Paper to be presented at the DRUID Academy conference in Rebild, Aalborg, Denmark on January

15-17, 2014

Understanding the evolution of eco-innovative activity on automotive sector: an investigation based on patent analysis

Lourenço Galvão Diniz Faria
Technical University of Denmark
Management Engineering/Technology and Innovation Management
loufa@dtu.dk

Abstract

The issue of achieving higher degrees of sustainable development through environmental innovations or eco-innovations is increasingly gaining relevance among firms, governments and scholars, as technological advancement can be considered both the source and the solution for some of the main environmental issues related with anthropogenic activities, and because of its singular features, the eco-innovative dynamics is being placed as an interesting case of how technologies evolve along time in response to the system in which they are immersed in an interactive process (NELSON & WINTER, 1982; LUNDVALL, 1988).

However, eco-innovation research is still in its early phases and most empirical studies are focused on qualitative, specific successful cases with policy-making implications (FRONDEL et al., 2008; CARRILLO-HERMOSILLA et al., 2010; among others) while few studies deal with generation and diffusion of eco-innovations in a sectoral perspective (OLTRA & SAINT JEAN, 2009; DECHEZLEPRÊTE et al., 2009). In addition of the lack of clear definitions and methodologies, firms and governments in general do not disclose much quantitative data about their eco-innovation efforts as would be desirable to construct comprehensive analyzes, hampering the construction of robust indicators. There is still a gap on developing comprehensive, quantitative analyzes of eco-innovation dynamics ? especially at sectoral levels - that needs to be filled.

In this sense, this paper aims to analyze the development of selected technologies considered as promising ?green technologies? in the automotive sector, and thus the evolution of eco-innovative activity, through a patent count methodology. Many scholars hold that patent counting is the best available source of quantitative data for disaggregated eco-innovation analyzes (POOP, 2005; OLTRA et al., 2010, among others). The methodology is composed by an analysis of: 1) the rate of growth in patenting of each technology (proxy of its importance and maturity degree); 2) the patent families as proxy of economic relevance and technological diffusion between countries; 3) the set of patents and the citations between them, to build networks of ideas and their relatedness; 4) the scientific citations included in patent filings to identify the sources of scientific knowledge that firms rely on when conducting R&D processes; 5) the leaders and laggards in each technology. The technologies covered in the paper are Hybrid-Electric vehicles, Electric propulsion with power supply external to vehicle (Plug-in electric vehicles), and Fuel Cells. The patent classes belonging to each technology are given by two classifications of ?green patents?, the ?IPC Green Inventory? and the OECD?s list of

Environmentally-sound technologies (EST), combined with specific keywords related with each technology. The database used for the patent search is the Derwent World Patent Index, from Thomson Reuters, and covers a broad period of time (from 1963 to 2013), which allows us to capture the key phase of eco-innovation emergence. With this study, we expect to contribute for the understanding of the evolution of eco-innovations and the greening of markets.

Andersen, M. M. (2008). ?Eco-Innovation - Towards A Taxonomy And A Theory?. Paper presented at 25th DRUID Celebration Conference 2008.
Carrillo-Hermosilla, J., Del Río, P., & Könnölä, T. (2010). Diversity of eco-innovations: Reflections from selected case studies. Journal of Cleaner Production, 18(10), 1073-1083.
Dechezleprêtre, A., Glachant, M., & Ménière, Y. (2013). What drives the international transfer of climate change mitigation technologies? Empirical evidence from patent data. Environmental and resource economics, 54(2), 161-178.
Frondel, M., Horbach, J., & Rennings, K. (2008). What triggers environmental management and innovation? Empirical evidence for Germany. Ecological Economics, 66(1), 153-160.
Lundvall, B. A. (1988). Innovation as an interactive process: from user-producer interaction to the national system of innovation. Technical change and economic theory, 369.
Nelson, R. & Winter, S. (1982). An Evolutionary Theory of Economic Change. Cambridge, MA: Harvard University Press.
Oltra, V., & Saint Jean, M. (2009). ?Sectoral systems of environmental innovation: an application to the French automotive industry?. Technological Forecasting and Social Change, 76(4), 567-583.
Oltra, V., Kemp, R., & De Vries, F. P. (2010). Patents as a measure for eco-innovation. International Journal of Environmental Technology and Management, 13(2), 130-148.
Popp, D. (2005). Using the triadic patent family database to study environmental innovation. Environment Directorate Working Paper ENV/EPOC/WPNEP/RD (2005), 2.

Jelcodes:O31,Q01

UNDERSTANDING THE EVOLUTION OF ECO-INNOVATIVE ACTIVITY ON AUTOMOTIVE SECTOR: AN INVESTIGATION BASED ON PATENT ANALYSIS

Lourenco G. D. Faria

1. INTRODUCTION

The relationship between technological advancement and the environment is complex and paradoxical (HEKKERT et al., 2007). On the one hand, much of the damage to the environment can be attributed to modern technology of product and process, which were gradually developed and improved over decades without, however, take into account the environmental issue. On the other hand, the development of more efficient technologies is certainly one of the greatest allies in efforts to reduce environmental impact.

In recent years, the automobile has been involved in a dilemma: while it is essential for the functioning of modern societies, it also imposes enormous costs in terms of environment harm and intensive use of nonrenewable resources. In order to reduce such environmental impact, the technological regime of the sector, traditionally characterized by the introduction of incremental innovations in product and process (creative accumulation), has become more dynamic and complex as alternatives to the dominant design (based on internal combustion engines, all-steel car bodies and multi-purpose character) are being tested (ORSATO & WELLS, 2007), with important impacts on firms' technological competences and specific assets.

In this sense, this paper aims to analyze the development of selected technologies considered as promising "green technologies" in the automotive sector, and thus the evolution of eco-innovative activity, through a patent count methodology. Our hypothesis is that firms on automotive sector are developing technologic competences and resources to deal with the new alternative technologies and, in this case, such firms are perceiving sufficient opportunities to do so even considering all the institutional, technologic, and organizational rigidities.

Our findings show that firms are diversifying their patent portfolios in response to institutional and demand pressures, as well as new technologic opportunities, in order to generate competitive advantages derived from the introduction of eco-innovations, especially from the beginning of this century and even more pronounced after the financial crisis in 2008. Therefore, this article supports the statement that a transition to the green economy can be a powerful mechanism to foster economic growth through the creation of new competitive advantages through the development and diffusion of eco-innovations.

The article is composed by a literature review on dynamic capabilities and technology life cycles in order to discuss elements that foster (and hinder) changes on technological competences. After, we briefly apply these elements on the automotive sector context. Then, we present the methodology based on patent counts and the preliminary data. Finally, we discuss the results of the patent portfolio analysis on the final section. This is the first, preliminary work of a series of articles dealing specifically with sectoral patterns of eco-innovations based on patent data.

