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Climate-friendly technologies in the mobile air-conditioning sector: A patent citation analysis

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Abstract

The development of climate-friendly technologies and its diffusion across countries is of key importance to slow climate change. This paper considers technologies in the mobile air-conditioning (MAC) sector which is a major contributor of fluorinated greenhouse gas emissions. Using patents as an indicator of innovations and patent citations as a proxy for knowledge flows the inducement of new environmental and non-environmental technologies and its diffusion within and across countries and within and across patent applicant- and firm-types is analyzed. We find that most environmental patents originate from Germany and the US and are filed by individuals rather than firms. Most knowledge flows take place within countries. Regarding cross-country flows most environmental knowledge diffuses from French and German patents, which is likely to be a result of regulatory activities in Europe and intensified research on environmentally benign MAC systems. Yet, this exchange of knowledge is not very intensive and stable, so that the impact of EU regulations on US and Japanese patenting behaviour remains fairly weak.

JEL Code: Q55, 033, 038, C21.
Keywords: Environmental innovation, patent, count data models.

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1. Introduction

The development of climate-friendly technologies and its diffusion across countries is of key importance to slow climate change. However, due to dual market failures investment in these technologies is limited (Jaffe et al., 2002): The first market failure is because of the public goods nature of knowledge which leads to underinvestment in R&D. External benefits arise because the inventor fails to account for the full value of social returns from R&D activities. The second market failure comes from the fact that resource prices do not reflect the true social costs of global warming with the result that there are insufficient incentives to reduce greenhouse gases. Unless there are ancillary benefits for inventors or users the market for climate-friendly technologies that reduce emissions will be limited. Yet, environmental and innovation policies can be an important driving force for investment. As these typically differ between countries the development and diffusion of new technologies proceedes unevenly.

The main focus of today's climate policies is on reducing carbon dioxide (CO_2). This is understandable, since CO_2 is by far the biggest contributor to the human-made greenhouse effect. However, there are other potent greenhouse gases which are less important in terms of absolute volume but have a high global warming potential and thereby represent a significant threat to the global climate when released. Among those other greenhouse gases are the fluorinated gases (F-gases) which are primarily used as refrigerants in air-conditioning and refrigeration equipment, as propellants for sprays, as insulating material or for fire extinguishers. F-gases currently cause about 2% of the greenhouse effect whereby their share is expected to rise to up to 6% by 2050. Relative to CO_2, the global warming potential of some of these gases is higher by a factor of several thousands. Recent policy efforts aim to reduce emissions by technical means (e.g. the use of leak tight systems), the replacement of gases with a high global warming potential by more benevolent alternatives and the use of alternative systems or equipment.

This paper considers technologies in the mobile air-conditioning sector which accounts for about a third of total greenhouse gas emissions from the air-conditioning and refrigeration sector. It attempts to link two main aspects of technological change, the inducement of new innovations and the diffusion of technologies. Such diffusion processes depend on country specificities (e.g. the size of the home market, the geographical distance between countries) and on sector specificities (e.g. the role of suppliers in the supply chain). We use patents from the World Patent Statistics Database (PATSTAT) as indicator of innovations and patent citations as a proxy for knowledge flows.

There's a growing literature dealing not only with induced innovations but also with the international diffusion of environmental technologies (see Popp, Newell and Jaffe, 2009 for a recent review). Lanjouw and Mody (1996) presented the first empirical evidence based on patent data from Japan, Germany, the US, and 14 developing countries that environmental technologies diffuse internationally. They identify the leader in environmental patenting and find that significant transfers occur from developed to developing countries, but that existing technologies need to be adapted to local conditions by additional R&D. For the US, Japan and Germany most patents are domestic patents. However, for some technologies (e.g. vehicle air emissions) the influence of foreign countries is more pronounced suggesting that regulations in one country can spur innovations by firms in other countries. Diffusion is conceptualized by looking at patent families and their variability over time as they give an indication of which patents are not only worth to be patented at home but also in other countries. Alternatively, some papers distinguish between the home country of the inventor and the source country of the filed patent. A more recent study is Dechezlepretre et al. (2010) focusing on 13 climate change-mitigation technologies. They suggest that innovation was mostly driven by energy prices until 1990, but that environmental policies and climate policies have induced more innovation more recently (particularly in Germany and Japan).

The paper also indicates that international technology transfers mostly occur between developed countries but that north-south transfers of climate technologies are growing more rapidly. Dekker et al. (2010) focus on the filing of patents at home and abroad for SO_2 abatement technologies before and after the signing of international agreements. Results indicate that international agreements (and not solely local regulations) reduce investment uncertainty for inventing firms and provide an additional signal about new opportunities for profitable investments and technology transfers. However, all these studies measure market-driven technology transfer and the private benefits that result for the inventor (and possibly the technology-using firms). By contrast, we are primarily interested in knowledge spillovers that may affect the productivity of R&D elsewhere without being mediated through the market. These externalities are commonly approximated through patent citations (Jaffe et al., 1993; Peri, 2005). Popp (2006) pioneered this approach for eco-innovations in his study on air pollution control technologies. He finds that earlier foreign patents are an important building block for domestic inventors and that the international transfer of technology occurs indirectly rather than directly through the purchase of equipment. More recent studies also indicate that spillovers between countries have a significantly positive impact on further environmental innovations (Verdolini and Galeotti, 2009 on energy-efficient technologies; Garrone, Piscitello and Wang, 2010 on renewable energy technologies).

Our paper follows this earlier work but is also different in the following aspects: Firstly, our focus is on the differences between environmental patents and other patents with respect to innovation and diffusion. Prior work has looked at (groups of) environmental technologies only. Secondly, we distinguish between the absolute amount and the relative intensity of spillovers. Finally, we do not only focus on spillovers across countries, but equally on spillovers across applicant- and firm-types (or “sectors”) to find out whether some sectors are more receptive to spillovers than others.

Section 2 provides some background information on the mobile air-conditioning sector, its technologies and the regulatory environment in different countries and regions. Section 3 presents the data and the way innovations and spillovers are measured. The various models and their results are discussed in section 4. Section 5 concludes.

2. The mobile air-conditioning sector: Technologies and regulations

Mobile air-conditioning (MAC) systems are designed to provide comfort to vehicle occupants during hot, warm or humid weather and to ensure safe driving during these conditions. MAC systems were first developed in 1939 by the American Packard Motor Car Company. Mass production started in the early 1960s in the US and in the 1970s in Japan and other Asian countries. In Europe where weather conditions all less extreme the number of air-conditioned cars only started to significantly increase much later, in the early to mid 1990s. Following the rapid growth in the late 1990s the air-conditioning penetration rates of new cars in Europe reached about 72% in 2004 and 82% in 2010. The penetration rate remains stagnant in North America at 97% and Japan at 98%, but it has also increased in China (2004: 84%; 2010: 94%) and in the rest of the world (2004: 46%; 2010: 57%) (Daly, 2006). As a consequence, there is a total stock of more than 400 million MAC systems worldwide.

A current basic MAC system consists of an engine-powered compressor activated by an electrical clutch compressing and heating up a refrigerant. Heat is rejected by a condenser heat exchanger to outside air and the refrigerant leaves the condenser in liquid phase. The refrigerant is then directed through various control valves and a fluid reservoir to an expansion valve. The expansion valve sprays the refrigerant into an evaporator coil and the refrigerant vaporises and cools the vehicle interior. MAC systems are either manually controlled, semi-automatic or automatic climate control systems (including on-board diagnostics, multiplex wiring and in-car temperature and humidity sensors).

Companies producing MAC systems or parts thereof are mostly focused on automakers (original equipment manufacturers, OEMs) and part of the automotive supply chain.[1] Worldwide there are about 15 major carmakers operating in oligopolistic market structures and another 20 to 25 companies operating in small market niches. The major OEMs operate globally and have increasingly created globalised production and sales networks to be close to their (changing) markets (Meißner and Jürgens, 2007). This includes daughter companies abroad, partnerships and joint ventures with other carmakers or supplier firms. The supply chain has become more differentiated along major production and service functions (e.g. R&D, finance, logistics). Moreover, there has been a trend toward outsourcing former OEM activities which has led to an increasing importance of the suppliers. The direct suppliers have by now become large global firms, which are either specialized in complex systems (modules), or integrators of several simpler subsystems. These new suppliers have substantial responsibility in the design and engineering of systems and coordinate the supply chain necessary for their manufacturing and assembly. In the MAC industry there are six global players which act as integrator of AC systems and directly compete with each other: Behr (GER), Denso (JP), Valeo/Zexel (FR), Delphi (US), Calsonic Kansei (JP) and Visteon (US). Except for Delphi which earns 5% of their operating revenue in the market for MAC, these companies earn between 20% and 40% (according to company annual reports). In addition, there are several components specialists (e.g. Sanden (JP) and Toyota industries (JP) for (MAC) compressors or Halla Climate (KR) for AC controls). Many of the system integrators are strongly focused on a few OEMs. Behr primarily supplies the German carmakers BMW and Mercedes, Denso is in close relationship with Toyota, Delphi is a former daughter company of GM, Visteon primarily supplies Ford and Calsonic Kansei makes most of its business with Nissan.

