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UNDERSTANDING THE EVOLUTION OF ECO-INNOVATIVE ACTIVITY IN THE AUTOMOTIVE SECTOR: A PATENT BASED ANALYSIS

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Abstract

The paper aims to analyze the evolution of eco-innovative activity and strategies in the automotive sector over time. We suggest to use a patent count methodology tracking the development of selected technologies considered as promising ?green technologies? in the automotive sector. The paper contributes to an understanding of the industrial dynamics of the greening of industry and the economy , a theme little analyzed despite the huge and rapidly increasing literature on sustainable development and innovation. Our findings show that all the major firms in the automotive industry are diversifying their patent portfolios in order to generate competitive advantages derived from the introduction of eco-innovations, activities emerging in the 1990s and accelerating in scope and radicality in the end zeroes. All the firms are engaging in developing new alternative green trajectories to the existing dominant design, even though there is some variety in the strategic responses of the firm. The main firms within the industry do go green at a fairly similar pace hinting at important horizontal dynamics of the greening of industry, whereas focus has tended to be on the vertical greening dynamics. The analysis demonstrates the current fluid emerging stage of the greening of the economy but also illustrates that eco-innovation is already an important competitive factor globally.

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ABSTRACT: The paper aims to analyze the evolution of eco-innovative activity and strategies in the automotive sector over time. We suggest to use a patent count methodology tracking the *development of selected technologies considered as promising "green technologies" in the* automotive sector. The paper contributes to an understanding of the industrial dynamics of the greening of industry and the economy , a theme little analyzed despite the huge and rapidly increasing literature on sustainable development and innovation. Our findings show that all the major firms in the automotive industry are diversifying their patent portfolios in order to generate competitive advantages derived from the introduction of eco-innovations, activities emerging in the 1990s and accelerating in scope and radicality in the end zeroes. All the firms are engaging in developing new alternative green trajectories to the existing dominant design, even though there is some variety in the strategic responses of the firm. The main firms within the industry do go green at a fairly similar pace hinting at important horizontal dynamics of the greening of industry, whereas focus has tended to be on the vertical greening dynamics. The analysis demonstrates the current fluid emerging stage of the greening of the economy but also illustrates that eco-innovation is already an important competitive factor globally.

1. INTRODUCTION

Technological advancement has a complex relationship with environment issues, as much of the damage to the environment can be attributed to actual product and production process technologies, but, on the other hand, the development of more efficient technologies is certainly one of the greatest allies in efforts to reduce environmental impact. The automobile is essential for the functioning of modern societies, but 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 green 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.

The paper aims to analyze the evolution of eco-innovative activity and strategies in the automotive sector over time. We have chosen to use a patent count methodology tracking the development of selected technologies considered as promising “green technologies” in the automotive sector. The paper contributes to an understanding of the industrial dynamics of the greening of industry and the economy, a theme little analyzed despite the huge and rapidly increasing literature on sustainable development and innovation. This literature tends to be either much focused on policy effects, on firm competitive effects and drivers (i.e. testing the Porter hypothesis on green competitiveness), or on macro-economic effects (Grove, Fisk, Pickett, & Kangun, 1996; Bartlett & Trifilova, 2010; Rennings, 2000; Hamdouch & Depret, 2010; Rennings & Rammer, 2011; Costantini & Mazzanti, 2012; Fankhauser et al., 2013). Specific analysis of green industrial dynamics per se are lacking (Andersen, 2008, 2012; Schiederig, Tietze, & Herstatt, 2011) and while there are some sectoral case studies on eco-innovation, there are none which situate these in a historical context as part of business cycles in a wider green economic evolution. They fail none the least to analyze how the greening of industries are interlinked and co-evolve with organizational and institutional changes. The research gap is caused by the fact that researchers of industrial dynamics and evolutionary economics have hitherto been little active in the environmental sustainability area (Andersen, 2012).

This paper is a preliminary work of a series of articles aiming to identify sectoral patterns of eco-innovations based primarily on patent data. The paper suggests to combine evolutionary theories of business cycles, trajectory change and techno-economic paradigm changes (Utterback & Abernathy, 1975; Arthur, 1989, Nelson & Winter, 1982) with theories on dynamic capabilities (Teece, Pisano, & Shuen, 1997; Langlois, 2003) and sectoral innovation patterns (Pavitt 1984; Dosi 1988; Malerba 2002) to understand how the dynamics of green economic evolution is linked to the greening of (varies) industries. This is key, we argue, to investigate the determinants of the rate and direction of green economic change. The overall theme of the paper - analyzing the greening of industries - hence contributes importantly to fundamental evolutionary economic questions on understanding paradigmatic changes in the economy and technology in real time. The analysis is made difficult by poor data availability. Rigorous definitions and statistics on eco-innovation are lacking, and there is particularly a lack of data at the sector and sub-sector levels (Andersen, 2006; Kemp and Pearson, 2007; OECD, 2011).