2. DYNAMIC CAPABILITIES, TECHNOLOGICAL COMPETENCES AND THE SOURCES OF ORGANIZATIONAL AND TECHNOLOGICAL INERTIA ON FIRMS

According to the "resource-based" view, firms can be understood as bundles of idiosyncratic resources and capabilities (Barney, 1991) and the role of management is to coordinate and optimize such bundles in order to perform firm's activities (i.e. transforming inputs in outputs, conducting product/process research and development, selling its products etc.), while developing the basis for their future resources and capabilities. The development and possession of firm-specific assets is historically acknowledged as an important source of sustained competitive advantages. Scholars as Edith Penrose (1959), for instance, used a similar notion to explain the profitability and growth of modern capitalist firms.

To achieve such advantages, firms adopt strategies that guide the development and coordination of internal resources in order to maximize their value. In this context, a strategy should not be understood only as operational effectiveness (Porter, 1996), but as continuous alignments between internal capabilities/competencies and external opportunities in unique, difficult-to-replicate arrangements (Christensen et al., 1987). The need for continued alignment imply that firms have to constantly develop new resources and/or adapt existing ones as a response to the environment, "(…) when time-to-market and timing is critical, the pace of innovation is accelerating, and the nature of future competition and markets is difficult to determine" (Teece & Pisano, 1994, p. 538).

The concept of dynamic capabilities, advanced by Teece & Pisano (1994) and Teece et al. (1997), was developed to deal with firms' capabilities/competences related with the ability to reconfigure internal and external resources to address changing environments, taking advantage of new opportunities and adapting to new constrains. The dynamic capabilities are built upon many internal and external elements, such as organizational and managerial processes (internal and external coordination, learning, transformation of asset structure), firm's position regarding technological, complementary, reputational, institutional, financial, and locational assets, as well as path dependencies and technological opportunities that affect strategic alternatives available to the firm.

The presence of dynamic capabilities can explain how firms obtain competitive advantages in scenarios of rapid technological, institutional, or demand change by developing/rearranging technological competences to create new products/processes with distinct, attractive features. However, these capabilities are not easy to acquire and manage: first, firms must not develop assets and technological competences at will if they are not supposed to be applied because they are costly to acquire and maintain. According to Pavitt (1998), "large firms may have competencies in a number of fields of technology but, in the contemporary world of highly specialized knowledge, the costs of mastering all of them clearly appear to outweigh the benefits" (p. 441).

On the other hand, technological discontinuities rarely require the rejection of all the knowledge and competences related with existent products and processes: "Typically they may affect the performance of a key component (e.g. transistors vs. valves) or provide a major new technique (e.g. gene splicing). But they do not destroy the whole range of related and complementary technologies (…) that are necessary for a complete product" (Pavitt, 1998, p. 441). Therefore, firms often have to choose which of existing assets and competences they should preserve and which they should get rid of.

Lastly, except perhaps by the acquisition of another firm (Coriat & Dosi 2002), changing or rearranging capabilities and competences can be costly and painful depending on how path dependencies affect the performance of the firms. In general, firms tend to direct innovative search to the neighborhood of the technologies currently developed in order to use existing firm-specific assets (e.g. knowledge bases, relationships with suppliers, capital goods etc.), technological competences and routines, sometimes generating core-rigidities (Leonard-Barton, 1995).

These difficulties in changing technological competences also relate with the nature of the evolution of technologies in a broader perspective. Assuming that technological change is an evolutionary process (Nelson & Winter, 1982), the mechanisms of selection adapted to existent technologies can difficult changes in technologic competences when these are not compatible with existent institutions (regulations, routines etc.), actor networks, and physical infra-structures.

According to the evolutionary perspective of technological change, agents are capable of introducing behavioral and technological novelties into the production system using new knowledge and/or new combinations of existent knowledge (Dosi & Nelson, 1994). This creative mechanism is equivalent to the biological notion of genetic mutation that leads to the emergence of new species with different features in a specific environment but, unlike its biological parallel, the technological diversity is not created just by random mutations, but can also be a response to changes on the environmental characteristics.

The environment is a complex structure of specific technological, socio-economic and institutional configurations, assuming that technological change (and potential market change) is a systemic process not lead just by scientific discoveries and firms' capabilities, but also by sociological and institutional factors (Malerba, 2002). It includes institutions, knowledge bases, consumer preferences and expectations, physical infra-structures, availability of natural resources and inputs, financial conditions, scientific, technological and organizational capabilities, and many other factors.

Both consumers and firms have imperfect information about new technologies and their potential risks, so in general they prefer to adopt well-known, established strategies to avoid risks. Thus, selective environments are characterized by relatively invariant and path-dependent routines that arise as a response to inherent uncertainty and risk that follows innovative activities and their outputs. Such routines are expressed in terms of, for example, dominant designs, basic heuristics used on R&D processes, general consumption preferences and prejudices - the "common sense", firms' common behaviors, political institutions, sectoral standards, and so on. Because of these routines, the processes of continuous technical change are not random walks, but usually follow defined trajectories.

The concept of routines can be better understood by analyzing how the environment changes as new technologies become mature. In the first phases of technologic life cycles, the rate of innovation is high and there is great diversity among products and processes, although they are relatively inefficient and there are no defined standards. Firms have more freedom to innovate (less strict ex-post selection mechanisms) and technological development focuses on improving the performance rather than reducing costs. As an industry begins its "maturation" process, products start to reach significant sales volumes. Their diffusion leads to standardization and processes become more specialized and segmented, consequently there are reductions in productive costs and inherent risks, which in turn reinforce the diffusion (Utterback & Abernathy, 1975; Arthur, 1989; Faber & Frenken, 2009; Nelson & Winter, 1977; Dosi, 1982; Anderson & Tushman, 1990).

On the other hand, once mature and widespread, a complex technology establishes a deep and solid relationship with the selective environment: the more a technology is used, the higher its utility for users becomes (David, 1985; Perez, 2010). New infra-structures and complementary technologies can emerge to support it, and agents start to associate essential activities with them – new routines are set. At the same time, products become fully standardized and productive processes are so integrated that it becomes very difficult to implement changes since, given their systemic nature, even small changes in the process may require replacement of several components (Utterback & Abernathy, 1975).

Thus many socio-economic "costs" of changing general and established routines and structures arise with such maturation process. These are not only financial costs related with implementing new physical infra-structures, but also the "psychological costs" of changing consumers' preferences and habits, costs of changing firms' organizational frameworks and perceptions of opportunity spaces, costs of changing political institutions, and all the opportunity costs related with giving up an existing (and somewhat successful) structure. Moreover, the more complex and well adapted are the existent technologies, the more "costly" tend to be these changes. As pointed by Perez (2010), "(…) organisational inertia is a well-known phenomenon of human and social resistance to change" (pp. 198) and, once established, routines "(…) give rise to intense resistance and require bringing forth even stronger change-inducing mechanisms" (pp. 199). New technologies have to offer sufficient incentives to induce agents to change their routines.

Therefore, the ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments is crucial to maintain competitive advantages in a broad range of sectors because of firm- and sectoral-level rigidities. The elements discussed call attention for the fact that changing firm-specific assets, capabilities and competences is costly (not only in financial terms), so firms will only engage on such processes if they have sufficient incentives to get out of organizational inertia. Given that, it is possible to say that observable changes in technological competences and firm-specific assets are indicators of perceived opportunities from new technologies, especially when they require new capabilities and resources to be applied to products and processes.