The air-conditioning and refrigeration sector accounts for about 70% of current global greenhouse gas emissions from chlorofluorocarbons (CFC), halogenated fluorocarbons (HCFCs) and so-called F-gases (fluorinated greenhouse gases) (Gschrey and Schwarz, 2009). Greenhouse gas emissions from mobile air-conditioning represent about a third of total greenhouse gas emissions from the sector and can be classified as direct or indirect emissions. Direct emissions result from refrigerant leaks in untight equipment, improper refrigerant handling during maintenance, disposal, etc or occur during accidents. Indirect emissions result from the energy consumption of operating the air-conditioning unit. About 70% of total emissions from mobile air-conditioning are direct emissions.

The sector is facing important regulatory challenges to minimize direct emissions from AC-R equipment. Ozone-depleting substances have already been addressed since 1987 in the well-known Montreal Protocol that has been ratified by 196 states. The protocol stipulates the fairly rapid decrease in the production and consumption of the most active CFCs until 1996. For the less active HCFCs the phase-out started only in 1996 and will continue until 2030.

In 2000, the European Commission mandated an accelerated phaseout of HCFCs in the production of new equipment by the year 2001/2004 in regulation 2037/2000/EC. Consequently, an additional stimulus was given to provide non-ozone-depleting solutions whether HFCs or other substances like natural refrigerants. In 2003, the European commission proposed also a regulation on fluorinated gases under the European climate change program. The regulation on F-gases (842/2006/EC) was adopted in 2006 and aims to reduce emissions from these gases via technical obligations (minimum requirements for leak control and refrigerant recovery), training requirements, product labelling and reporting obligations for industry. Moreover, the European Union has put into effect a separate

[1] This is less so for component specialists producing multiple-use products like valves which may be used in MAC systems or in other applications.

Directive relating to emissions from air-conditioning systems of motor vehicles (2006/40/EC). The original proposal was also launched in 2003. The European Institutions went then through a negotiation process that led to the adoption of the final text in May 2006. The EU-Directive issues i.a. a ban on F-gases with a global warming potential (GWP) of more than 150 for new car models from 2011. R134a, a widespread HFC refrigerant in mobile air-conditioning systems with a GWP of 1410, is thus covered by this measure. However, R152, which has a global warming potential of 120, could still be used after that date. R744 (CO_2) with a GWP of 1 thus emerged as the most likely alternative to current systems. From 2017 there will be a ban on F-gases with GWP of more than 150 for all cars. These two regulations were mostly supported by Member States that had already previously (since about 1998) followed a restrictive HFC policy, e.g. via stricter containment rules (Sweden, the Netherlands, Germany), the ban of HFC in certain equipments (Austria, Denmark, Switzerland, Luxembourg), financial support for non-HFC technologies (especially Germany) and taxes or deposits on HFC import and production (Norway, Denmark, Sweden). R&D activities to use other refrigerants than R134a were initiated in the mid-1990s. The EU financed RACE-project (1994-1997) investigated the suitability of the natural refrigerants CO^2 for mobile air-conditioning and highlighted what was needed to use it on a wider scale. Most of the major European car OEMs and system and component suppliers participated in the project. These research activities were then picked up before and after the ratification of regulation 2006/40/EC.

Compared to Europe the phaseout of CFCc was less rapid in the US (by 1.1.2000) and is only scheduled for 2015 for substances with a ozone-depletion potential of less than 0.2 (including HCFCs). The US has issued regulations under the Clean Air Act to minimize the emissions of refrigerant by maximizing the recovery and recycling of such substances during the service, repair or disposable of ACR equipment. In 1994, the US Environmental Protection Agency established the Significant New Alternative Program (SNAP) to review alternatives to ozone-depleting substances in motor vehicle air-conditioning. The EPA regularly publishes a list with acceptable and unacceptable replacements based on information from manufacturers and independent testing laboratories. CO_2 has been proposed as an alternative subject to use conditions. The final rule to list CO_2 as an alternative is still pending. Thus, compared to Europe few regulatory actions (like bans, leak requirements) have been taken to reduce direct refrigerant emissions damaging the climate and to favour the use of natural refrigerants. Instead, a number of partnerships with industry have been established to voluntarily reduce emissions. In 1998, the American Society of Automotive Engineers, the mobile air-conditioning society worldwide, and the US Environmental Protection Agency formed a voluntary global partnership to reduce the climate impacts of mobile air-conditioning. The partnership includes members from Australia, Canada, Europe and Japan. In 2004, the partnership announced the improve mobile air-conditioning 30/50 project with the goal to reduce mobile air-conditioning fuel consumption by at least 30% and cut refrigerant emissions by 50%. In 2005, the partnership has also standardized the certification of low-leak mobile air-conditioning systems and harmonized the testing and engineering standards.

In Japan there are similar regulations to recover and destroy used refrigerants and to recycle equipment. More direct regulatory actions for natural refrigerants are not noticeable. However, the government has set additional tax incentives to increase energy efficiency in the ACR sector after the Kyoto Protocol has been adopted and promotes R&D on natural refrigerants.

On a global scale, mobile air-conditioning summits have been organized since 2003 and promoted the exchange of research and the coordination of regulatory actions across countries. Apart from the global partnership I-MAC mentioned above there have also been cooperative research programs since 2001 on alternative refrigerants (ARCRP I and II).

Direct greenhouse gas emissions can in principle be reduced by improvements in the current R134a-systems or by the replacement of R134a with more benevolent refrigerants (especially natural refrigerants, like CO_2). Improvements in R134a-systems include mostly measures to prevent or minimize refrigerant leaks. A reduction of leaks may be achieved via improved materials, redesign of components (e.g. use of O-rings, shaft seals, brazed joints) and leakage detectors. Another option is to lower refrigerant charge per unit of cooling capacity (e.g. by using microchannel- type heat exchangers, optimized piping systems and a miniaturization of components). Moreover, it is important to recover refrigerant during service and at the end-of-life of the vehicle. The use of non-HFC refrigerants often requires changes in cooling system design and a modification of components. This is particularly true for ACR systems operating with CO_2 as a refrigerant. CO_2 has a low critical temperature and, consequently, a low latent heat of evaporation. Therefore, they operate in the transcritical range and use an additional gas cooler (to absorb additional heat) and a second internal heat exchanger (to lower the temperature of the refrigerant before entering the expansion valve and the evaporator). CO_2-systems also operate under a higher pressure than conventional systems which requires more robust components (special CO_2 valves, heat exchangers with a smaller diameter etc.).
Indirect abatement measures related to energy/fuel efficiency improvements include more efficient compressors with variable capacity control, power saving control devices, the use of recirculated air or a number of system-related measures. However, it is unclear whether these innovations amount to net environmental benefits as they may also give rise to rebound effects by making air-conditioned driving more attractive than previously. Therefore, model results in section 4 only treat direct abatement measures as environmental technologies.
Other recent innovation activities are related to the refinement of automatic or semi-automatic MAC systems which are more sophisticated and complex (About Publishing Ltd, 2004). Many cars now have multi-zone controls which allow rear seat passengers to adjust their localized climate control. An additional challenge for manufacturers is that air-conditioning systems are increasingly being expected not only to cool vehicle interiors but also have demisting, air cleaning and circulation properties. These features are also attractive for customers driving in moderate and cooler climates.

3. Data, specification and measurement

Patents are widely used in the literature to measure knowledge spillovers. A patent assigns the right to the inventor to exclude others from the unauthorized use of the disclosed invention for a predetermined period of time. For a patent to be granted, the invention must be novel, non-trivial, and useful (i.e. economically valuable). A patent contains information about the invention, the inventor, the assignee, relevant technology classes according to the international patent classification (IPC), and the technological antecedents of the invention, including citations to previous patents. The applicant has a legal duty to disclose any knowledge of the prior art in order for the scope of the property rights to be properly delimited.[2] There is an in-built incentive to get the number of citations right, since extraneous citations would only restrict the scope of the patent and excluded (but appropriate) citations can expose a patent applicant to patent infringement lawsuits or sanctions. The previous patents cited by a new patent are an indicator of previous knowledge upon which the inventor builds. Therefore, backward patents citations are useful to track the influence of past inventions across time and geographic and technological boundaries. They allow to measure the direction and intensity of knowledge flows. Inversely, cited patents contain information that is useful for others and have been shown to be higher economic value than non-cited patents (Harhoff, 1999).