Our findings show that all the major firms in the automotive industry 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, emerging and becoming more pronounced after the financial crisis in 2008. All the firms are engaging in developing radically different alternative green trajectories to the existing dominant design, even though there is some variety in the strategic responses of the firms. The main firms within the industry do go green at a fairly similar pace hinting at important horizontal dynamics of the greening of industry, whereas focus has tended to be on the vertical greening dynamics. The analysis demonstrates the current fluid emerging stage of the greening of the economy but also illustrates that eco-innovation is already an important competitive factor.

The article is composed of a literature review on dynamic capabilities and technology life cycles in order to discuss elements that foster (and hinder) changes in technological competences and capabilities. Thereafter, we briefly apply these elements on the automotive sector, linking with its recent transformations on institutions, demand behavior and complementary technologies. Then, we present the methodology based on patent counts and the preliminary data. Finally, we discuss the results of the patent portfolio analysis in the final section.

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, compare the semantic work of Penrose (1959), who 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 to 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 entail 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 strategic response to changes in the selection environments.

The selection 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 led 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 the existent technologies are, the more "costly" these changes tend to be. As pointed out 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 to the fact that changing firm-specific assets, capabilities and competences is costly (not only in financial terms), so firms will only engage in 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 IN THE AUTOMOTIVE SECTOR

Traditionally, the automotive sector 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 – firms targeted at improving such fundamental features of the automobiles' performance and attributes (price, autonomy, power, noise, velocity, comfort etc.).

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, the profits of which 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 technologies and institutions in 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.

The dominant design has been challenged by a combination of new technological opportunities (and possibilities) from ICT and microelectronics as well as more lately with rising green demands, not only from policymakers but also from the market: It has been increasingly recognized that the automobile imposes enormous costs in terms of environmental 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 total anthropogenic emissions of carbon dioxide (CO_2) each year. With the rise of the strong climate mitigation agenda based on the alignment of energy supply and security policies around 2006-2009, automobiles were increasingly under attack.

The rising disclosure of information and the personal perception of individuals are changing some values of customers, which are considering, slowly and gradually, the importance of environmental issues in their consumption decisions. Due to its huge negative and quite visible 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. In fact car driving has become a symbol of unsustainable living, leading to severe legitimacy problems for the automotive industry. 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 overall been seriously questioned by incorporating 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 they 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 to 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 in the development of incremental innovations grounded on the current technological paradigm, as alternatives for further developments will be depleted with time, becoming more complex and costly to develop (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 considered and intermediary rather than a 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 - such as hydrogen and battery electric 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 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" TECHNOLOGICAL COMPETENCES AND RESOURCES AS A COMPETITIVE STRATEGY

The economy has since the beginning of the 1990s undergone a slow transition to a green economy, where the environment increasingly is becoming a driver for business; a transition which initially was very slow but has picked up more pace in the end zeroes (Andersen, 2012). The rise of the green economy should be seen as partly the result of the search to find other competitive factors than costs in the high costs economies threatened by globalization, partly the result of 40-50 years of learning effects in industry from environmental policies supported by a general maturity of the environmental debate in society and research, and partly more informed customers facilitated by ICT and general education (Andersen, 2012). Specifically, up during the 1990s, policies have increasingly sought to promote proactive green strategies in companies realizing the shortcomings of prior policies and the need to internalize green decision and competence building already in the early phases of the innovation process, in order to achieve sufficient environmental solutions (Andersen 2008). The current economic and financial crisis of the rich economies has brought increasing policy and societal attention to green growth as a possible mechanism to escape from the current downturn, and foster new types of competitive advantages based on "green performance", through the development and diffusion of eco-innovations (Andersen, 2008; 2012; European Comission, 2011; UNEP, 2011; United Nations & OECD, 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 (reduce the use of natural resources, including materials, energy, water and land, and decrease 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 with globalization, 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 that are not related with the dominant design.

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 in these if they see enough opportunities to do so.

5. AN ANALYSIS OF ECO-INNOVATIVE CHANGES IN OEM TECHNOLOGICAL COMPETENCES THROUGH PATENT DATA

In this section we investigate the emergence of eco-innovative activities and competences of automotive OEM using patent portfolio analysis. Our starting point of analysis is that the greening of the economy is a global techno-economic paradigm change affecting all industries but in different ways (Andersen, 2008, 2012). Derived from this our hypothesis is that firms in the automotive sector are facing sufficiently similar competitive conditions and possess sufficiently similar technologic competences and resources to go green at a similar pace. But the firms are also amply heterogeneous and influenced by different institutional settings to develop each their competitive strategy and business model. We seek to trace how the OEM firmsseekto take advantage of and shape the greening of the economy. At the firm level firms will only change to green business models and eco-innovative activities if they perceive sufficient business opportunities to do so, considering the cost pressures, institutional rigidities and costs of developing new technological competences.