3. DYNAMIC CAPABILITIES AND TECHNOLOGIC CHANGE ON AUTOMOTIVE SECTOR

The automotive sector traditionally has been pointed out as one of the clearest examples of a technologically mature industry. For instance, Abernathy & Clark (1984), among others, used the evolution of automotive technologies to illustrate the transition between the phases of technologic life cycles until their maturity. The automotive value-chain is dominated by relatively few Original Equipment Manufacturers (OEM) competing in a well-established oligopolistic structure. Competitive forces are strong and operational efficiency is prerequisite for survival in this sector, which induces firms to focus on their core competencies (Prahalad & Hamel, 1990).

Until recently, the technological regime has been characterized mainly by the introduction of incremental innovations (creative accumulation) based on a dominant-design composed by three fundamental features: internal combustion engines, all-steel car bodies and multi-purpose character (ORSATO & WELLS, 2007), and fully integrated productive processes. Since the early twentieth century until recently, innovative processes - as well as technological competences and firm unique resources - intended to improve the automobiles' performance and attributes (price, autonomy, power, noise, velocity, comfort etc.) were focused on such fundamental features.

Thus the structure and performance of internal combustion engines (ICE) were being improved for decades and determined the development of many sub-systems such as fuel injection, engine cooling, lubrication, exhaustion, transmission etc., as well as other features like weight distribution and organization of the components. A complex support structure was also built comprising, for example, a comprehensive network of production and distribution of fuel and components, streets and highways, parking lots, maintenance services, specific laws and regulations, and even more subjective aspects, such as the automobile culture.

Additionally, organizational frameworks were established within firms and networks were built between OEMs and suppliers around the current paradigm. The integration of the body on an all-steel body improved the design of automobiles and reduced its time and costs of production (Nieuwenhuis & Wells, 2007). The multi-purpose character - which refers to the fact that modern cars are designed for different conditions of use – also provides benefits to manufacturers and consumers. For the former, it allowed a car to meet a larger share of consumers, reducing the need for a very extensive range of vehicles for different demands, an important advantage for an industry which profits are dependent on large scale production. For the latter, it allowed a car to serve various conditions of use that it can possibly come across, e.g. long trips, carrying many people and luggage, unpaved roads etc.

In short, the automotive sector has been recognized as a "successful" case of co-evolution between technologies, routines and structures – a classic case of technological evolution from earlier stages of technologic life cycle until its maturation. By following the dominant design, OEM generated an economically efficient product, well adapted to consumers' habits and preferences and physical structures. The development of particular problem-solving methods increased the competences and capabilities of OEM in specific directions in a process of mutual reinforcement. The automobile based on this dominant design became an essential part of modern society, not only because its transportation function but also economically. As pointed by Dosi & Nelson (1994),

> People who learned to drive in their parents' or friends' car powered by an internal combustion engine naturally were attracted to gas powered cars when they themselves came to purchase one, since they knew how they worked. At the same time the ascendancy of automobiles powered by gas burning internal combustion engines made it profitable for petroleum companies to locate gasoline stations at convenient places along highways. It also made it profitable for them to search for more sources of petroleum, and to develop technologies that reduced gasoline production costs. In turn, this increased the attractiveness of gasoline powered cars to car drivers and buyers. (p. 168).

However, in recent years many important transformations on technological regimes and institutions on the automotive sector are taking place, some with potential to challenge the current dominant design. Firstly, with the emergence of new general purpose technologies, such as microelectronics and information and communication technologies (ICT), automotive firms started to invest in the incorporation of such technologies to automobiles and their productive processes, which expanded the range of technological opportunities in the sector. Nevertheless, the incorporation of microelectronics and ICT per se has not defied the dominant design. Rather, the improvement of systems such as emission controls, electronic fuel injection, security and navigation systems, as well as the use of robotics, design software and operational control software, gave an extra boost to the current paradigm, greatly improving ICE vehicles' attributes.

In fact, the dominant design has been challenged by a combination of new technological opportunities (and possibilities) from ICT and microelectronics with profound changes in the opinion of society as a whole in relation to current automobiles: it has been recognized that the automobile imposes enormous costs in terms of environment harm and intensive use of non-renewable resources. According to data from OICA (Organisation Internationale des Constructeurs d'Automobiles), fossil-fueled motor vehicles are responsible for about 16% of anthropogenic emissions of carbon dioxide (CO2) each year.

The disclosure of information and the personal perception of individuals are changing some values of the society, which is considering, slowly and gradually, the importance of environmental issues in its consumption decisions. Due to its huge negative impact on the environment and its importance as a mean of transport on a global level, it is natural that the automobile is among the main targets of these consumption changes. Coupled with the environmental issue is also the instability of oil prices, which affects directly the fuel prices, causing consumers to seek more efficient cars. The notion of efficiency that guided engineers' heuristics and consumer preferences towards the established dominant design has being questioned by incorporating pollution and environmental issues.

Following these transformations, it is possible to point out at least three potential technologic alternatives. The first option involves incremental advancements on technologies that are well adapted to the current dominant design, routines and structures. They can generate important reductions on environmental impact: only a quarter of the energy contained in the fossil fuel is actually converted into mechanical motion, the rest is "wasted", going to the exhaust and cooling systems, as the engine is built to run on different, non-optimal speed and torque ranges. Advances in ICE's technologies have focused on eliminating this loss by reducing friction, increasing combustion efficiency through control valves, thermal efficiency and advances in architectural and the structure of the engine and related systems such as transmission and ignition (NRC, 2010a).

Most of these new technologies refer to the introduction of advanced electronic systems and new lighter and/or resistant materials for the traditional gasoline engines, but also deal with neutralization of some of diesel-powered engines' main disadvantages - noise levels and higher emissions, as they are more efficient, develop higher torque and have less energy losses compared to similar gasoline-powered engines.

The second option, hybrid propulsion technologies, is the intermediate choice between ICE and full electric (and fuel cell) propulsion engines. Their main advantages are the utilization of current infrastructure (but not for plug-in hybrid vehicles), relatively fewer required investments in R&D when compared electric and fuel cell propulsions, and higher environmental benefits in relation to the conventional ICE, as potentially higher efficiency and significant reduction of greenhouse gases (GHG) emissions.

Nevertheless, given the nature of ICE engines, it is virtually impossible to reduce their direct GHG emissions to zero – even hybrid ones. Moreover, there are increasing marginal costs for the development of incremental innovations grounded on current technological paradigm, as alternatives for further developments will be depleted with time, becoming more complex and costly to develop them (NRC, 2010b). Investing in technologies related with ICE engines generates end-of-pipe and integrated innovations that are important to reduce the automobile impact in the short-term because they are more adapted to the current selective environment. However, they are not the final solution for the environmental issue in the long term.

The third alternative relates to the development of more radical, disruptive alternatives to ICE vehicles. They require major changes in routines and structures, but also have technical "bottlenecks" that have prevented further developments and diffusion to the market. The hydrogen fuel cell propulsion, for example, needs several technological breakthroughs to be commercially viable, e.g. low reliability and durability of propulsion systems and high weight and volume of hydrogen tanks onboard.