[2] The ultimate decision on which citations to include rests with the patent examiner, however.

Patent and patent citation data are subject to certain limitations. Most importantly, not all inventions are patented. Instead of going through a costly and sometimes lengthy patenting procedure some firms prefer to keep their inventions secret or realize lead times vis-à-vis their competitors. Similarly, the part of technology that is non-codifiable or tacit will necessarily be missed by patents. Unfortunately, we have little idea of the extent to which patents are representative of the wider universe of inventions, since there's no systematic data on inventions that are not patented. For the same reason, we cannot capture knowledge diffusion that does not culminate in new patented innovations (e.g. diffusion via reverse engineering, informal contacts). The results presented here should thus be considered a lower bound on the amount of knowledge diffusion taking place.

Another limitation is that some citations occur where there is no spillover. Jaffe, Trajtenberg and Fogarty (2000) interviewed approximately 160 patent owners with questions about their inventions, the relationship of their patents to the patents they cited, as well as the relationship to other patents that were technologically similar to the cited patents but are not cited. The study concludes that about half of the citations correspond to some knowledge flows from the cited patents to the citing patents, and the other half does not seem to correspond to any kind of knowledge flow between them. This confirms that citations do contain important information about knowledge spillovers, but with a substantial amount of noise.

A third limitation is that we have no information on whether learning about other patents involves costs. Therefore, we cannot derive the benefits net of the learning costs that the patent applicant may have incurred. Finally, citation behaviour differs across countries and time which may be a result of country-specific institutional or legal practice. Therefore, we have to control for these effects (see section 4 below).

For patents and patent citations, we use the World Patent Statistics Database (PATSTAT, version April 2007), recently constructed by the European Patent Office and the OECD[3]. PATSTAT is unique in that it covers more than 80 patent offices and contains over 60 million patent documents. PATSTAT includes information on the title and abstract of an application, the filing and publication dates of an application, the names and origin of the inventors and applicants, and the technological domain of an application according to the international patent classification (IPC). In addition, PATSTAT contains harmonized citation data (cited and citing patents).

For the purpose of this study, we first extract all patents from the following IPC classes:

- B60H 1/00 (arrangements or adaptations of heating, cooling, ventilating, or other air treating devices specially for passenger or goods spaces of vehicles),
- F25B (refrigeration machines, plants, or systems; combined heating and refrigeration systems; heat pump systems),
- F04B (positive displacement machines for liquids; pumps) and
- F04C (rotary-piston, or oscillating piston, positive displacement machines for liquids; rotary piston, or oscillating piston, positive displacement pumps).

Secondly, we isolate patents related to mobile air-conditioning in passenger vehicles using a number of well-defined key words applied to the patent abstracts (see De Vries and Withagen, 2005 for a similar approach). This includes words like "climate control", "HVAC", or "conditioning" to exclude pure ventilating or heating devices. For classes F04B and F04C we additionally use words like "compressor", "compression" and "refrigera*", "conditioning" to include refrigerant compressors, which are the heart of refrigeration and air conditioning systems.[4] Out of 86,712 initial patents (with 12,221 from B60H 1/00) we are left with 10,076

[3] See http://www.epo.org/patents/patent-information/raw-data/test/product-14-24.html

[4] To exclude unrelated patents left in the sample we conduct further cross-checks. For example, the word "compression" is not well defined as it may be used both in refrigeration and air-conditioning and audio and video technology. The latter patents are excluded using further key words.

patents. As expected about 75% belong to the most well suited class B60H 1/00. This sample of around 10,000 MAC patents includes 82% firm patents and 18% other patents (mostly single inventors, but also some patents from research institutes, universities and government institutions). We further subdivide firms into three classes: carmakers (OEMs) (21% of all firm patents), integrated MAC system suppliers (38%) and other firms (40%).
Thirdly, we examine on this basis whether patents contribute to environmental protection or resource conservation. For this purpose, we first apply keyword search to the abstracts of the 10.076 patents. Around 300 keywords are used based on a review of the literature on emission abatement measures in MAC (e.g. IPCC/TEAP, 2005, Umweltbundesamt, 2004). The most prominent keywords include "seal", "efficien*" or "heat pump" (see table 1). As a result, we are left with 3,230 potential eco-patents where each patent contains at least one keyword. Then, we read the abstracts of these potential eco-patents to determine the likely eco-patents. This is important since some keywords are fairly imprecise or ambiguous (e.g. "efficien*", see again table 1). At the end, only 50% (or 1,685) of the potential eco-patents are classified as likely eco-patents. These remaining eco-patents are further classified according to the kind of environmental improvement. About two thirds lead to a reduction of indirect greenhouse gas emissions via reduced energy or fuel consumption or increased fuel efficiency. This includes i.a. measures to improve capacity control, AC units that are combined with heat pumps or measures to use solar energy. About one in six of all environmental patents reduce direct emissions without an (obvious) change of refrigerant. These are primarily measures to improve the leak tightness of conventional air-conditioning units and to avoid leakage. About 10% of the eco-patents reduce direct emissions by changing to a natural refrigerant (mostly CO_2). Another 4% reduce both direct and indirect emissions (e.g. CO_2 systems that are particular energy-efficient). The remaining eco-patents include all other environmental improvements. The main focus of this article is on those (slightly over 500) eco-patents that reduce direct greenhouse gas emissions (relative to all other patents).[5]
Patent citation data are extracted for all 10.076 patents related to mobile air-conditioning. To these reference patents we merge all backward citations, including the needed information (publication year, country etc.) contained in the cited patents. 42% of the reference patents do not contain citations and are subsequently dropped for the citation analysis. Still, the number of cited patents is originally much higher than the number of citing patents. However, 54% of the cited patents do not show up in the reference data set of the citing patents. Excluding these patents allows to alleviate a self-selection bias that results from the fact that any cited patents is not only cited from patents included in the above-mentioned IPC classes, but equally from other (unknown) patents. Therefore, the small subset restricts the focus on the population of citing and cited mobile air-conditioning patents.[6] Alternatively, we also run regressions with the larger sample to check for robustness.[7] We eliminate all observations with the same firm name or the firm name of the parent company, since self-citations are not spillovers.[8] Their number is limited, however, less than 1% of the citation pairs.

[5] Indirect abatement measures are not only more difficult to delimit and classify. Their environmental effects are also more dubious.
[6] This approach is different from Popp (2006) who creates an artificial pool of potentially cited patents by considering only patents from the most cited US patent classification for each of the pollution technologies considered.
[7] Results are broadly similar and not reported here.
[8] There are no self-citations among patents of individuals.

Tab. 1: Most important environmental keywords before and after reading of the patent abstracts

environmental keywords	occurrence before reading	environmental keywords	occurrence in final sample
seal	438	efficien*	284
efficien*	401	seal	225
Defrost	294	Heat pump	198
Heat pump	210	variable displacement	157
accumulator	180	solar	92
solar	175	variable capacity	78
variable displacement	160	Defrost	75
leak	116	leak	72
Waste heat	93	Waste heat	68
variable capacity	82	gas cooler	63
recirculated air	68	carbon dioxide	60
carbon dioxide	66	accumulator	56
gas cooler	66	CO2	53
temperature sensors	65	capacity control	44
vehicle seat	58	vehicle seat	42
CO2	58	power consumption	41
safety	58	solenoid valve	31
solenoid valve	55	temperature sensors	31
capacity control	48	safety	30

Source: PATSTAT, own calculations

The final data set is essentially organized as an origin-destination table where the origin is the cited patent and the destination is the citing patent. This basic data set is then extended with cells representing countries, years, firm type as well as if the cited or citing patent is an environmental patent.

4. Models and results

In the following we use a number of models that test the relative influence and significance of certain independent variables while controlling for other factors. Descriptive statistics are presented along with the models. Given our interest in the number of patents or the number of citations count models are estimated to depict the development and diffusion of MAC technologies. Since our dependent variable is a nonnegative count variable, we use a negative binomial regression model. The advantage of the negative binomial model is that it accounts for the over-dispersion in the data and allows to include in the analysis also those observations for which the dependent variable equals zero over the sample. This is important, since for many pairs of citation flows there is no citation link in the data. Alternatively, we also tested zero inflated models, but did not find any clear sign based on the Vuong test that these models should be used.