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. Although patent analyses on eco-innovation are new and limited, some 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 represent technologies at an early stage in an inventive process - when firms still have substantial uncertainly about the economic returns or even the applicability and functionalities of the technology - and so many patented inventions do not even go to the market, and 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, those patents should be considered as inputs for

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

innovative activity. On the other hand, if we consider those patents which represent the outcome of a R&D process (new pharmaceutical drugs, for example), those 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: 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 reveal 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 and strategies towards environmental goals. Furthermore, patent *applications are a very good indicator 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's study on eco-innovation (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 technological group of patents, we adopted selected International Patent Classification (IPC) codes related with 'green patents' in different technological fields as defined from the recent IPC Green Inventory and the OECD's list

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

of Environmentally-sound technologies (EST), a classification that has been little analyzed so far (See Annex 1).

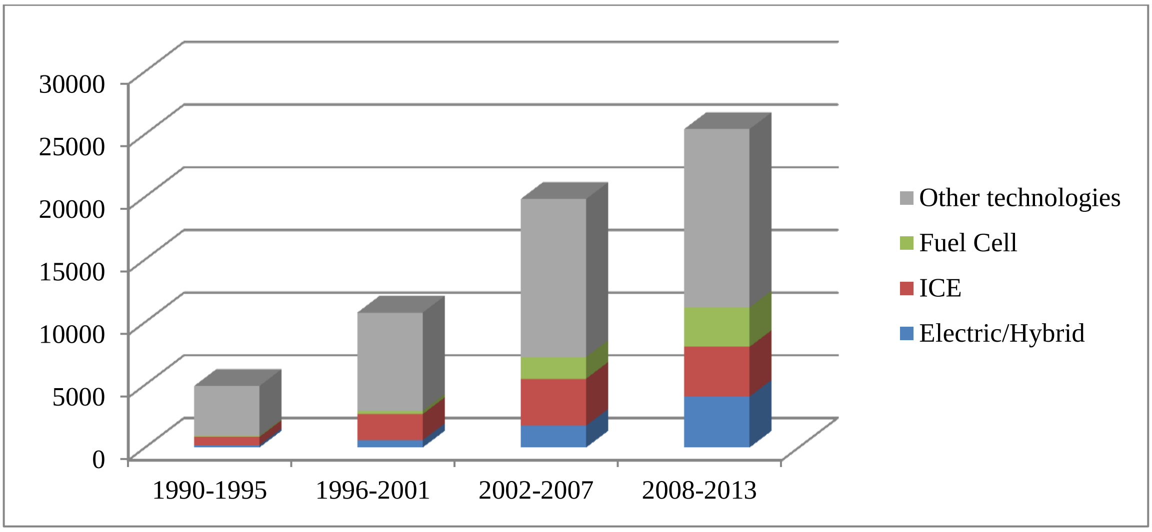
The sample of OEM was chosen based on two requirements: 1) the firm must be listed on OICA's World Motor Vehicle Production ranking 2012[3]; and 2) the number of patents filled on the selected patent offices must be above 500[4]. Based on these criteria, we selected 15 car manufacturers as follows: BMW, 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 it impossible to perform the portfolio analysis in this period. Second, some important OEM from emerging countries – especially China and India – were excluded because they don't have sufficient patents from the selected patent offices. However, we believe that the sample is robust, as it contains the main firms spread over the three main current 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 data on Annex 2). While firms continue to rely also on incremental improvements for conventional ICE through post combustion and integrated innovations, there is a change movement towards alternative technologies like hybrid and electric cars and fuel cells beginning in the early 1990s, increasing slowly around the millennium, then growing quite considerably in the last period. It is possible to see, however, that firms on our sample have notably different strategies, given the presented technologies. Such differences are the result of distinct business models, knowledge bases, and technological competences, as well as other institutional factors.

