04,24), F02K1/46,F16K47/02,F16L55/02] & {"absorb*", "reduc*", "abate*", "barrier", "prevent*", "deaden*", "dampen*, "anti"} ; {"sound", "noise"} & {"absorb*", "reduc*", "abate*", "barrier", "prevent*", "deaden*", "dampen*, "anti"} ; {"silencer"} NOT F01N ; {"sound", "noise"} & {"absorb*", "reduc*", "abate*", "barrier", "prevent*", "deaden*", "dampen*, "anti"} NOT[F41,G01,H01,H02,H03,H04,H05]
•***Environmental monitoring**:* G01N ; {"toxi*","pollu*","contamin*","monitor*"} & {"waters","water","air","airs","atmos*","soil","soils"};{"waters","water","air","airs","atmos*","soil","soils"}&{"effluent","flue","exhaust","waste"};{"environment*"}&{"waters","water","air","airs","atmos*","soil","soils"};{"waters","water","air","airs","atmos*","soil","soils"} & {"analys*","measure*"};(G01H NOT G01H1) & {"Noise"} ; [G01N33/(18,24)];[G01T(1,7)] NOT [G01T1/(29,3*,40)]
For further details
International Patent Classification, 7th edition, 2000: www.wipo.int/classifications/fulltext/new_ipc/index.htm;
Reformed IPC, 8th edition, 2006: http://www.wipo.int/classifications/ipc/ipc8.

References

Arundel, A. (2000) Patents the Viagra of Innovation Policy, internal report for project "Innovation Policy in a Knowledge-Based Economy" commissioned by the European Commission.

Breschi S., Lissoni F. and Malerla F., (2003) Knowledge-relatedness in firm technological diversification, *Research Policy,* Vol.32, pp.69-87.

Brouwer E. and Kleinknecht A. (1999), "Innovative output and firms propensity to patent. An empirical investigation", *Research Policy,* Vol.28, pp.615-624.

Crépon B., E. Duguet et J.Mairesse (2000), "Mesurer le rendement de l'innovation" *Economie et Statistique,* n° 334, pp.65-78.

De Vries, F., and C. Withagen (2005) Innovation and Environmental Stringency: The Case of Sulfur Dioxide Abatement, CentER discussion paper 2005-18, Tilburg.

Engelsman E.C. and Van Raan A.F.J. (1991), "Mapping of Technology, A First Exploration of Knowledge Diffusion Amongst Fields of Technology", *Report to the Netherlands Ministry of Economic Affairs* (1991) published in the Policy Studies on Technology and Economy (BTE) Series, Nr. 15 (ISSN 0923-3164), The Hague.

Engelsman E.C. and Van Raan A.F.J. (1994), "A patent-based cartography of technology", R*esearch Policy,* Vol.23(1), pp.1-26.

Eurostat (2006) Statistics in Focus. Science and Technology, 16/2006, Eurostat, Luxemburg.

Frenken K., Hekkert M. and Godfroij P. (2004) 'R&D portfolios in environmentally friendly automotive propulsion: variety, competition and policy implications', *Technological Forecasting and Social Change*, vol.71, pp. 485-507.

Jaffe, A.B., and K. Palmer (1997) 'Environmental Regulation and Innovation. A Panel Data Study', *Review of Economics and Statistics* 79: 610-619.

Griliches, Z (1990), Patent Statistics as Economic Indicators: A Survey, *Journal of Economic Literature* 28: 1661-1707.

Johnson D.K.N. (2002), "The OECD Technology Concordance (OTC): Patents by industry of manufacture and sector of use", OECD, DSTI, Working Paper n°2002/5.

Johnstone, N. (2005) Environmental Policy, Technological Innovation and Patent Activity: Initial Empirical Results and Project Progress, report of Working Party on National Environmental Policy, June 16-17, 2005, Washington D.C.

Kammen, D.M., and G.F. Nemet (2005) Real Numbers. Reversing the incredible shrinking energy R&D budget, *Issues in Science and Technology,* Fall 2005, 81-88.

Kleinknecht A., K. van Montfort, E. Brouwer (2002) 'The non-trivial choice between innovation indicators', *Economics of Innovation and New Technologies*, Vol. 11(2): 109 – 121.

Lanjouw, J.O., and A. Mody (1996) 'Innovation and the International Diffusion of Environmentally Responsive Technology', *Research Policy* 25: 549-571.

Marinova, D. and McAleer, M. (2003a) 'Environmental Technology Strengths: International Rankings based on US patent data', http://ideas.repec.org/p/tky/fseres/2003cf204.html

Marinova, D. and McAleer, M. (2003b) 'Modelling trends and volatility in ecological patents in the USA', *Environmental Modelling and Software* 18:195-203.

Marinova, D. and McAleer, M. (2003c) Nanotechnology Strength Indicators: International Rankings Based on US patents, *Nanotechnology* 14, R1-R7.

Nameroff T.J., Garant R.J., Albert M.B. (2004) 'Adoption of green chemistry: an analysis based on US patents', *Research Policy*, Vol.33, pp. 959-974.

Oltra, V., and M. Saint Jean (2006) Variety of technological trajectories in low emission vehicles (LEVs): a patent data analysis, paper presented at the International Schumpeter Society, Nice Sophia Antipolis, May 2006.

Oltra, V., and M. Saint Jean (2007) Incrementalism of environmental innovations *versus* paradigmatic changes: A comparative study of the automotive and chemical industries, paper for the 5th European Meeting on Applied Evolutionary Economics (EMAEE), Session on Environmental Innovations, 17-19 May 2007, Manchester.

Popp, D. (2001) "Pollution Control Innovations and the Clean Air Act of 1990," *NBER Working Paper #8593.*

Popp, D. (2003), 'Pollution Control Innovations and the Clean Air Act of 1990', *Journal of Policy Analysis and Management,* 93, 390-409.

Popp D. (2005), "Lessons from patents: using patents to measure technological change in environmental models", *Ecological Economics,* Vol.54, n°2, pp.2096226.

Popp, D. (2006), 'International Innovation and Diffusion of Air Pollution Control Technologies: The Effects of NO_X and SO_2 Regulation in the U.S., Japan and Germany', *Journal of Environmental Economics and Management*, 51, 46-71.

Taylor, M.R., E.S. Rubin and D.D. Hounshell (2003), 'Effect of government actions on technological innovations for SO_2 control', *Environmental Science and Technology*, 37, 4527-4534.

Verspagen, B. (2005) Mapping Technological Trajectories as Patent Citation Networks. A Study on the History of Fuel Cell Research, MERIT-Infonomics Research Memorandum Series 2005-020.

Yarime M. (2005), "Coevolution of Environmental Regulation and Innovation Network: The Development of Lead-Free Solders in the United States, Europe, and Japan" Paper presented at the Fourth European Meeting on Applied Evolutionary Economics, Utrecht, The Netherlands, May 19-21 (2005).