Table 2: Development of environmental and non-environmental technologies

	Variable refers to all patents		**Variable refers to additional effect of environmental patents**	
	Coef.	**Std. Err.**	**Coef.**	**Std. Err.**
ptypepriv	reference		reference	
ptypefirmOEM	.923766***	.1109811	-1.09364	.2381974
ptypefirmMAC	.9098441***	.1087906	-.558754	.2197271
ptypefirmOTH	1.587108***	.1081099	-.7580361	.2192035
ptypeother	-2.463281***	.1765301	-.9325175	.5629166
pGER	reference		reference	
pUS	-.6086097***	.1174828	.0470315	.2259738
pRoW	-2.216261***	.1035195	-1.186807	.2692192
pJP	-.1856067	.11433	-.4055508	.2216426
pFR	-.3103629***	.1201407	-.7187677	.238183
pYear06	.5132622**	.2366255	-1.778437	.3653154
pYear05	.6911196***	.2371858	-1.793376	.35392
pYear04	.8822996***	.2373139	-2.010192	.3577062
pYear03	.8675045***	.2370788	-1.919036	.3639878
pYear02	.7686256***	.2386057	-2.032187	.3806866
pYear01	.7043915***	.2374049	-1.782324	.3723678
pYear00	reference		reference	
pYear99	.3798659	.2385464	-1.575693	.3882151
pYear98	.3472499	.2388827	-1.947137	.4017297
pYear97	.037174	.2443925	-1.626762	.4216618
pYear96	-.3306819	.2451981	-1.906777	.4638712
pYear95	-.1927649	.2469534	-1.997902	.4431546
pYear94	.01625	.2469174	-2.570649	.4866401
pYear93	-.2494297	.2492967	-1.729975	.4467468
pYear92	-.2667642	.2514805	-1.791534	.4736966
pYear91	-.3505141	.2534868	-3.21557	.6886298
pYear90	-.2819121	.2517764	-3.629961	.7990405
pYearBefore	-.4407531**	.1577023	-2.328046	.2380496
_cons	-21.70841	.1655077		
gdpcurrhead	(exposure)			
alpha	.9343853	.0588105		

Negative binomial regression; number of observations: 2450
Log likelihood= -3374.8945; LH-ratio test alpha=0: chibar2(01) = 4143.61 Prob>=chibar2 = 0.000
Dependant variable: number of patents; *, ** and *** indicate significance at 1%, 5% and 10% level
ptypepriv = individuals, ptypefirmOEM = carmakers; ptypefirmMAC = MAC suppliers; ptypefirmOTH = other firms; ptypeother = other applicants;
GER = Germany; US = United States ; FR = France; JP = Japan; RoW = rest of the world

As a starting point, we focus on technology development with respect to years, countries, applicant-/firm-types and environmental orientation. This model does not include any citation flows. The dependent variable is simply the count of patents. All the following models include citation flows and consider potential spillovers in MAC technologies. We run separate models for country flows and flows between applicant/firm types distinguishing between technologies that reduce direct greenhouse gas emissions and other technologies. Moreover, we present separate regressions for absolute citation flows and for the intensity of flows. The dependent variable is the number of backward citations flowing from one subcategory (firmtype, country etc.) to another subcategory. All results should be interpreted in relation to the reference category.

The first model related to the development of environmental and non-environmental technologies over time is presented in table 2. To account for the different levels of economic development across countries GDP per capita in current prices is included as an exposure variable. As regressors we use the above-mentioned categories, namely:

- Applicant-/firm-type, with ptypepriv for private applicants, ptypefirmOEM for carmakers, ptypefirmMAC for integrated MAC system suppliers, ptypefirmOTH for other firms and ptypeother for other applicants (e.g. universities).
- Countries, with pGER for Germany, pUS for the United States, pJP for Japan, pFR for France and pRoW for the rest of the world.
- Years, including single years between 1990 and 2006 and all other years before 1990.

Regressors in the 4th column can be interpreted as the additional effect for environmental patents. The omitted reference categories are private applicants, Germany and the year 2000.

The number of patents is significantly influenced by firms relative to private applicants. The additional effect for environmental patents reveals that environmental patenting by individuals is relatively important.[9] Surprisingly, carmakers are the least active applicant type in environmental patents. This is even more so when considering only environmental patents based on natural refrigerants. In this case other applicants (like universities, public organizations) gain more importance in patenting. An obvious explanation is that public research plays an important role for the generation of environmental technologies. With respect to countries Germany plays the leading role in patenting followed by Japan (at the same level), France, the US and the rest of the world. For environmental patents US patents are about as important as German patents. They are less important, however, when considering only patents based on natural refrigerants. The distribution across publication years shows a rising trend in the number of patents (more patents after 2000 than before 2000) except for the last two years (since not all applied patents have been published yet). Relative to all patents published in 2000 there are fewer environmental patents in each year as expected. Looking closely at the coefficients for environmental patents there's a relatively strong rise in environmental patenting, first from 1992 to 1993, in 1997, between 1999 and 2001 and in 2005 (relative to the rising time trend). The first two periods coincide with the national implementation of the Montréal protocol. An additional stimulus may have resulted from the Kyoto protocol adopted in 1997. The rise around the turn of the century could be a result of the more intense research activities on alternative refrigerants and the regulatory activities of some EU Member States. Finally, patenting in 2005 most likely reacted on the upcoming EU MAC regulation.

[9] This can be seen by subtracting the coefficients for environmental patents (e.g. uptypefirmA) from the respective non-environmental patents (e.g. ptypefirmA).

Table 3: Absolute level of citation flows between countries
for citing environmental and non- environmental patents

	Destination is an environmental patent		**Destination is a non-environmental patent**	
Origin country-destination country	**Coef.**	**Std. Err.**	**Coef.**	**Std. Err.**
GER-GER	reference		2.519278***	.1393735
GER-US	-1.66271***	.3670014	.7947308***	.2613437
GER-JP	-1.260311***	.4649392	1.309319***	.2548211
GER-FR	-.9478824***	.3271675	1.270795***	.2689329
GER-RoW	-2.361678***	.6260103	-.7162216**	.3199947
US-US	-.87489***	.3222878	1.332763***	.2576632
US-GER	-2.574883***	.4204063	.2002985	.1673867
US-JP	-2.484777***	.7530721	.8873428***	.257322
US-FR	-3.55618***	.7548911	-.3733571	.2921314
US-RoW	-3.724159***	1.120162	-1.233605***	.3299683
JP-JP	.0459516	.3322187	2.802842***	.2450383
JP-GER	-1.180178***	.2443015	1.582774***	.1453133
JP-US	-2.902805***	.5595426	1.317431***	.2587062
JP-FR	-2.258783***	.461673	.8621158***	.2700201
JP-RoW	-3.255172***	.9162154	-1.252824***	.3318229
FR-FR	-2.282278***	.4889169	.8879285***	.2736726
FR-GER	-3.25902***	.6193538	.8787097***	.1600801
FR-US	-2.998724***	.6100588	-.5019979*	.2935747
FR-JP	-2.27892***	.7548629	.5629079**	.2684999
FR-RoW	-4.538058***	1.764565	-1.626186***	.350498
RoW-RoW	-2.927367***	.5834208	-2.331063***	.340331
RoW-GER	-2.385639***	.2759905	-.3206931**	.1577872
RoW-US	-6.916699***	2.463307	-1.210446***	.2828191
RoW-JP	-5.26789***	2.016227	-.7332968***	.2770413
RoW-FR	-4.302592***	.7535471	-.5736533**	.2791375
yearDiff	-.0209128	.0137488		
yearDiff2	-.0036893***	.0004301		
_cons	-25.27314***	.2038963		
alpha	1.316486	.0625646		

Negative binomial regression; number of observations: 45036
Log likelihood= -10916.433; LH-ratio test of alpha=0: chibar2(01) = 2091.88 Prob>=chibar2 = 0.000
Dependant variable: number of backward citations; *, ** and *** indicate significance at 1%, 5% and 10% level
Control variables (not shown): year of the cited patents, year-country variables for citing patents, GDP per capita; yeardiff and yeardiff2 account for the time lapse between the citing and cited patents in absolute and quadratic terms.
GER = Germany; US = United States ; FR = France; JP = Japan; RoW = rest of the world
Example: GER-US (2^{nd} column) denotes flows from Germany to the US originating from environmental US patents citing environmental and non-environmental German patents.