Figure 1. Number of patents of major selected automakers by technology

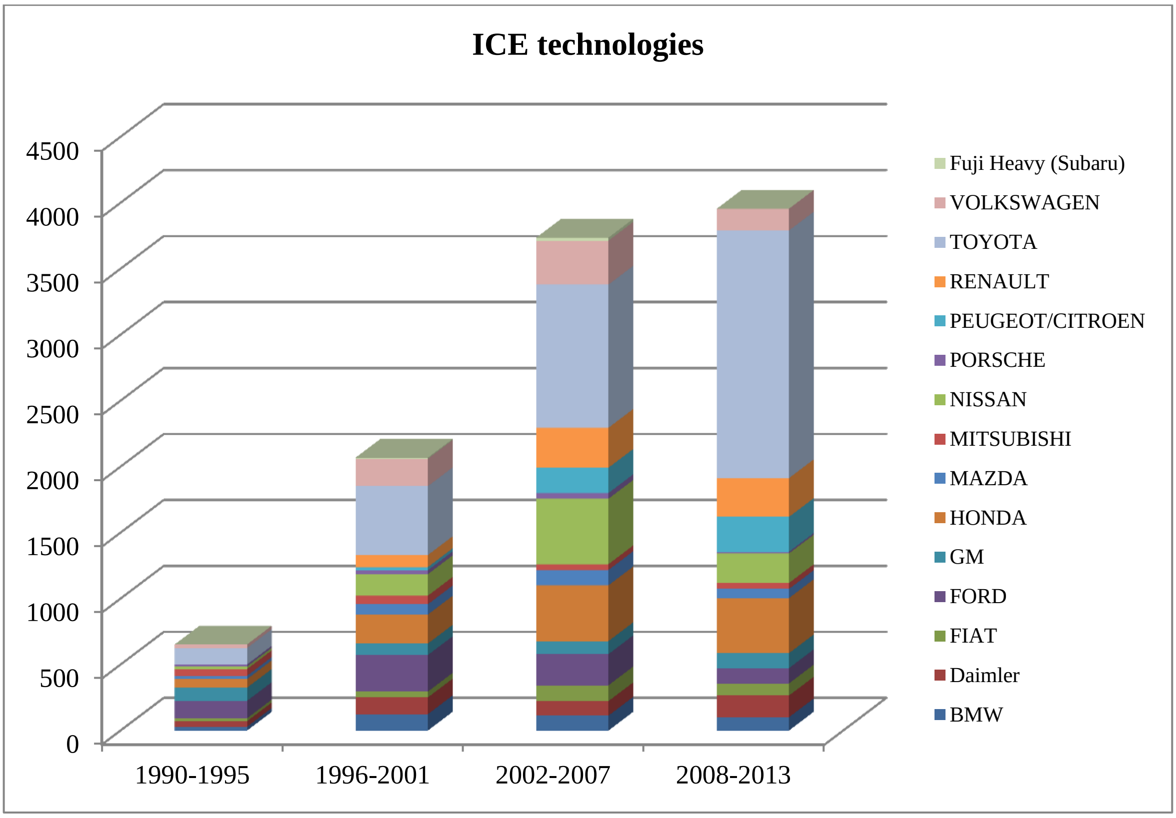
[3] See http://www.oica.net/wp-content/uploads/2013/03/worldpro2012-modification-ranking.pdf

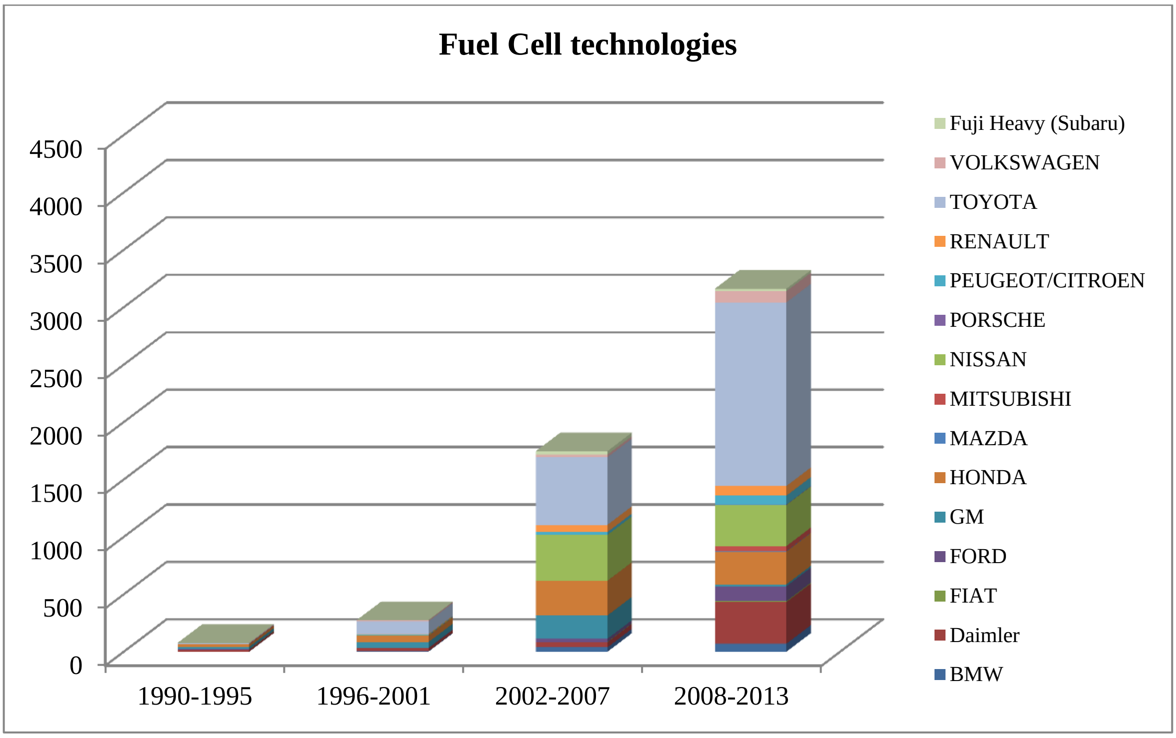
[4] In fact, with this criterion, some of the big OEM from developing countries - especially China - were eventually excluded from the sample, which represents a loss to the analysis. However, we believe that it is impossible to compare the quality and quantity of Chinese patents with the ones filled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

