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Published in:
Industry and Innovation

Link to article, DOI:
10.1080/13662716.2017.1319801

Publication date:
2017

Document Version
Peer reviewed version

Citation (APA):
Faria, L., & Andersen, M. M. (2017). Sectoral dynamics and technological convergence: an evolutionary analysis of eco-innovation in the automotive sector. *Industry and Innovation*, *24*(8), 837-857. https://doi.org/10.1080/13662716.2017.1319801

Sectoral Dynamics and Technological Convergence: an evolutionary analysis of eco-innovation in the automotive sector

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Abstract: We know from evolutionary theory that sectoral characteristics are important to innovation. This paper investigates if sectoral characteristics also are important to eco-innovation, a hitherto under researched theme. We argue that research into possible sectoral patterns in eco-innovation is key to understanding green industrial dynamics and the greening of the economy. This paper investigates to what degree the economy is greening horizontally (sector-wise). Starting with a sectoral case study, we undertake a longitudinal analysis of the breath and strength of the greening of the automotive sector from 1965 to 2012, focusing on powertrain technologies. The empirical analysis is based on patent data amongst big car producers and focuses on identifying changes in two main aspects: 1) the convergence/divergence of firms' green strategies and technologies within the automotive sector; and 2) the contribution of alternative key green technological trajectories relative to the dominant design. Our findings indicate that the evolution of relative green patenting has followed a positive, linear growth over the last decades with increasing participation of alternative propulsion technologies and increasing convergence of automakers' strategies towards a diversified portfolio.

Keywords: eco-innovation; green economy, evolutionary theory; automotive sector; sectoral dynamics;

1. Introduction

With few notable exceptions, the origins, dynamics and extent of sectoral "greening" remain little understood in empirical terms and even less as part of an evolutionary process of technological change (Kemp & Soete, 1992; Oltra & Saint Jean, 2009a; 2009b; Wesseling et al., 2014). The empirical literature on eco-innovation tends to be either focused on policy and institutional issues, or on individual case studies (e.g. Faber & Frenken, 2009; Geels, 2002; Horbach et al., 2012; Reid & Miedzinski, 2008)

This paper seeks to explore an evolutionary economic perspective on the greening of the economy built upon behavioral theory of the firm (Faber & Frenken, 2009) and sectoral patterns of innovation, both of which, we argue, are key dimensions to understand green industrial dynamics. The overall research question investigates to what degree the economy is greening horizontally (sector-wise) as opposed to vertically (chain wise) (Andersen & Faria, 2015). Many evolutionary scholars have demonstrated that firms in the same sector could be subject to some convergence in their innovation strategies and performance, forming sector-specific technological trajectories (Pavitt, 1984; Breschi & Malerba, 1996; Klevorick et al., 1995; Malerba, 2002;). While this is a strong and well recognized argument in evolutionary research, it is also been contested since the strength and range of sectoral patterns of innovation is relative and other dimensions may also affect innovative activities (Peneder, 2010a).

We offer a contribution to framing and empirically testing this issue. This is a complex problem, which ideally calls for long term, cross-sectoral studies. Due to time and methodological constraints, this paper seeks to feed into this discussion with a sectoral case study. This does not allow for cross-sectoral comparison but it does allow for an analysis of the dynamics (homogeneity) and extent (convergence) of sectoral "greening" over time as part of an evolutionary process of technological change that shapes the two main research questions of this paper.

More specifically, the empirical analysis focuses on capturing sectoral changes over time in two main specific aspects: 1) the degree of strategic and technological convergence into eco-innovation activities, and 2) the contribution of alternative key green technological trajectories relative to the dominant design the total patenting activity of the sector. These research questions differs from other sectoral green case studies (both within the automotive industry and other industries) by not looking specifically for the drivers of eco-innovation (e.g. policy changes), but rather inquiring into possible patterns in industrial greening over a larger time frame, including the recent transformations after the 2008 crisis. We aim specifically to look into the convergence/divergence in the automakers' strategies over time. Accordingly, this paper feeds into the discussion of the degree to which the automotive sector is greening, i.e. to investigate the extent, timing and character of sectoral greening.