Table 4: Absolute level of citation flows between countries
for cited environmental and non- environmental patents

	Destination is an environmental patent		**Destination is a non-environmental patent**	
Origin country-destination country	**Coef.**	**Std. Err.**	**Coef.**	**Std. Err.**
GER-GER	reference		2.072657***	.1484025
GER-US	-1.045502***	.3465259	.7017348***	.2568045
GER-JP	-1.356884***	.4093822	.9029604***	.2501328
GER-FR	-1.424309***	.3663566	.8546841***	.263871
GER-RoW	-3.226089***	.5080849	-1.136625***	.3203703
US-US	-.3569267	.308142	1.302343***	.2535345
US-GER	-2.219718***	.3747069	-.2451826	.1754024
US-JP	-1.753695***	.4500054	.5131739**	.2539319
US-FR	-2.385849***	.4786452	-.8710236***	.2899373
US-RoW	-3.918164***	.6528246	-1.657349***	.3311237
JP-JP	-.7297459**	.3558584	2.410733***	.2407408
JP-GER	-1.472126***	.2935941	1.105642***	.1533496
JP-US	-2.273335***	.5174781	1.191461***	.2540183
JP-FR	-4.092151***	1.034889	.3991124	.265268
JP-RoW	-4.095699***	.734051	-1.70197***	.3319977
FR-FR	-1.019524***	.3964107	.2316422	.2685015
FR-GER	-1.287912***	.3327752	.1785403	.1662716
FR-US	-1.34091***	.4665297	-.7912815***	.2903408
FR-JP	-1.547706***	.5678714	-.0028061	.2639847
FR-RoW	-5.182038***	1.558806	-2.196777***	.3506512
RoW-RoW	-6.65581***	2.468513	-2.889912***	.3373702
RoW-GER	-2.219106***	.4085134	-.9808247***	.1637692
RoW-US	-3.476669***	.9052578	-1.553427***	.2787383
RoW-JP	-4.154005***	1.436644	-1.350241***	.2731697
RoW-FR	-3.539755***	.8395228	-1.304687***	.2748353
yearDiff	-.0160216	.0131107		
yearDiff2	-.0040086***	.0004175		
_cons	-.8619385***	.1992461		
alpha	.7345382	.0451894		

Negative binomial regression; number of observations: 45036
Log likelihood= - 10366.302; LH-ratio test alpha=0: chibar2(01) = 951.16 Prob>=chibar2 = 0.000
Dependant variable: number of backward citations; *, ** and *** indicate significance at 1%, 5% and 10% level
Control variables (not shown): year of the cited patents, year-country variables for citing patents, GDP per capita
yeardiff and yeardiff2 account for the time lapse between the citing and cited patents in absolute and quadratic terms.
GER = Germany; US = United States ; FR = France; JP = Japan; RoW = rest of the world
Example: GER-US (2nd column) denotes knowledge diffusion from Germany to the US whereby the cited German patents are environmental and the citing patents include environmental and non-environmental US patents.

Table 5: Intensity of citation flows between countries
for citing environmental and non- environmental patents

	Destination is an environmental patent		**Destination is a non-environmental patent**	
Origin country-destination country	**Coef.**	**Std. Err.**	**Coef.**	**Std. Err.**
GER-GER	reference		.7372866***	.2729084
GER-US	-.616774*	.354209	-.1837298	.3221372
GER-JP	-1.025878**	.4507908	-.4326197	.3298658
GER-FR	-.1532326	.3197581	.1155201	.3263109
GER-RoW	-1.276677**	.6300201	-.9966146***	.365359
US-US	1.357514***	.3098871	1.535512***	.321343
US-GER	-1.328584***	.4180183	-.4226952	.2899257
US-JP	-1.049036	.7457419	.2818201	.3347777
US-FR	-1.526117**	.7529259	-.3387752	.3475377
US-RoW	-1.26986	1.122754	-.3049529	.376431
JP-JP	.307054	.3137313	1.087361***	.3232927
JP-GER	-1.116471***	.2387939	-.1613908	.2760158
JP-US	-1.786841***	.5516115	.3734535	.3205506
JP-FR	-1.418241***	.4570819	-.2499028	.3280602
JP-RoW	-2.026864**	.9191989	-1.4626***	.3753836
FR-FR	-.1299216	.4851203	1.091788***	.3326532
FR-GER	-1.937078***	.6173017	.3824512	.2858954
FR-US	-.5463991	.60271	-.1054537	.3491388
FR-JP	-.6739752	.7462893	.1440913	.3434542
FR-RoW	-2.030354	1.765873	-.5458192	.3945988
RoW-RoW	.5258231	.5932021	-.2857028	.3913119
RoW-GER	-.1405102	.2828261	.1558116	.2935348
RoW-US	-3.562173	2.462756	.1366605	.3483152
RoW-JP	-2.783773	2.014573	-.2272035	.3568182
RoW-FR	-1.213928	.7548013	.5484528	.3446112
directZ	-.3395894***	.0829084		
ljahr1	.8201733***	.0229371		
ljahr2	.5699742***	.0512031		
_cons	-8.16962***	.3552833		
alpha	.4516232	.0339359		

Negative binomial regression; number of observations: 45036
Log likelihood = -9670.1478; LH-ratio test alpha=0: chibar2(01) = 535.98 Prob>=chibar2 = 0.000
Dependant variable: number of backward citations; *, ** and *** indicate significance at 1%, 5% and 10% level
Control variables (not shown): year of the cited patents, year-country variables for citing patents;
ljahr1 (ljahr2) is the logarithm of a variable that measures the frequency of patent combinations for country, publication year and environmental orientation for cited (citing) patents. The dummy directZ is 1 for citing environmental patents and 0 for other patents.
GER = Germany; US = United States ; FR = France; JP = Japan; RoW = rest of the world
Example: GER-US (2^{nd} column) denotes flows from Germany to the US originating from environmental US patents citing environmental and non-environmental German patents.

Table 6: Intensity of citation flows between countries
for cited environmental and non- environmental patents

	Destination is an environmental patent		**Destination is a non-environmental patent**	
Origin country-destination country	**Coef.**	**Std. Err.**	**Coef.**	**Std. Err.**
uGER-GER	reference		.3012941*	.1571245
uGER-US	-.5702823	.3481753	-.6270764**	.2601973
uGER-JP	-1.379062***	.4085292	-.8508986***	.2480861
uGER-FR	-.6417378*	.3709088	-.2642968	.2718726
uGER-RoW	-1.678928***	.5280259	-1.415935***	.3545661
uUS-US	.9264834***	.3042282	1.133379***	.2519094
uUS-GER	-1.320318***	.3734716	-.8578318***	.1759052
uUS-JP	-1.010532**	.4454317	-.1267623	.2474751
uUS-FR	-.9204431*	.4800355	-.8068939***	.2932913
uUS-RoW	-1.544152**	.6684355	-.7009996*	.3608181
uJP-JP	.0704092	.3490138	.6607235***	.2379696
uJP-GER	-.4907023*	.2914111	-.6347525***	.1607278
uJP-US	-.8657835*	.5149586	-.1081172	.2566952
uJP-FR	-2.536869**	1.035286	-.6772917**	.2731102
uJP-RoW	-1.644849**	.7479734	-1.904761***	.3642391
uFR-FR	.3403837	.4003606	.6357478**	.2718032
uFR-GER	-.5253336	.3333089	-.1165889	.1666541
uFR-US	-.2506843	.4672005	-.5929227**	.2880083
uFR-JP	-.8822665	.5652055	-.2792117	.2576862
uFR-RoW	-3.001539*	1.565241	-.925551**	.3780937
uRoW-RoW	-2.834699	2.473305	-.6124149*	.3665644
uRoW-GER	.0391773	.4117552	-.2580313	.1675178
uRoW-US	-.7708336	.905877	-.3488298	.278542
uRoW-JP	-1.977739	1.436211	-.6727018**	.2687229
uRoW-FR	-.6431363	.8420466	.090069	.2798369
directP	-.779238***	.2537052		
ljahr1	.819985***	.0233029		
ljahr2	.5781438***	.0508945		
_cons	-7.787846***	.3940003		
alpha	.4537122	.0340773		

Negative binomial regression; number of observations: 45036
Log likelihood= -9687.9277; LH-ratio test of alpha=0: chibar2(01)= 537.59 Prob>=chibar2 = 0.000
Dependant variable: number of backward citations; *, ** and *** indicate significance at 1%, 5% and 10% level
Control variables (not shown): year of the cited patents, year-country variables for citing patents;
ljahr1 (ljahr2) is the logarithm of a variable that measures the frequency of patent combinations for country, publication year and environmental orientation for cited (citing) patents. The dummy directP is 1 for cited environmental patents and 0 for other patents.
GER = Germany; US = United States ; FR = France; JP = Japan; RoW = rest of the world
Example: GER-US (2nd column) denotes knowledge diffusion from Germany to the US whereby the cited German patents are environmental and the citing patents include environmental and non-environmental US patents.

Models 2a and 2b refer to the absolute level of citation flows within and between countries. For this purpose, the variable yeardiff and yeardiff2 account for the time lapse between the citing and cited patents in absolute and quadratic terms. The variables are negative (but not always significant) indicating that older patents are less often cited than more recent ones. We also control for the year of the cited patents and include a proxy for the year- and country-specific likelihood of citations given institutional peculiarities between countries and years. The latter includes a combination of year-country variables (e.g. Pyear96JP for all Japanese citing patents published in 1996). Finally, we control again for GDP per capita as a proxy for demand.