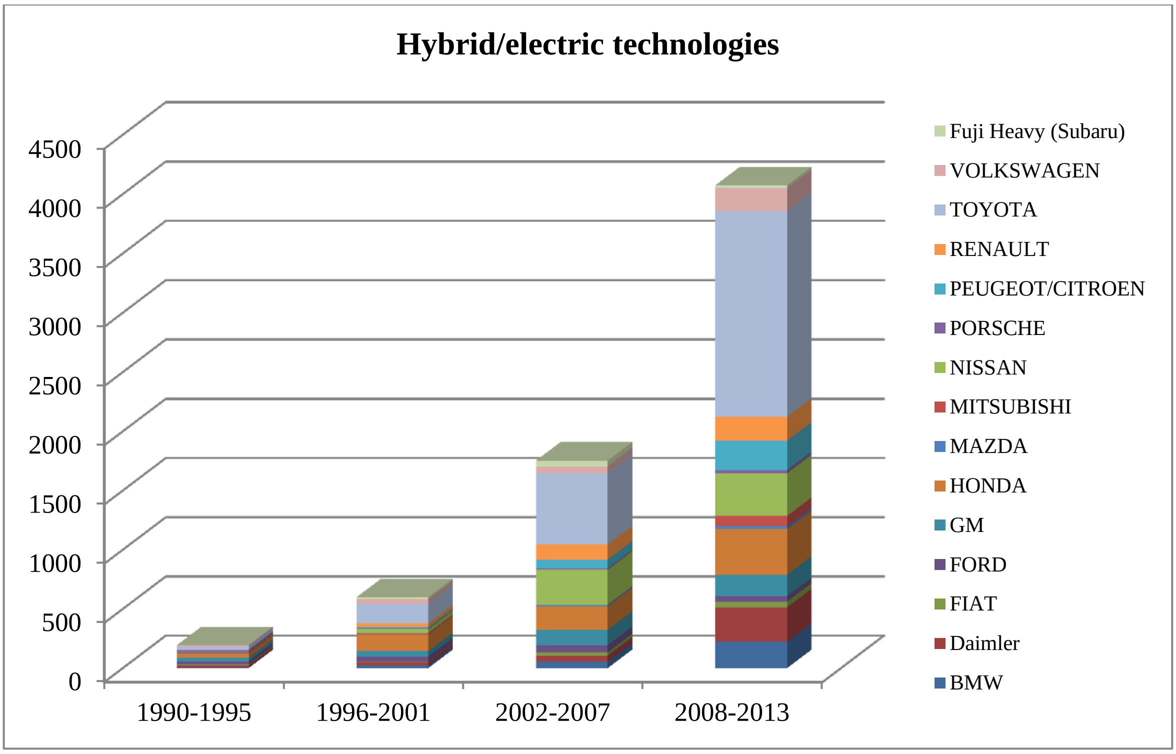


Source: own elaboration, based on Derwent World Patent Index data.

Figures 2-4. Evolution of patent applications on selected technologies





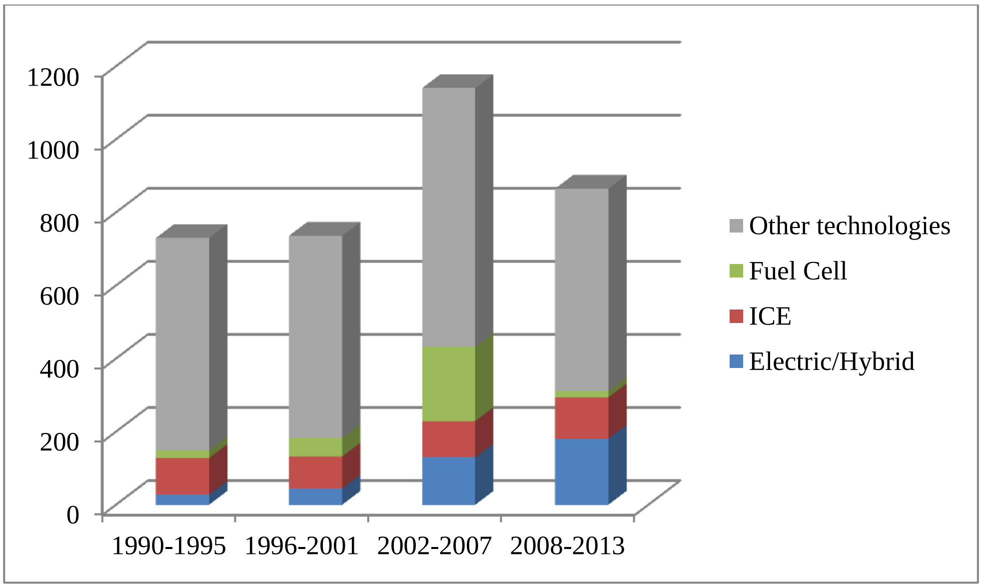


Source: own elaboration, based on Derwent World Patent Index data.