Using patent data, the paper analyses eco-innovation activities in the automotive sector from 1965 to 2012, allowing us to cover the main period of its greening process to date. The eco-innovations are restricted to the core automotive innovation, the powertrain. This is partly to delimit the analysis, which is quite comprehensive by nature, and partly to allow for an interesting comparison between the mature dominant design, the combustion engine, and the upcoming competing green trajectories (related to respectively hybrid/electric cars and fuel cell based cars). We use the firms' patent portfolios and two specialization indexes (Herfindahl-Hirshman index and Relative Technological Specialization Index) to identify patterns of convergence/divergence in the firms' green technological strategies, and argue that these may be seen as a proxy for the overall main greening trend of the sector.

The automotive industry is chosen as a case due to several reasons. It is an interesting case of a 'dirty', very mature, quite concentrated but also highly innovative industry. The sector has been traditionally pointed out as one of the clearest examples of a technologically mature industry (Abernathy & Clark, 1985; Fukasaku, 1998; Seidel et al., 2005), characterized by the introduction of incremental innovations constrained by a dominant-design that has as main elements the internal combustion engines (ICE), all-steel car bodies, multi-purpose character, and fully integrated productive processes (Orsato & Wells, 2007).

In recent years, however, many important transformations on technological regimes and institutions in the automotive sector are taking place. Some of these transformations carry the potential to challenge the current dominant design. Examples of these transformations include the incorporation of microelectronics and information and communication technologies[1] (Seidel et al., 2005), the growing pressures to generate energy efficient products, as governments and users are increasingly aware[2] of the negative externalities in terms of environment harm and intensive use of non-renewable resources associated with automobiles.

A more methodological reason to choose the sector is that the green product technologies targeted can be easily recognized since they are predominately related to major changes in the main components of the motor: the powertrain (Oltra & Saint-Jean, 2009a). It is therefore an example of an industry with distinguishable product eco-innovations (and not just process eco-innovations), which enables a discussion on the market side of the green economic evolution (as opposed to process eco-innovations which are often driven primarily by policies).

Our findings indicate that the evolution of relative green patenting has followed a positive, linear growth over the last decades with increasing participation of alternative propulsion technologies, increasing convergence of automakers' strategies towards a diversified portfolio, and consequently a substantial reduction of concentration of green patents among the share. Contrary to

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[1] While a significant part of these technologies are related with the dominant design, some were crucial to alternative propulsion systems. For instance, the early development of Lithium-ion batteries was intended to increase the performance of mobile devices such as mobile phones and laptops, though their relatively high density and low weight also created opportunities for application in hybrid and electric vehicles as alternative to lead-acid batteries (Brodd, 2009).

[2] Key publications such as the "Brundtland Report" (WCED, 1987) and the Intergovernmental Panel on Climate Change assessment reports increased the awareness of policymakers and the general public about the environmental agenda and particularly the negative effects of automobiles' use to the environment. See http://www.ipcc.ch/.

other findings in the literature (i.e. Bakker, 2010; Sierzchula, Bakker, Maat, & van Wee, 2012; Wells & Nieuwenhuis, 2012, see Section 5), the development of all green technologies has been conducted simultaneously, as we shall further expand.

Apart from contributing to these insights on green industrial dynamics, the paper also contributes with methodological developments, given the poor quality of eco-innovation data and problems in defining green technologies and products (Andersen, 2008; Arundel & Kemp, 2009; Fukasaku, 2005; Horbach et al., 2005; Oltra & Saint-Jean, 2009b). The methodology expands and complements other patent-based analysis of eco-innovation in the automotive sector (Frenken, Hekkert, & Godfroij, 2004; Oltra & Saint-Jean, 2009a) by: 1) expanding the scope of patents considered, i.e. the previous studies were limited to a single patent office, usually USPTO or EPO; 2) including the period post-2008 crisis (up to 2012), in which the greening process intensified itself considerably; 3) including green patents by IPC codes (instead of keywords), thus including those inventions that do not present keywords such as "electric vehicle" in their titles and abstracts. Moreover, the two indexes are calculated for all the firms over the period considered, offering a broader picture of the convergence of firms' technological strategies and the dynamics, which could be applied to other research intensive industries (but not to the less research intensives where patent based studies would make little sense) and hence allow for cross-sectoral analysis of patterns in the greening of industries.