Battery electric vehicles (BEV), on the other hand, seem to be a more promising alternative to ICE vehicles on the medium term, although their mass diffusion also depends on technological breakthroughs. The main technological bottlenecks for the mass diffusion of BEV refer to production costs, performance attributes and limited characteristics of batteries (weight, autonomy, efficiency in the transformation of chemical energy into electrical energy). The infrastructure for generation and supply of clean electricity for BEV - and hydrogen for fuel cell electric vehicles and the necessity of change in consumer routines are also remarkable issues.

4. NEW “GREEN” TECHNOLOGIC COMPETENCES AND RESOURCES AS SOURCES OF COMPETITIVE ADVANTAGES

The ongoing economic and financial crisis has brought increasing attention to a broadly defined transition to the green economy as a powerful mechanism to escape from the current downturn and foster economic growth through the creation of new competitive advantages based on “green performance” through the development and diffusion of eco-innovations (Andersen, 2008; European Comission, 2011). Eco-innovations can be broadly defined as new or significantly improved products and processes which provide customer and business value but significantly decrease environmental impacts (reduces the use of natural resources, including materials, energy, water and land, and decreases the release of harmful substances across the whole life-cycle) when compared with relevant alternatives (James, 1997). Moreover, eco-innovations can include not only new technical artifacts, but also new social and institutional structures (Rennings, 2000).

Facing increasingly competitive markets and cost pressures, OEM are constantly seeking ways to obtain firm-specific assets and capabilities that generate competitive advantages over their rivals. In a broad sense, alternative propulsion technologies offer one core advantage in relation to existing, traditional ones: substantially lower environmental impact and consequently greater attractiveness for consumers concerned about environmental issues, as well as greater chances to meet future (stricter) emission requirements in important markets.

Mastering the technological competences necessary to produce vehicles based on alternative technologies at a competitive cost (and with technical advantages) over ICE-based vehicles could be one important source of competitive advantages. Following Utterback & Suárez (1993), "(…) creative synthesis of a new product innovation by one or a few firms results in a temporary monopoly situation, high unit profit margins and prices, and sales of the innovation in those few market niches where it possesses the greatest performance advantage over other competing alternatives" (p. 2). Although in the automotive industry this dynamics is closer to an incremental process of de-maturity than radical introduction of new products in a creative destruction framework, the idea seems equally valid, given the complexity of automotive technologies and the advantages given by incremental but important innovations of new and established technologies.

However, firms need to use dynamic capabilities in order to manage new and existent technological competences and resources required for developing alternative propulsion technologies. Battery Electric Vehicles, for instance, require technological competences on batteries and related systems that are not crucial for ICE. They also require the control of new branches on the value chain (through new networks with suppliers or vertical integration) to supply necessary components. Because of the nature of the product and production process, both new and traditional technologies are complex and systemic. Therefore, such competences and firm-specific assets require a large amount of time, resources and management to be developed and OEM will only engage on it if they see enough opportunities to do so.

5. AN ANALYSIS OF CHANGES IN TECHNOLOGICAL COMPETENCES THROUGH PATENT DATA

On this, section we investigate the changes of technological competences of automotive OEM using patent portfolio analysis. Our hypothesis is that firms on automotive sector are developing technologic competences and resources to deal with the new alternative technologies and, in this case, such firms are perceiving sufficient opportunities to do so even considering all the elements that work against this choice (e.g. cost pressures, institutional rigidities, difficulties and costs of developing new technological competences etc.). Thus, this hypothesis would give support to the assumption that eco-innovations in this sector are being perceived as (at least potential) sources of business value and future profits (Andersen, 2008).

So far, firms in general do not disclose much quantitative data about their eco-innovation efforts as would be desirable to construct comprehensive sectoral analyzes. Many scholars hold that the best available source of quantitative data for sectoral eco-innovation analyzes is patents (Popp, 2005; Dechezleprêtre et al., 2008; Oltra et al., 2008). As for innovation in general, patent counts can be used as a proxy for the level of eco-innovation activity and also to analyze changes in the technological trajectory in a given sector. The rate of growth in patenting in a certain technologic field can be used as proxy of its importance and maturity degree.

The use of patents to measure innovative activity is far from perfect. In fact, a patent is a direct - but not perfect - measure of inventive, not innovative activity. According to Pakes (1986), most patents represents technologies at an early stage in inventive process - when firms still have substantial uncertainly about its economic returns or even its applicability and functionalities - and so much of patented inventions do not even go to the market, so do not become innovations. Furthermore, patents are not the only way to protect an invention: in some sectors, firms prefer to use other means as, for example, industrial secrets. Many inventions simply cannot be patented and many innovations are not patented because it is much easier – and safer - to restrict competitors' access to technical information about new industrial processes instead of disclosing the information required for patenting them[1]. Lastly, there is no consensus on the nature of the relationship between patents and innovative activity. If we consider, for example, those patents that are applied in the earlier stages of research processes and therefore tend to be used only as knowledge inputs for further developments, so patents should be considered as inputs for innovative activity. On the other

[1] This is the case for many process innovations and complex products, like automobiles.

hand, if we consider those patents which represent the outcome of a R&D process (new pharmaceutical drugs, for example), so patents should be considered as outputs of innovative activity[2].

However, as Van Pottelsberghe et al. (2001) pointed out, "(…) patent counts should not be discarded as a statistical indicator just because of these limitations. Many statistical indicators, including the most widely utilized, such as GNP (gross national product) also have flaws, sometimes major ones" (p. 137). It is also possible to relativize such limitations: first, patenting an invention can be an expensive, time-consuming process, so is an indicator of the importance of it as – at least – a new relevant knowledge piece for firms that desire to protect it.

Patent analysis can reveals information about eco-innovation activities whereas R&D data cannot because, so far, firms in general make no clear distinction between R&D expenditures on eco-innovation and on "traditional" innovation. Otherwise, the level of disaggregation of patent data allows us to analyze the evolution of the green technologies - and the transformation of traditional technologies towards lower environmental-harm standards. In the case of eco-innovations, an increase on the level of patenting in green technologies –even when they don't go to the market – can be an important indicator of changes in technological trajectories, once they indicate that firms are changing their heuristics towards environmental goals. Furthermore, patent applications are a very good i*ndicator of firms' technological competences*, because patenting is an indicator that the firm has sufficient competences to produce knowledge pieces that are on the technological frontier in a given technological field (Breschi et al., 2003).

Our patent portfolio analysis follows the methodology used by Oltra & Saint Jean (2009), but with different database and selection criteria. We used the Derwent World Patent Index, from Thomson Reuters from 1990 to 2013, allowing us to capture the key phase of eco-innovation emergence. This database can distinguish patent families, avoiding counting the same invention multiple times. To avoid low-quality patents, we selected only patents filled on European Patent Office (EPO) or World Intellectual Property Organization (WIPO). Moreover, instead of using selected keywords to define each technologic group of patents, we adopted selected International Patent Classification (IPC) codes related with green patents in different technological fields from the IPC Green Inventory and the OECD's list of Environmentally-sound technologies (EST) (See Annex 1).