From the data above, it is clear that automakers are investing increasingly in both alternative and mature technologies. Toyota stands out and has contributed immensely to this growth in all three technologies, but especially on fuel cells, followed by Nissan, Honda and Daimler. From the temporal perspective, some firms started to change their technological competences earlier than others. In the first period (1990-1995), pioneering firms like Toyota, Honda, GM, and Volkswagen already presented in their portfolios a small number of patents related to alternative propulsion technologies, while many simultaneously had patents related with ICE "green" incremental technologies (a reflection of the restrictions adopted in previous decades). However, fuel cell technologies only arose as relevant alternative on the 2000's, when the pressures (and opportunities) related with these alternatives became more evident (NRCb, 2010). Lastly, some laggards as Fiat, BMW, Ford, Mazda, and Mitsubishi only very recently started to develop competences on hybrid/electric and fuel cell technologies and still rely mostly on ICE.

Indeed, automakers seem to agree that hybrid/electric vehicles offer increased technological opportunities that compensate the costs and risks of developing new green technological competences, as all of them have dedicated some part of their portfolios to this technology. Investing on the development of fuel cells, however, is not characterized by the same level of a consensus, nor is it a linear trend. General Motors, for instance, gave up investing in this technology, possibly after the apathy that has taken over the U.S. Government in relation to this technologic field during the first Obama's administration (NRC, 2010). Moreover, its main "green product", the Chevrolet Volt, is a hybrid/electric vehicle that has achieved relative success in the market, influencing opportunity perceptions on this technology (see Figure 5).

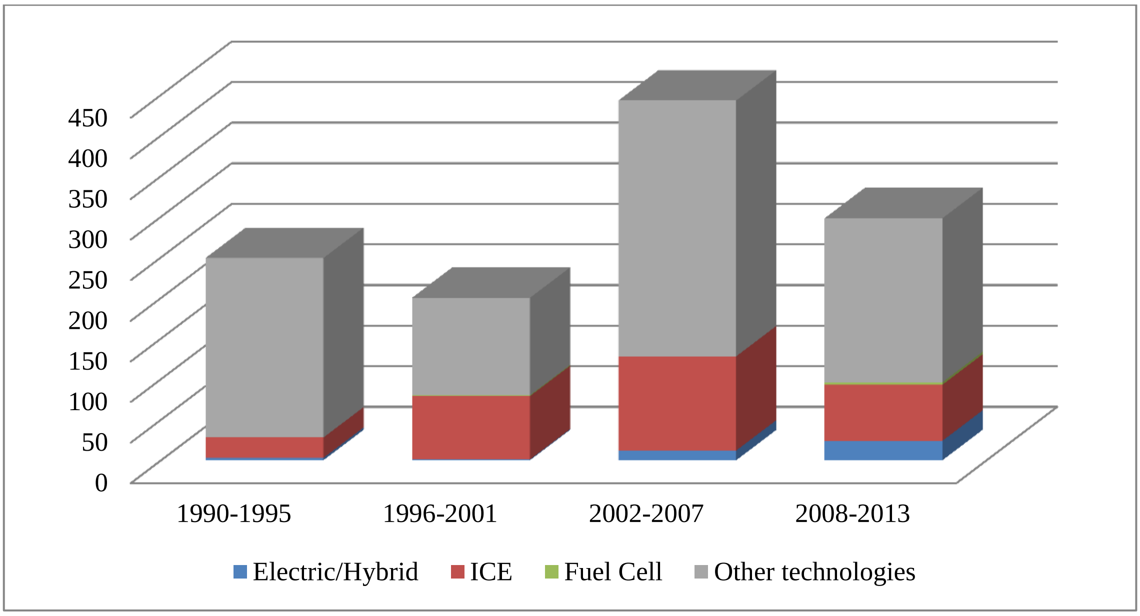
Figure 5: General Motors' patent portfolio



Source: own elaboration, based on Derwent World Patent Index data.

Mazda is the only company which openly has adopted a strategy of only developing more efficient ICE engines instead of alternative technologies. Mazda's Building Block strategy states that "(…) even in 2020, Mazda expects that the world's key energy sources will continue to be mainly petroleum-based and that the majority of vehicles will still be powered by internal combustion engines. Consequently, Mazda's Building-Block Strategy prioritizes improvements in base technologies such as improving the engine's thermal efficiency and reducing the weight of the vehicle body."[5] This strategy is reflected on Mazda's patent portolio, which has the smallest share of fuel cell and hybrid/electric technologies and only taken on recently (Figure 6). However, even Mazda has plans to launch hybrid vehicles but using licensed technology from Toyota[6]. Their strategy of late entrance on the green market and reliance on others green R&D may prove to be a cost –efficient way to green growth.