For the country flow regressions model 2a distinguishes between citing environmental patents and citing non-environmental patents. The omitted reference categories are flows within Germany originating from citing environmental patents flowing to all other German patents and the year 2000. Not surprisingly, most of the country flows from citing non-environmental patents are more frequent than the reference case given that there are more non-environmental than citing environmental patents in the data set. In line with the literature we find that flows within big countries are more frequent than flows across countries (see e.g. Beise and Rennings, 2003 on the importance of the home market for innovations). At least this is true for Germany and Japan - with about the same level of intranational flows – and also for the US (with a slightly lower level of intranational flows). By contrast, France and the rest of the world depend more strongly on knowledge input from these big three countries. Both environmental and non-environmental patents from France more often cite German patents than other French patents. The same is true for citing environmental patents from the rest of the EU (citing Germany). Germany is obviously an important repository for environmental knowledge for other European countries. By contrast, environmental citing patents from "Tiger" states (China, Korea, Malaysia) often cite US patents.[10] This pattern indicates that to some extent geographical or cultural distance influences the amount of knowledge diffusion.

However, other channels also influence knowledge diffusion. Both for citing environmental and non-environmental patents there is a strong mutual exchange between Japan and Germany. As Germany has a leading role in car manufacturing and Japan has a long tradition in mobile air conditioning and the development of relevant technologies, it is understandable that these two countries interact to exploit opportunities in the global mobile air-conditioning market. There also important knowledge flows from Japan to the US, but interestingly mainly for non-environmental US patents. Environmental knowledge is primarily absorbed by the US and Japan from Europe. At least this is true for citing environmental patents based on natural refrigerants: Germany is almost cited as often by US and Japanese patents as other US and Japanese patents. However, the overall amount of spillovers across countries is limited relative to intra-national spillovers. Intra-national spillovers are also more prevalent for environmental than for other patents (based on relative differences in the intranational and international coefficients). This is particularly true for Japan and the US.

Model 2b takes a different perspective focusing on cited (as opposed to citing) environmental and non-environmental patents. While the previous two models are primarily interested in the knowledge sources of environmental and other patents, this model looks at the diffusion of environmental and other knowledge to all later patents. The omitted reference categories are flows within Germany originating from cited environmental patents and the year 2000. Most knowledge diffusion is again intra-national (similar to model 2a). The most pronounced diffusion across borders is from Germany to the US and between Japan and Germany (in both directions). Most environmental knowledge diffuses from French and German patents, whereas the diffusion from Japan and the US is less important by an order of magnitude

[10] These results are taken from a closer look at the countries summarized under the rest of the world.

(except for the diffusion of environmental knowledge from Japanese patents to German patents). This pattern indicates clearly that European countries have a first-mover advantage in environmental patents that was stimulated by the stricter regulatory framework for fluorinated greenhouse gases. By contrast, for other knowledge the strongest knowledge diffusion takes place from Japan to the US. These results confirm the previous findings.

Model 2c and 2d refer to the intensity of flows between country pairs. Looking at patent intensity allows to focus on the closeness and exclusivity of citation links between countries. In that sense, links may be relatively exclusive but not very important in absolute terms. The intensity is approximated by including the logarithm of a variable that measures the frequency of patent combinations for country, publication year and environmental orientation both for cited patents (ljahr1) and citing patents (ljahr2). The model also controls for the year of the cited (environmental) patents and includes again a proxy for the year- and country-specific likelihood of citations. The dummy directZ (directP) is 1 for citing (cited) environmental patents and 0 for other patents. The negative sign indicates that the number of forward (backward) citations is lower for environmental patents.

The omitted reference categories in model 2c are flows within Germany originating from a citing environmental patent and the year 2000. Looking at the country flows reveals that intra-national flows are again more important in terms of citation flow intensity. In contrast to model 2a intranational flows within the US are now significantly more important than intranational flows within Germany or Japan, indicating that there a close research ties within the large American market. Knowledge flows within France are now also more prevalent than previously (model 2a) and more important than any knowledge input to France from abroad. However, for citing environmental patents intra-national flows are not significant for France and Japan. Apparently the ties for environmental research are not as close in Japan and France compared to the US and Germany. Japanese and French researchers primarily rely on knowledge from Germany for their environmental patents, but the intensity of these ties is fairly low (given the low level of the coefficients). The closest international relationship for the generation of environmental patents exists between Germany and Japan and Germany and the US (in both ways). While the importance of knowledge flows between Germany and Japan has already been shown in model 2a and b, the mutual exchange between Germany and the US is more clearly highlighted in model 2c. Thus, the absolute level of exchange of environmental knowledge between Germany and the US is relatively modest (model 2a), but the intensity (and probably the importance) of exchange is not. This exchange could have been stimulated by the yearly meetings and conferences organized since the late 1990s by the Mobile Air-conditioning Society Worldwide, the US Environmental Protection Agency and the German Car Manufacturers Association. But overall there are few intense and significant international knowledge flows for all patents.

Model 2d relates again to cited environmental and non-environmental patents. The omitted reference categories are flows within Germany originating from cited environmental patents and the year 2000. Intra-national knowledge diffusion is once more most pronounced in the US and Germany. For international knowledge diffusion there is no clear-cut picture as many flows are not significant: For cited environmental patents Germany cites Japanese environmental patents and France German environmental patents relatively intensely. For non-environmental patents the US cites German and French patents relatively intensely. As a consequence, the result found in model 2b that most environmental knowledge diffuses from French and German patents to the US and Japan is not confirmed in terms of knowledge intensity. This indicates that the transfer of environmental knowledge is somewhat unstable or difficult to separate from general knowledge diffusion.

Table 7: Absolute level of citation flows between firm-/applicant-types for citing environmental and non- environmental patents

	Destination is an environmental patent		**Destination is a non-environmental patent**	
Origin type-destination type	**Coef.**	**Std. Err.**	**Coef.**	**Std. Err.**
OTHF-OTHF	reference		2.590877***	.2607784
OTHF-OEM	-1.777229**	.696514	1.764342***	.271242
OTHF-MAC	-.7273851	.4460632	2.437864***	.2615315
OTHF-OTHAP	-.4105227	.3882919	1.06334***	.2732265
OEM-OTHF	-.7012479	.4353608	2.23843***	.2641703
OEM-OEM	-.787744	.4916783	2.227154***	.2644543
OEM-MAC	-.5307102	.4311173	2.746792***	.2591488
OEM-OTHAP	-.8225017*	.4542571	1.185182***	.2721999
MAC-OTHF	-.7071685*	.4288994	2.058136***	.2669516
MAC-OEM	-1.674351**	.6748033	1.926732***	.2699789
MAC-MAC	-.2496393	.3849017	2.585154***	.2604228
MAC-OTHAP	-.8039609*	.4427753	1.454067***	.2661636
OTHAP-OTHF	.9758576***	.2825729	3.790592***	.252243
OTHAP-OEM	.2007766	.3319718	3.360596***	.2533582
OTHAP-MAC	.9958615***	.2873158	3.964737***	.2514767
OTHAP-OTHAP	.8041618***	.2877854	2.628063***	.2531069
yearDiff2	-.0038581***	.0004121		
yearDiff	-.0494853***	.0129258		
_cons	-2.438626***	.2682177		
alpha	.9111216	.0391666		

Negative binomial regression; number of observations: 27611
Log likelihood= -10244.212; Likelihood-ratio test of alpha=0: chibar2(01)= 2101.39 Prob>=chibar2=0.000
Dependant variable: number of backward citations; *, ** and *** indicate significance at 1%, 5% and 10% level;
Control variables (not shown): year of the cited and citing patents;
OTHF = other firms; OTHAP = other applicants (individuals); OEM = carmakers; MAC = MAC suppliers;
yeardiff and yeardiff2 account for the time lapse between the citing and cited patents in absolute and quadratic terms.
Example: OTHF-OEM (2nd column) denotes flows from other firms to carmakers originating from environmental patents of carmakers citing environmental and non-environmental patents from other firms.