[2]For a further discussion about this topic, see Griliches (1990) and Trajtenberg (1987).

The sample of OEM was chosen based on two requirements: 1) the firm must be listed on OICA's World Motor Vehicle Production ranking[3]; and 2) the number of patents filled on the selected patent offices must be above 500[4]. Based on these criteria, we selected 15 car manufacturers as follows: BMW, Daimler, Fiat, Ford, Fuji Heavy Industries (Subaru), General Motors, Honda, Mazda, Mitsubishi, Nissan, Porsche, PSA (Peugeot-Citroen), Renault, Toyota, and Volkswagen. This sample has two drawbacks: first, one of the main American automakers, Chrysler group, was excluded from the sample, as it merged with Daimler from 1998 to 2007 and was acquired by Fiat group in 2009, making impossible to perform the portfolio analysis on this period. Second, some important OEM from emerging countries – especially China and India – were excluded because they don't have sufficient patents on the selected patent offices. However, we believe that the sample is robust, as it contains the main firms spread over the three main markets – Europe, North America, and Japan.

The following figures present the patent portfolio for four distinct periods of six years each, from 1990 until 2013 (see the raw data on Annex 2). It is possible to see that, among our sample, firms have notably different strategies, given the presented technologies. While some firms continue to rely far more on incremental improvements for conventional ICE through post combustion and integrated innovations, others are changing their portfolios through alternative technologies like hybrid and electric cars and fuel cells. These differences are the result of the differences on the cognitive skills of firms, as both incentives and opportunities can be perceived in different ways by individual firms as a consequence of the history of the corporations and specific institutional settings (Dosi, 1988).

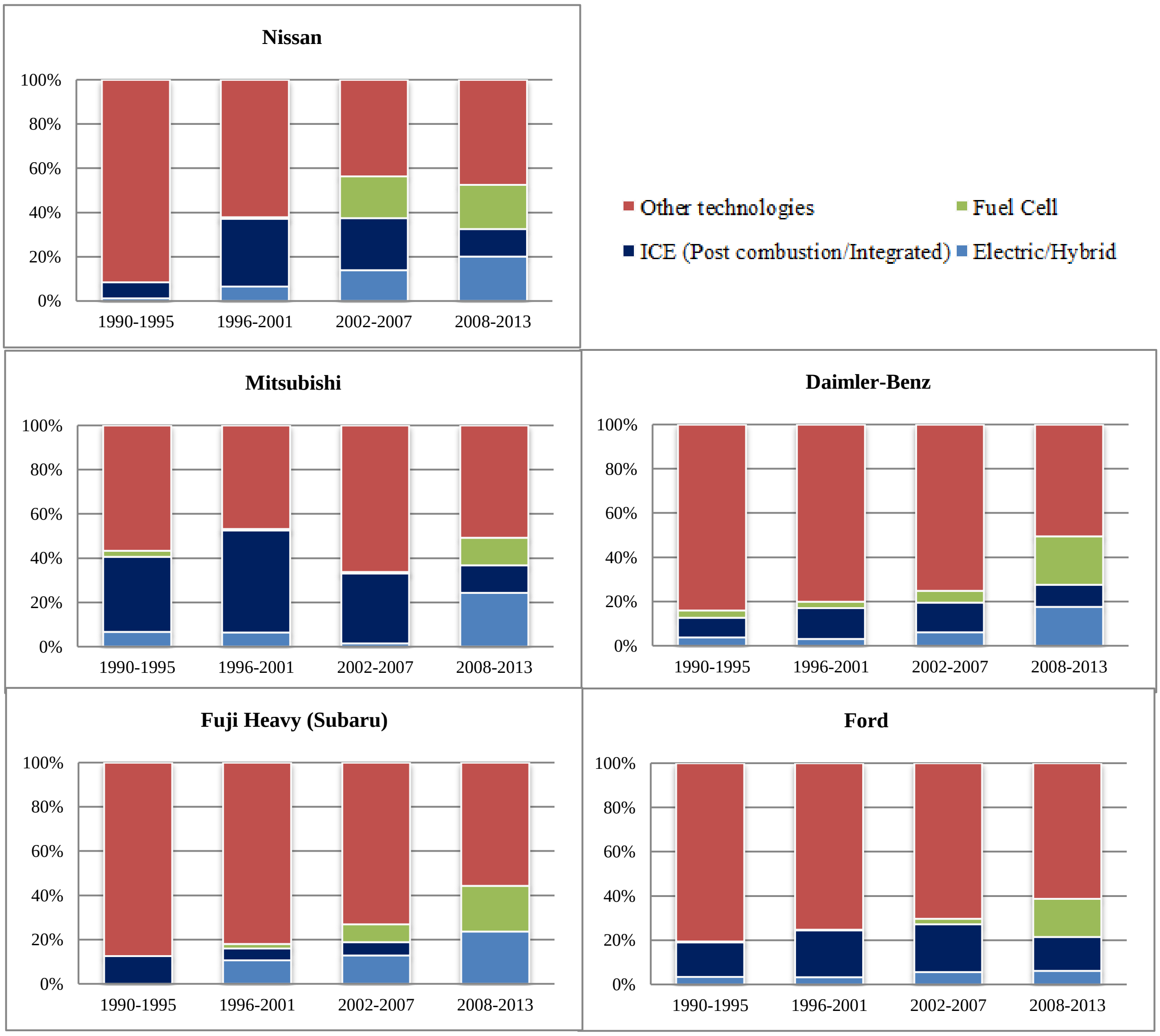
Indeed, automakers seem to agree that hybrid/electric vehicles offer technological opportunities that compensates the costs and risks of developing new technological competences, as all of them have significant shares of patents on these technologies. Some, like Mazda, Fiat, BMW, Renault, PSA and General Motors are focusing specifically on the development of this technology, together with the ICE green technologies. Investing on the development of fuel cells is not a consensus among the firms. General Motors seems to have given up investing on this technology, possibly after the apathy that has taken over the U.S. Government in relation to this technologic