Figure 6: Mazda's patent portfolio



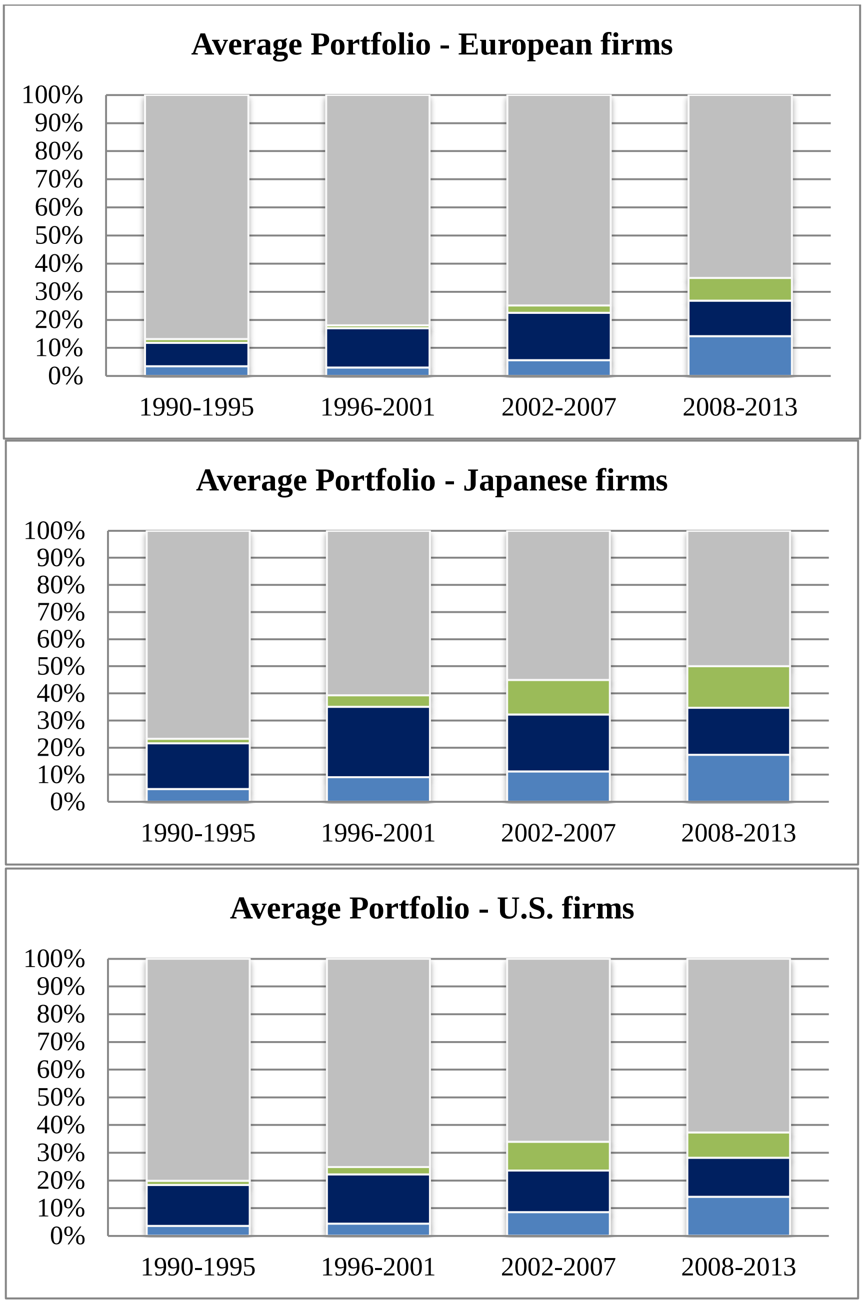
Source: own elaboration, based on Derwent World Patent Index data.

From the geographical point of view, there are, interestingly, not many differences between American, European, and Japanese firms' green patent portfolios.

[5] Source: http://www.mazda.com/csr/environment/vision/sustainable.html.

[6] Source: http://www.reuters.com/article/2013/11/19/us-autoshow-tokyo-mazda-idUSBRE9AI15C20131119

Figures 7-9. Average patent portfolio by geographic position



Source: own elaboration, based on Derwent World Patent Index data.

The only major difference is that Japanese firms are investing more in fuel cells than American and European firms. The Japanese firms started investing in these technologies earlier, as in average almost 10% of their patents were green already in the second period (1996-2001). From 2002 and onwards, Japanese firms have become the leaders on these technologies, and have a much bigger average number of fuel cell per firm (See figures below), corroborating the conclusions of Oltra and Saint Jean (2009) that Asian firms in general have preference by alternative propulsion technologies. This does not mean that within the same country there is an assimilation of strategies. Mazda and Toyota, for instance, are both Japanese and follow very different strategies. Similarly, while GM gave up investing in fuel cells, Ford only recently started to build technological competences in this technology. It is interesting to notice that there are no apparent differences between European an American companies given the much earlier attention to green and energy efficient cars in Europe than in the US, an area which needs further studies.

Overall, elements such as institutional environment and cultural factors seem to have a limited influence on their green strategies. This is understandable as competition in the automotive industry is very globalized and the firms analyzed all are major global players. But it is still interesting given the general high attention to national and regional environmental policies and cultures as a determinant of eco-innovation (e.g. Kemp and Rotmans, 1991; Rotmans, Kemp and Van Asselt, 2001; Horbach, Foxon, Kemp, Steward, & Andersen, 2005; Faber and Frenken 2009; Kemp and Pontoglio, 2011).