Table 8: Absolute level of citation flows between firm-/applicant-types for cited environmental and non- environmental patents

	Destination is an environmental patent		Destination is a non-environmental patent	
Origin type - destination type	**Coef.**	**Std. Err.**	**Coef.**	**Std. Err.**
OTHF-OTHF	reference		2.265418***	.2937137
OTHF-OEM	-1.236547**	.593704	1.551806***	.3037734
OTHF-MAC	-.672522	.4815296	2.207586***	.2948161
OTHF-OTHAP	-.6382808	.4301023	.9925576***	.3050586
OEM-OTHF	-.2437021	.4485527	1.870213***	.2970149
OEM-OEM	-1.406059**	.707285	2.026327***	.2975004
OEM-MAC	-.2593913	.4601928	2.492219***	.2929154
OEM-OTHAP	-1.439855**	.6153597	1.066209***	.3038404
MAC-OTHF	-.6805511	.484252	1.704128***	.2986088
MAC-OEM	-.9090561*	.5334094	1.683811***	.302408
MAC-MAC	.0625237	.3972987	2.297007***	.2934382
MAC-OTHAP	-.8622096*	.4609518	1.337667***	.2989396
OTHAP-OTHF	1.127206***	.3104078	3.616737***	.2870155
OTHAP-OEM	.2479226	.3461519	3.347604***	.2883458
OTHAP-MAC	.7779446**	.3212939	3.929515***	.2865324
OTHAP-OTHAP	.2896489	.3258043	2.694908***	.287916
yearDiff2	-.0038786***	.0004126		
yearDiff	-.0482012***	.0129631		
_cons	-2.144778***	.3002857		
alpha	.9629071	.040952		

Negative binomial regression; number of observations: 27611
Log likelihood = -10470.388; LH-ratio test of alpha=0: chibar2(01) = 2192.97 Prob>=chibar2 = 0.000
Dependant variable: number of backward citations; *, ** and *** indicate significance at 1%, 5% and 10% level;
Control variables (not shown): year of the cited and citing patents ;
OTHF = other firms; OTHAP = other applicants (individuals); OEM = carmakers; MAC = MAC suppliers;
yeardiff and yeardiff2 account for the time lapse between the citing and cited patents in absolute and quadratic terms.
Example: OTHF-OEM (2nd column) denotes knowledge diffusion from other firms to carmakers whereby the cited patents from other firms are environmental and the citing patents include environmental and non-environmental patents from carmakers.

Table 9: Intensity of citation flows between firm-/applicant-types for citing environmental and non- environmental patents

	Destination is an environmental patent		**Destination is a non-environmental patent**	
Origin type - destination type	**Coef.**	**Std. Err.**	**Coef.**	**Std. Err.**
OTHF-OTHF	reference		.3793917	.2621932
OTHF-OEM	-1.338065*	.6919793	-.1831295	.2702115
OTHF-MAC	-.7534892*	.4392506	.0655967	.2657972
OTHF-OTHAP	-.857135**	.381393	-.6894824**	.2775941
OEM-OTHF	-.8825102**	.4290753	-.0826602	.2657989
OEM-OEM	-.5603188	.4853203	.1082156	.2640959
OEM-MAC	-.7696509**	.4242016	.2028453	.2638228
OEM-OTHAP	-1.464149***	.4485298	-.7347951***	.2764463
MAC-OTHF	-.9454222**	.4226702	-.275492	.2675837
MAC-OEM	-1.608511**	.6703762	-.2294498	.2685605
MAC-MAC	-.6101149	.3773712	-.0134376	.2652338
MAC-OTHAP	-1.611999***	.4371982	-.6556726**	.2720126
OTHAP-OTHF	-.5617476**	.2784339	.1572121	.2588745
OTHAP-OEM	-1.013385***	.3279593	-.0602199	.2578451
OTHAP-MAC	-.6608712**	.2827876	.1723661	.261449
OTHAP-OTHAP	-1.246433***	.2843425	-.6900396***	.2628861
ljahr1	.8834641***	.0229944		
ljahr2	.7408767***	.0276931		
_cons	-9.169651***	.3018492		
directZ	-.2514116***	.0863754		
alpha	.0921651	.0119251		

Negative binomial regression; number of observations: 27611
Log likelihood= - 7753.5248; LH-ratio test of alpha=0: chibar2(01) = 112.92 Prob>=chibar2 = 0.000
Dependant variable: number of backward citations; *, ** and *** indicate significance at 1%, 5% and 10% level;
Control variables (not shown): year of the cited and citing patents;
OTHF = other firms; OTHAP = other applicants (individuals); OEM = carmakers; MAC = MAC suppliers;
ljahr1 (ljahr2) is the logarithm of a variable that measures the frequency of patent combinations for country, publication year and environmental orientation for cited (citing) patents. The dummy directZ is 1 for citing environmental patents and 0 for other patents.
Example: OTHF-OEM (2nd column) denotes flows from other firms to carmakers originating from environmental patents of carmakers citing environmental and non-environmental patents from other firms.

Table 10: Intensity of citation flows between firm-/applicant-types for cited environmental and non- environmental patents

	Destination is an environmental patent		**Destination is a non-environmental patent**	
Origin type - destination type	**Coef.**	**Std. Err.**	**Coef.**	**Std. Err.**
OTHF-OTHF	reference		.2406762	.2861247
OTHF-OEM	-1.027505*	.5851948	-.3341492	.2958195
OTHF-MAC	-1.005957**	.4718309	-.0668535	.2870271
OTHF-OTHAP	-.697542*	.4217244	-.8294842***	.2981871
OEM-OTHF	-.0501018	.4381882	-.2670617	.2901867
OEM-OEM	-1.092243	.7001225	-.0287541	.2903156
OEM-MAC	-.3431429	.4498955	.0367338	.2858688
OEM-OTHAP	-1.094238*	.609162	-.8971823***	.2975819
MAC-OTHF	-.5629344	.4743884	-.4384396	.2924212
MAC-OTHAP	-.9595273**	.4531923	-.8404322***	.2940935
MAC-OEM	-.6041247	.5239161	-.4122259	.2957796
MAC-MAC	-.2434138	.385385	-.1797821	.2873942
OTHAP-OTHF	.0879805	.300906	-.0305325	.2904558
OTHAP-OEM	-.6596568**	.3370853	-.2217514	.2915629
OTHAP-MAC	-.630729**	.312411	.0238884	.290223
OTHAP-OTHAP	-.8596488***	.3188809	-.8550557***	.2923323
ljahr1	.884901***	.0231499		
ljahr2	.7468028***	.0275576		
_cons	-9.051755***	.3374141		
directP	-.7112742***	.097384		
alpha	.0911642	.0118771		

Negative binomial regression; number of observations: 27611
Log likelihood= -7744.2685; LH-ratio test of alpha=0: chibar2(01) = 110.90 Prob>=chibar2 = 0.000
Dependant variable: number of backward citations; *, ** and *** indicate significance at 1%, 5% and 10% level;
Control variables (not shown): year of the cited and citing patents;
OTHF = other firms; OTHAP = other applicants (individuals); OEM = carmakers; MAC = MAC suppliers;
ljahr1 (ljahr2) is the logarithm of a variable that measures the frequency of patent combinations for country, publication year and environmental orientation for cited (citing) patents. The dummy directP is 1 for cited environmental patents and 0 for other patents.
Example: OTHF-OEM (2nd column) denotes knowledge diffusion from other firms to carmakers whereby the cited patents from other firms are environmental and the citing patents include environmental and non-environmental patents from carmakers.

Model 3a to 3d report the results for the citation flows between applicant/firm-types. As indicated in section 3 we distinguish between three firm types (carmakers/OEM, integrated MAC system suppliers, other firms) and all other applicants (mostly individuals). Models 3a and 3b refer to the absolute level of citation flows between applicant/firm-types. The omitted reference category are flows from environmental patents from "other firms" to all other patents from "other firms" and the year 2000. As controls we include years for the citing and cited patents.[11] The most striking result in model 3a for citing patents is that most knowledge spillovers result from individuals. A possible explanation is that firms are more capable of protecting their knowledge. Among firms most knowledge flows take place between other firms, between MAC suppliers and from MAC supplies to carmakers. Interestingly, citations from MAC suppliers to carmakers are considerably more important than citations from carmakers to MAC suppliers, indicating that MAC suppliers adapt their technological development to the needs of carmakers. Many of the system integrators are indeed strongly focused on a few OEMs. Behr (GER) primarily supplies the German carmakers BMW and Mercedes, Denso (JP) is in close relationship with Toyota, Delphi (US) is a former daughter company of GM, Visteon (US) primarily supplies Ford and Calsonic Kansei (JP) makes most of its business with Nissan. Comparing citing environmental patents and citing non-environmental patents reveals no major differences, except maybe that there is a more pronounced knowledge diffusion among other firms for citing environmental patents. Obviously, environmental knowledge can often be transferred to other applications or technologies beyond the narrow scope of MAC.

Model 3b focuses on cited environmental and non-environmental patents. The omitted reference category are flows from patents from "other firms" to environmental patents from "other firms" and the year 2000. For non-environmental cited patents most knowledge diffuses to individuals. Most environmental cited patents are not significantly different from the reference category. This indicates that most patents do not specifically cite certain types of environmental patents. Only patents from other firms benefit significantly from environmental patents from individuals or research organizations.