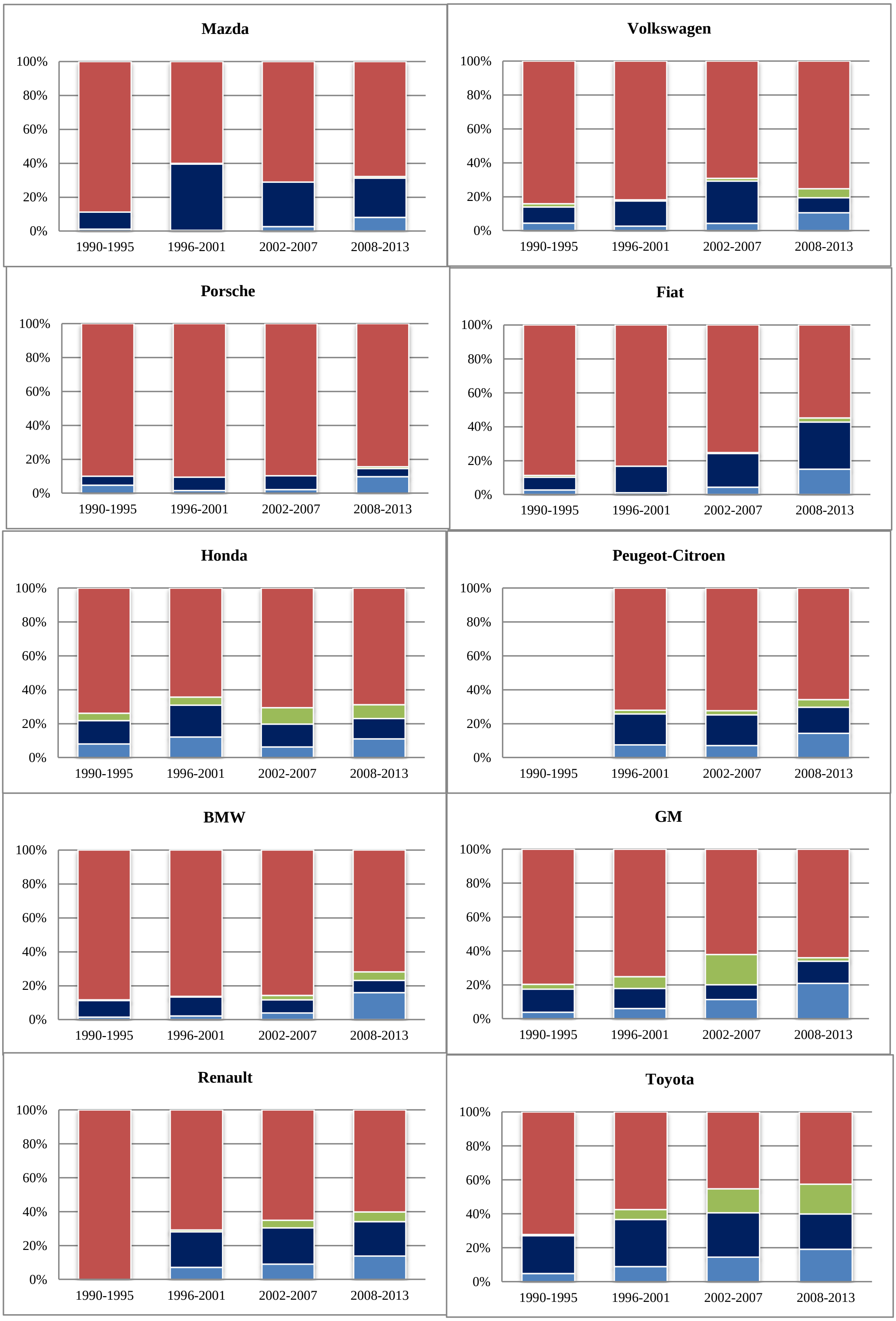
[3] See http://www.oica.net/wp-content/uploads/2013/03/worldpro2012-modification-ranking.pdf

[4] In fact, with this criterion, some of the big OEM from developing countries - especially China - were eventually excluded from the sample, which represents a loss to the analysis. However, we believe that it is impossible to compare the quality and quantity of Chinese patents with the ones filled on the patent offices chosen.

field during the first Obama's administration (NRC, 2010b). Moreover, its main "green product", the Chevrolet Volt, is a hybrid vehicle that has achieved relative success in the market.

Figure 1 – 15: Patent portfolio of selected OEM (Source: own elaboration)





Mazda
Volkswagen
Porsche
Fiat
Honda
Peugeot-Citroen
BMW
GM
Renault
Toyota
100%
80%
60%
40%
20%
0%
1990-1995
1996-2001
2002-2007
2008-2013

From the temporal perspective, some firms started to change their technological competences earlier than others. In the first period (1990-1995), some firms like Toyota, Honda, GM, and Volkswagen already presented in their portfolios a small number of patents related to alternative propulsion technologies, while many had patents related with ICE "green" incremental technologies (a reflection of the restrictions adopted in previous decades). Nissan, Renault, Subaru and others followed the leaders in the subsequent periods. Most firms that invested in fuel cell technology started in the beginning of this century, when the pressures (and opportunities) related with these alternatives became more evident. Lastly, some laggards as Fiat, BMW, Ford, Mazda, and Mitsubishi only very recently started to develop competences on hybrid/electric and fuel cell technologies.

6. DISCUSSION

Our hypothesis on this article is that firms on automotive sector are developing technologic competences and resources to deal with the new alternative technologies and, in this case, such firms are perceiving sufficient opportunities to do so even considering all the elements that work against this choice (e.g. cost pressures, institutional rigidities, difficulties and costs of developing new technological competences etc.).

From the patent data presented, we can argue that, for most firms, the strategy seems to be investing on at least two of the possible alternatives. On one hand, it requires a larger number of resources and technological competences to properly manage so different and complex technologies. However, this strategy is a safeguard, as future scenarios remain uncertain no one knows which technology (or group of technologies) will be economically viable in the future. Moreover, even with all the financial difficulties and cost pressures that followed the crisis, firms have been able to allocate resources to manage technological competencies that enable them to generate knowledge on technologies as diverse as fuel cells and ICE incremental technologies. Especially in the last period, one can see at least one consensus among all automakers regarding the development of new technological competences, as hybrid/electric vehicles are become increasingly important for all of them except perhaps for Ford, which is betting on fuel cells.

Following the portfolios across the last 23 years, one can note how firms are diversifying their patent portfolios in response to institutional and demand pressures, as well as new technologic opportunities, in order to generate competitive advantages derived from the introduction of eco-innovations, especially from the beginning of this century and even more pronounced after the financial crisis in 2008. Our findings support the statement that a transition to the green economy can be (at least on the point of view of automakers) as a powerful mechanism to foster economic growth through the creation of new competitive advantages through the development and diffusion of eco-innovations.

This article is a first draw of a broader study, in which we analyze, based on patent data, the patent families as proxy of economic relevance and technological diffusion between countries, the set of patents and the citations between them, to build networks of ideas and their relatedness, the scientific citations included in patent filings to identify the sources of scientific knowledge that firms rely on when conducting R&D processes, as well as one econometric model to understand sectoral eco-innovation patterns (comparing different sectors).

REFERENCES:

Abernathy, W. J. & Clark, K. B. (1984). Innovation: Mapping the winds of creative destruction. Research Policy, 14, p. 3-22.

Andersen, M. M. (2008). Eco-Innovation - Towards A Taxonomy And A Theory. Paper presented at 25th DRUID Celebration Conference 2008. Link: http://www2.druid.dk/conferences/viewpaper.php?id=3150&cf=29

Anderson, P., & Tushman, M. L. (1990). Technological discontinuities and dominant designs: A cyclical model of technological change. Administrative science quarterly, vol. 31, pp. 604-633.

Arthur, W. B. (1989). Competing technologies, increasing returns, and lock-in by historical events. The economic journal, 99(394), 116-131.

BARNEY, J. B. (1991). Firm resources and sustained competitive. Journal of Management, 17(1), pp. 99-120.