6. Conclusions

This article is a first draw of a broader study in which analyze the industrial dynamics of the greening of industry, aiming to identify sectoral patterns in eco-innovation. We argue that such a meso perspective is a neglected an important step for investigating the industrial dynamics of the greening of the economy from an evolutionary economic perspective. While realizing that patents can only inform us partly on sectoral eco-innovation activities and the early, preliminary nature of the analysis so far, the analysis has proven valid for documenting a considerable green competitive restructuring of the automotive industry. However, while the R&D intensity of the automotive sector and the dominance of large players has made it an obvious case for patent based eco-innovation analysis whereas many other sectors will be less suitable for this methodology and other indicators need to be considered.

Our findings show that all the major firms in the automotive industry 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, activities emerging in the 1990s and accelerating in scope and radicality from the mid zeroes. While company strategies vary somewhat, there are clear distinct phases and trends in the eco-innovative activities of the automotive sector. All the firms (except one) are engaging in developing new alternative green trajectories to the existing dominant design even though there is some variety in the strategic responses of the firms. These big players within the industry do seem to go green at a fairly similar pace hinting at important horizontal dynamics of the greening of industry, whereas focus hitherto has tended to be on the vertical green industrial dynamics (Andersen, 2002; Srivastava, 2007; Xu & Xuxu, 2011; De Marchi, 2012). The analysis demonstrates the current fluid emerging stage of the greening of the economy but also illustrates that eco-innovation is already an important competitive factor globally.

It is interesting that almost all the major players are investing in the radical alternative green trajectories emerging despite the great uncertainty as to which trajectory is going to be the dominant design, the quite early development stage of these technologies and their dependence on a considerable amount of complementary innovations and institutional and cultural (e.g. driving patterns of small electric cars) change. Firms are, clearly, within this industry perceiving sufficient green business opportunities to do so. 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 radical alternatives. This requires, on one hand, a large number of resources and technological competences to properly manage such different and complex technologies as diverse as fuel cells and ICE incremental technologies. However, this strategy is a safeguard, as future scenarios remain highly uncertain: no one knows which technological trajectory (or group of technologies) will be economically viable in the future. Clearly, each player is eager to set the standard for the future car based on a combination of one or more technologies. The analysis hence illustrates the current fluid emerging and uncertain stage of the greening of markets and the economy but also illustrates convincingly that eco-innovation is already an important global competitive factor in this industry.

Despite huge regional differences in environmental policies, particularly back in the earlier greening phases of the 1960s to 1980s, the eco-innovative activities across this industry are relatively similar, suggesting a process of assimilation of firms’ strategies within the industry. They all face the same legitimacy problem of the polluting car which is damaging to society, and they are all trying to develop the low-carbon car of the future which may solve transport problems in a sustainable, comfortable and efficient way.

We have demonstrated that eco-innovative activities have intensified markedly from the mid zeroes gaining considerable size and scope relative to other innovations in the industry, following the topical climate and energy supply agenda and the financial crisis. The environmental agenda will, however, continue to undergo changes and new technologies will be tossed up in response. The (big) companies, it seems, are increasingly attentive to this and have by now the green business models, competences and tools to handle such challenges which seem to form a still more integrated part of the modern economy. Our findings overall support the claim that the green economy has reached such a level of maturity (at least on the point of view of automakers) that it has become an important source of new competitive advantages through the development and diffusion of eco-innovations. It is, therefore, appropriate to talk about a 'green economy' the evolution of which is in need of much further study.

Several inquiries remain in order to take this analysis further. Both to understand more in detail the strategies and eco-innovative activities of the individual OEM companies and their temporal and spatial distributions. The patent analysis will be further developed, looking into e.g. technological diffusion between countries, the formation of networks of ideas and their relatedness and the sources of scientific knowledge that firms rely on when conducting green R&D processes. The patent analysis will be complemented by qualitative studies of green business models in the industry.

More demanding are the analysis of the aggregate level of sectoral eco-innovation patterns and business cycles. While the data problems remains considerable, such a study may inform us importantly on the dynamics and scope of green economic change and it seems likely we can get important part of the answers from patent investigations into the more science based industries but other indicators need to be considered too. Situating the current analysis into a wider cross sectoral analysis could bring a number of new interesting insights. E.g. we need to know more of the role of the greening of the automotive industry relative to other industries for the aggregate greening of the economy. Investigations such as identifying the degree to which the automotive sector has been an early or late entrant into the green economy, the induced effect of the automotive industry on other industries and vice versa on eco-innovation, and on the degree of green market maturity relative to other industries. This may allow us to discuss whether the automotive industry may be characterized as a 'carrier industry' for the greening of the economy or not.

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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		229	1143	924	1393
Total Patents	562	1884	4162	9062	**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