Instead of absolute flows model 3c and 3d consider the intensity of flows (like in models 2c and 2d). The dummy directZ (directP) is 1 for citing (cited) environmental patents and 0 for other patents. The negative sign indicates that the number of forward (backward) citations is lower for environmental patents. The omitted reference category are flows from environmental patents from "other firms" to all other patents from "other firms" and the year 2000. For non-environmental citing patents the intensity of the flows are not significantly different from the reference category. At the same time the reference category is more important than any other flow from citing environmental patents, as can be seen from the negative coefficients for the applicant/firm-types. The intensity of research ties is therefore generally higher for non-environmental patents.

Interestingly, most of the citing environmental private patents do not seem to transmit knowledge that is on average more valuable than knowledge flows between other firms (i.e. the reference category). Therefore, private environmental patents are important in absolute terms but not so much in terms of citation intensity. Overall, knowledge spillovers between other firms are not only important in absolute terms, but also turn out to be intensive (and probably valuable). The same is true for flows between carmakers and between MAC suppliers for environmental citing patents (both are not significantly different from the reference category). The close citation links between carmakers and between MAC suppliers suggest that carmakers and MAC suppliers each compete for the environmentally most promising technological options.

[11] It is not necessary here to control for "citation culture" as in the models 2a-d, since it is not reasonable to assume that citation varies by the type of firm/applicant.

Model 3d refines these results comparing environmental and non-environmental cited patents. The omitted reference category are flows from all patents from “other firms” to environmental patents from “other firms” and the year 2000. Results basically confirm model 3c from a different perspective. Research diffuses most intensely from other firms to environmental patents from other firms (reference category). It diffuses also more intensely to other patents than to environmental patents given that most flows are not significantly different from the reference case.

5. Conclusion

The creation and diffusion of climate-friendly technologies is a primary objective of today`s climate policies. This paper considers technologies in the mobile air-conditioning sector. Mobile air-conditioning units are developed for the global automobile market and contribute to climate change via the emission of fluorinated and energy-related greenhouse gases. Environmental improvements can primarily be realized through leak-tight systems based on the conventional refrigerant R134a or through the replacement of R134a units with systems based on more benevolent (natural) refrigerants. Environmental and non-environmental technologies are identified by patents in this paper and the diffusion is tracked down by patent citations. While most previous studies focus on market-driven technology transfer, a patent citation analysis allows to identify positive spillovers which are created by the investment in research and development and benefit other inventors.

Our results indicate that German companies have generated most of the MAC patents. Considering the subgroup of environmental patents the US has been almost equally innovative. However, in Germany a relatively stronger research focus has been put on patents based on natural refrigerants where is in the US most of the likely direct emission reductions have been achieved through improvements in current R134a-systems. The evolution in time indicates that the national implementation of the Montréal protocol and - somewhat less so - the regulatory activities to curb fluorinated greenhouse gases in Europe have stimulated environmental patenting relatively strongly.

The patent citation analysis reveals that most knowledge diffuses only intra-nationally, which is a frequent finding in the literature. This is even more so for environmental patents and indicates that environmental regulations are still too diverse to allow for a more widespread diffusion of climate friendly technologies. Another limiting factor for the diffusion of knowledge across “sectors” is likely to be the competition between firms. Therefore, most knowledge diffuses from privately owned patents.

However, a substantial amount of knowledge also crosses borders. Most environmental knowledge diffuses from French and German patents, which is likely to be a result of regulatory activities in Europe and intensified research on environmentally benign MAC systems. Yet, this exchange of knowledge is not very intensive and stable, so that the impact of EU regulations on US and Japanese patenting behaviour remains fairly weak. Possibly, this will change during the continued phase-out of fluorinated greenhouse gases in Europe. The reorganization of MAC systems in the car fleet in Europe could have knock-on effects in the American and Japanese car fleet. There is also a sizable and intense mutual exchange of knowledge between Germany and Japan, but no major difference exists between environmental and non-environmental technologies. Finally, the US benefits from Japanese knowledge, mainly with respect to non-environmental technologies, and from German knowledge, mainly with respect to key environmental technologies.

The sectoral-level analysis suggests that knowledge diffusion is not restricted to the major players in MAC systems (OEMs and MAC suppliers). Important knowledge is also produced and absorbed by firms and individuals that are not directly active in this market. Within the MAC market MAC suppliers adapt their technological development to the needs of carmakers. There is also an indication that carmakers and MAC suppliers each compete for the environmentally most promising technological options.

The analysis presented here could be improved in a number of ways. Firstly, the range of examined technologies could be extended. For example, other automotive technologies or other uses of air-conditioning could be studied. This would create more variation in the data set and shed more light on how certain countries or sectors specialize technologically. Secondly, the assumption that the rate of diffusion is time invariant, in the sense that it is independent of the citation lag, could be relaxed. This would allow a closer look at how fast certain technologies are picked up in other countries or sectors. Finally, it would be desirable to extend the analysis along the lines of Verdolini and Galeotti (2009). They use estimates on knowledge flows to construct internal and external available knowledge stocks and assess how the process of innovation responds to changes in technological opportunities (measured by the knowledge stock proxies) and demand. For the latter it would be necessary to have more satisfactory measures of the effectiveness of environmental and innovation policy to pin down the role of policy for innovation activities.

References

About Publishing Ltd. (2004): The Global Market for Heating, Ventilation and Air Conditioning Systems, London, http://www.aboutpublishinggroup.com/.

Beise, M. and Rennings, K. (2003): Lead markets of environmental innovations: a framework for innovation and environmental economics, Discussion Paper No. 03-01, Zentrum für Europäische Wirtschaftsforschung, Mannheim.

Daly, S. (2006): Automotive Air-Conditioning and Climate Control Systems, Elsevier: Oxford.

De Vries, F.P. and C. Withagen (2005): Innovation and environmental stringency: the case of sulfur dioxide abatement, CentER discussion paper No. 2005-18, Tilburg University, the Netherlands.

Dechezlepretre, A. et al. (2010): Invention and transfer of climate change mitigation technologies on a global scale: a study drawing on patent data, Centre for Climate Change Economics and Policy, Working Paper No. 19, Grantham Research Institute on Climate Change and the Environment

Dekker, T. et al. (2009): Inciting Protocols - How International Environmental Agreements Trigger Knowledge Transfers, Tinbergen Institute Discussion Papers No. 09-060/3, the Netherlands.

Garrone, P., Piscitello, L. and Wang, Y. (2010): Energy Innovation at the Country Level: The Role of Cross-Country Knowledge Spillovers, Working Paper, December 1, 2010, Available at SSRN: http://ssrn.com/abstract=1661627.

Gschrey, B. und Schwarz, W. (2009): Projections of global emissions of fluorinated greenhouse gases in 2050, on behalf of the German Federal Environment Agency, Climate Change 17/2009, Berlin.

Harhoff, D. et al. (1999): Citation Frequency and the Value of Patented Inventions, *The Review of Economics and Statistics*, Vol. 81 (1999), pp. 511-515.

IPCC/TEAP (2005): Safeguarding the Ozone Layer and the Global Climate System: Issues Related to Hydrofluorocarbons and Perfluorocarbons, IPCC Special Reports.

Jaffe, A., Tratjenberg, M., Henderson R. 1993. Geographic localization of knowledge spillovers as evidenced by patent citations. *The Quarterly Journal of Economics* 108(3), pp. 577-98.

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

Meißner, H.-R. and Jürgens, R. (2007): Zur Lage der deutschen Automobilzuliefererindustrie im Jahre 2007, Studie im Auftrag der Fraktion Die Linke.

OECD, 2008. Environmental Policy, Technological Innovation and Patents, Paris: OECD.

Palandre, L. et al. (2003): Estimation of the Weld Wide Fleets of Refrigerating and Air Conditioning Equipment in Order to Determine Forecasts of Refrigerant Emissions, the Earth Technology Forum, Washington.

Peri, G., 2005. Determinants of knowledge flows and their effect on innovation, Review of Economics and Statistics 87 (2), 308– 322.

Popp, D., 2006. International Innovation and Diffusion of Air Pollution Control Technologies: The Effects of NOx and SO2 Regulation in the US, Japan, and Germany. *Journal of Environmental Economics and Management* 51(1), 46-71.

Umweltbundesamt (2004): Fluorinated Greenhouse Gases in Products and Processes, Technical Climate Protection Measures, Berlin.

UNEP (2006): 2006 Report of the Refrigeration, Air-Conditioning and Heat Pumps Technical Options Committee, UNEP Nairobi, Ozone Secretariat.

Veloso, F. (2000): The automotive supply chain organization: Global Trends and Perspectives, Working paper, Massachusetts Inst. of Tech., Cambridge, MA.

Verdolini, E. and Galeotti, M. (2009): At Home and Abroad: An Empirical Analysis of Innovation and Diffusion in Energy-Efficient Technologies, Nota di Lavoro 123/2009, Fondazione Eni Enrico Mattei.

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