Breschi, S., Lissoni, F. & Malerba, F. (2003). Knowledge relatedness in firm technological diversification. Research Policy, 32(1), 69-87.

Christensen, C. H., Angela, R., Rosane K. G. (1987). An Empirical Investigation of the Factors Influencing Exporting Success of Brazilian Firms, Journal of International Business Studies, 18, 61-77.

David, P. A. (1985). Clio and the Economics of QWERTY. The American economic review, 75(2), 332-337.

Dechezleprêtre, A., Glachant, M., & Ménière, Y. (2013). What drives the international transfer of climate change mitigation technologies? Empirical evidence from patent data. Environmental and resource economics, 54(2), 161-178.

Dechezleprêtre, A., Glachant, M., Ménière, Y. (2008). The Clean Development Mechanism and the international diffusion of technologies: An empirical study, Energy Policy (in press).

Dosi, G. & Nelson, R. R. (1994). An introduction to evolutionary theories in economics. Journal of evolutionary economics, v. 4, n. 3, pp. 153-172.

Dosi, G. (1982). Technological paradigms and technological trajectories: a suggested interpretation of the determinants and directions of technical change. Research policy, 11(3), 147-162.

Dosi, G. (1988). Sources, Procedures, and Microeconomic Effects of Innovation. Journal of Economic Literature, Vol. 26 (3), pp. 1120-1171.

Dosi, G.; Coriat, B. (2002). The nature and accumulation of organizational competences/capabilities. Revista Brasileira de Inovação, v. 1, n. 2, jul./dez. 2002.

European Commission (2011). European Commission (EC) (2011) Roadmap to a resource efficient Europe, COM(571). Final, Brussels.

Faber, A., & Frenken, K. (2009). Models in evolutionary economics and environmental policy: Towards an evolutionary environmental economics. Technological Forecasting and Social Change, 76(4), 462-470.

Griliches, Z. (1990). Patent Statistics as Economic Indicators: A Survey, Journal of Economic Literature, American Economic Association, vol. 28(4), pages 1661-1707, December.

James, P. (1997). The Sustainability Circle: a new tool for product development and design, in The Journal of Sustainable Product Design, Issue 2, (July 1997), pp 52-57.

Leonard-Barton, D. (1995). Wellsprings of Knowledge: Building and Sustaining the Sources of Innovation, Boston, MA, Harvard Business School Press.

Malerba, F. (2002). Sectoral Systems of Innovation and Production. Research Policy 31 (2002), pp. 247-264.

Nelson, R. & Winter, S. (1977). In Search of a Useful Theory of Innovations". Research Policy, v.6, n.1, pp. 36-76.

Nelson, R. & Winter, S. (1982). An Evolutionary Theory of Economic Change. Cambridge, MA: Harvard University Press.

Nieuwenhuis, P. & Wells, P. (2007). The all-steel body as a cornerstone to the foundation of the mass production car industry. Industrial and Corporate Change, Vol. 16, n. 2, p. 183-211.

NRC, (2010a). Assessment of Technologies for Improving Light Duty Vehicle Fuel Economy, National Research Council. National Academies Press. Available at: http://www.nap.edu/catalog/12924.html.

NRC, (2010b). Review of the Research Program of the FreedomCAR and Fuel Partnership: Third Report. National Research Council. National Academies Press. Available at: http://www.nap.edu/catalog/12939.html.

Oltra, V. & Saint Jean, M. (2008). Sectoral systems of environmental innovation: An application to the French automotive industry. DIME Working Papers on Environmental Innovation, nº 4. Disponível em: http://www.dime-eu.org/wp25/wp.

Oltra, V., & Saint Jean, M. (2009). Sectoral systems of environmental innovation: an application to the French automotive industry". Technological Forecasting and Social Change, 76(4), 567-583.

Oltra, V., Kemp, R., & De Vries, F. P. (2010). Patents as a measure for eco-innovation. International Journal of Environmental Technology and Management, 13(2), 130-148.

Orsato, R. J. & Wells, P. (2007). U-turn: the rise and demise of the automobile industry. Journal of Cleaner Production 15 (2007), pp. 994-1006.

Pakes, A. (1986). Patents as Options: Some Estimates of the value of Holding European Patent Stocks. Econometrica, 54(4), 755-84.

Pavitt, K. (1998). Technologies, Products & Organisation in the Innovating Firm: What Adam Smith tells us and Joseph Schumpeter doesn't. Industrial and Corporate Change. 7, 433-457.

Penrose, E. T. (1959). The Theory of the Growth of the Firm, 3rd ed., Oxford: Oxford University Press.

Perez, C. (2010). Technological revolutions and techno-economic paradigms. Cambridge Journal of Economics, 34(1), 185-202.

Popp, D. (2005). Using the triadic patent family database to study environmental innovation. Environment Directorate Working Paper ENV/EPOC/WPNEP/RD (2005), 2.

Porter, M. E. (1996). "What is Strategy?", Harvard Business Review, November-December: 61-78

Prahalad, C. K., & Hamel, G. (1990). The core competence of the corporation. Boston (MA).

Rennings, K. (2000). Redefining Innovation - Eco-innovation Research and the contribution from Ecological Economics, in Ecological Economics, 32, pp. 319-322.

Teece D., Pisano G., Shuen A. (1997). Dynamic capabilities and strategic management. Strategic Management Journal 18(7): 509-533.

Teece, D. &Pisano, G. (1994). The dynamic capabilities of firms: an introduction. Industrial and corporate change, v. 1, n. 3, 1994.

Trajtenberg, M. (1987). Towards an Industrial and Technological Policy for Israel: Analytical Foundations and some Specific Proposals (with M. Justman and M. Teubal, in Hebrew), The Economic Quarterly, 37, February 1987, 978-989.

Utterback, J. M. & Abernathy, W. J. (1975). A dynamic model of process and product innovation Omega, Volume 3, Issue 6, December 1975, pp. 639-656.

Utterback, J. M., & Suarez, F. F. (1993). Innovation, competition, and industry structure. Research policy, 22(1), 1-21.

Van Pottelsberghe P., B. & Lichtenberg, F. (2001), Does foreign direct investment transfer technology across borders. Review of Economics and Statistics 83(3).

Annex 1: Correspondence between IPC classes and green technologies

1. Internal combustion engines

1.1 Integrated Emissions Control

IP=(F01N-011/00 OR F01N-009/00 OR F02B-047/06 OR F02D-041/* OR F02D-043/* OR F02D-045/00 OR F02M-023/* OR F02M-025/00 OR F02M-025/02* OR F02M-025/03* OR F02M-025/06 OR F02M-025/08 OR F02M-025/10 OR F02M-025/12 OR F02M-025/14 OR F02M-027/* OR F02M-003/02 OR F02M-003/04* OR F02M-003/05* OR F02M-003/06 OR F02M-003/07 OR F02M-003/08 OR F02M-003/09 OR F02M-003/10 OR F02M-003/12 OR F02M-003/14 OR F02M-031/02 OR F02M-031/04 OR F02M-031/06 OR F02M-031/07 OR F02M-031/08* OR F02M-031/093 OR F02M-031/10 OR F02M-031/12* OR F02M-031/13* OR F02M-031/14 OR F02M-031/16 OR F02M-031/18 OR F02M-039/* OR F02M-041/* OR F02M-043/* OR F02M-045/* OR F02M-047/* OR F02M-049/* OR F02M-051/* OR F02M-053/* OR F02M-055/* OR F02M-057/* OR F02M-059/* OR F02M-061/* OR F02M-063/* OR F02M-065/* OR F02M-067/* OR F02M-069/* OR F02M-071/* OR F02P-005/*)

1.2 Post Combustion emissions control

IP=(B01D-041/* OR B01D-046/* OR B01D-053/92 OR B01D-053/94 OR B01D-053/96 OR B01J-023/38 OR B01J-023/40 OR B01J-023/42 OR B01J-023/44 OR B01J-023/46 OR F01M-013/02 OR F01M-013/04 OR F01N-011/00 OR F01N-003/01 OR F01N-003/02* OR F01N-003/03* OR F01N-003/04 OR F01N-003/05 OR F01N-003/06 OR F01N-003/08 OR F01N-003/10 OR F01N-003/18 OR F01N-003/20 OR F01N-003/22 OR F01N-003/24 OR F01N-003/26 OR F01N-003/28 OR F01N-003/30 OR F01N-003/32 OR F01N-003/34 OR F01N-005/* OR F02B-047/08 OR F02B-047/10 OR F02D-021/06 OR F02D-021/08 OR F02D-021/10 OR F02M-025/07 OR G01M-015/10)

2. Electric/Hybrid propulsion

2.1 Propulsion using Electric motors

IP=(B60K-001/* OR B60K-016/00 OR B60L-011/* OR B60L-015/* OR B60L-007/1* OR B60L-007/20 OR B60L-008/00 OR B60R-016/033 OR B60R-016/04 OR B60S-005/06 OR B60W-010/08 OR B60W-010/26 OR B60W-010/28 OR H02J-015/00 OR H02J-003/28 OR H02J-003/30 OR H02J-003/32 OR H02J-007/00 OR H01M-010/44 OR H01M-010/46 OR H01G-011/00 OR H02J-007/00 OR OR H01M 10/0525 OR H01M 10/50 OR H01M-010/04)

2.2 Hybrid-electric propulsion

IP=(B60K-006/* OR B60L-007/16 OR B60W-020/00 OR F16H-003/* OR F16H-048/00 OR F16H-048/05 OR F16H-048/06 OR F16H-048/08 OR F16H-048/10 OR F16H-048/11 OR F16H-048/12 OR F16H-048/14 OR F16H-048/16 OR F16H-048/18 OR F16H-048/19 OR F16H-048/20 OR F16H-048/22 OR F16H-048/24 OR F16H-048/26 OR F16H-048/27 OR F16H-048/28* OR F16H-048/29* OR F16H-048/30).

3. Fuel Cells

IP=(H01M-012/* OR H01M-002/* OR H01M-004/86 OR H01M-004/88 OR H01M-004/9* OR H01M-008/* OR B60L-011/18)

Annex 2 – Patent portfolio – Raw data (number of patents filled on EPO and WIPO)

BMW	1990-1995	1996-2001	2002-2007	2008-2013	Daimler	1990-1995	1996-2001	2002-2007	2008-2013
Electric/Hybrid	4	24	56	223		18	28	51	290
ICE (Post combustion/Integrated)	29	124	113	101		42	127	110	164
Fuel Cell	1	4	38	70		15	26	44	362
Other technologies	259	959	1252	1009		396	728	620	831
Total Patents	293	1111	1459	1403		471	909	825	1647
FIAT	**1990-1995**	**1996-2001**	**2002-2007**	**2008-2013**	**FORD**	**1990-1995**	**1996-2001**	**2002-2007**	**2008-2013**
Electric/Hybrid	8	3	26	49		28	43	61	46
ICE (Post combustion/Integrated)	22	44	120	92		132	277	236	116
Fuel Cell	3	0	3	8		3	3	28	130
Other technologies	262	234	455	181		679	984	769	462
Total Patents	295	281	604	330		842	1307	1094	754
GM	**1990-1995**	**1996-2001**	**2002-2007**	**2008-2013**	**HONDA**	**1990-1995**	**1996-2001**	**2002-2007**	**2008-2013**
Electric/Hybrid	28	45	130	181		38	142	198	384
ICE (Post combustion/Integrated)	100	87	99	113		65	220	423	418
Fuel Cell	21	51	203	17		21	55	301	285
Other technologies	581	553	708	554		348	750	2208	2385
Total Patents	730	736	1140	865		472	1167	3130	3472
MAZDA	**1990-1995**	**1996-2001**	**2002-2007**	**2008-2013**	**MITSUBISHI**	**1990-1995**	**1996-2001**	**2002-2007**	**2008-2013**
Electric/Hybrid	3	1	12	24		10	9	2	88
ICE (Post combustion/Integrated)	25	78	116	69		51	65	44	45
Fuel Cell	0	1	0	3		4	1	1	45
Other technologies	221	120	315	202		85	66	92	184
Total Patents	249	200	443	298		150	141	139	362
NISSAN	**1990-1995**	**1996-2001**	**2002-2007**	**2008-2013**	**PORSCHE**	**1990-1995**	**1996-2001**	**2002-2007**	**2008-2013**
Electric/Hybrid	3	35	295	361		14	6	11	27
ICE (Post combustion/Integrated)	19	163	496	224		16	30	43	13
Fuel Cell	0	4	399	358		0	0	0	3
Other technologies	239	331	920	853		269	344	474	234
Total Patents	261	533	2110	1796		299	380	528	277
PEUGEOT/CITROEN	**1990-1995**	**1996-2001**	**2002-2007**	**2008-2013**	**RENAULT**	**1990-1995**	**1996-2001**	**2002-2007**	**2008-2013**
Electric/Hybrid	0	10	75	248		0	31	128	202
ICE (Post combustion/Integrated)	0	24	192	264		0	91	303	294
Fuel Cell	0	3	25	78		0	5	63	84
Other technologies	0	95	764	1134		2	307	920	875
Total Patents	0	132	1056	1724		2	434	1414	1455
TOYOTA	**1990-1995**	**1996-2001**	**2002-2007**	**2008-2013**	**VOLKSWAGEN**	**1990-1995**	**1996-2001**	**2002-2007**	**2008-2013**
Electric/Hybrid	27	168	601	1732		12	37	58	194
ICE (Post combustion/Integrated)	125	522	1085	1877		26	208	333	165
Fuel Cell	4	110	589	1599		5	10	22	97

Other technologies	406	1084	1887	3854
Total Patents	562	1884	4162	9062

	229	1143	924	1393
Total Patents	272	1398	1337	1849

Fuji Heavy (Subaru)	**1990-1995**	**1996-2001**	**2002-2007**	**2008-2013**
Electric/Hybrid	0	16	49	25
ICE (Post combustion/Integrated)	1	8	23	0
Fuel Cell	0	3	31	22
Other technologies	7	123	280	59
Total Patents	8	150	383	106