The paper is organized as follows: in Section 2, we explain the theoretical argument and the main hypotheses. Section 3 discusses the data collection and methodological steps. The results of the analysis are presented in Section 4 and discussed in the Section 5. The final remarks are presented thereafter.

2. Sectoral eco-innovation and green economy dynamics under an evolutionary perspective

Within evolutionary theory, many scholars have demonstrated how innovation sources, demand and technology characteristics, and institutions are constrained by sectoral boundaries, therefore indicating that firms in the same sector could be subject to some convergence in their innovation strategies, forming sector-specific technological trajectories (Breschi & Malerba, 1996; Klevorick et al., 1995; Malerba, 2002; Pavitt, 1984).

We posit that, as for innovations in general, it is possible to identify sectoral eco-innovation patterns because 1) environmental impacts are often technology/product/activity-specific; 2) the existence and strength of vertical environmental policies; 3) the demand for “green” vis à vis “grey” products varies from sector to sector, so that elements like consumer routines and environmental awareness and the price elasticity of demand are product-specific; and 4) industrial characteristics (e.g. competitive and organizational structures) affect the willingness of firms to retain resources to the development of green technologies (Andersen & Faria, 2015). These elements influence firms’ perceptions of risks and opportunities associated with a technology. Since firms have limited resources to allocate in technological development (Patel & Pavitt, 1997), their technological strategies (i.e. how they allocate resources in different technologies) are also affected by such perceptions.

In Figure 1, we suppose that a Firm A allocate its resources in three competing technologies, X, Y and Z, and that these technologies have different levels of “greenness” (i.e. environmental impacts). The perceptions of the firm on the technological risks and opportunities will likely be reflected in the allocation of resources over the three technologies and changes in the firms’ perceptions would be reflected in their resource allocation. The dynamics of this mechanism is deeply rooted in the micro foundations of the evolutionary perspective on innovation (Nelson, 1991).

[FIGURE 1 HERE]

Likewise, all the other firms in the same sector of Firm A would have to make similar choices among the three technologies depending on their own perceptions about risks and opportunities. Extrapolating this micro analysis to the sectoral level, it is possible to infer how these firms share perceptions about these three technologies by analyzing the degree of convergence in their resource allocation over time (Patel & Pavitt, 1997). The level of convergence/divergence at the meso level would indicate the presence and strength of sectoral patterns of eco-innovation.

The strength and range of sectoral patterns of innovation is relative, since other dimensions also affect the technological strategies of the firms (Peneder, 2010b). First of all, intra-sectoral firm-specific differences in firms’ cognitive abilities, competences, learning and assets influence their perceptions about opportunity conditions and risks related with each technology, being reflected in heterogeneous innovation strategies (Barney, 1991; Nelson, 1991). A second important argument and core to evolutionary theory is that time and space dependent nature of innovation, none the least related to the co-evolution of technologies, organizations and institutions over time (Lundvall, 1992a).

Accordingly, country-specific and region-specific characteristics could play an important role in defining firms' innovative strategies (Cooke et al., 1997; Lundvall, 1992). National and regional institutions and markets may influence innovative activities by forcing or encouraging domestic firms to invest in new technologies to meet consumers and/or policymakers demands (Patel & Pavitt, 1997), and firms may develop technological competences by using local resources and spillovers (Patel & Vega, 1999). Both arguments could reduce the influence of global sectoral patterns in innovation and eco-innovation.

The literature on the eco-innovation strategies in the automotive sector indicates successive shifts in the firms' perceptions on the main technologies in the sector, with interspersed periods of excitement and disappointment ("hypes") towards automakers' investments in alternative propulsion technologies during the past decades caused by fluctuations in the regulatory environment, public and private R&D spending and incentives, public awareness, among other factors (Bakker, 2010; Penna & Geels, 2014; Robert van den Hoed, 2005). Accordingly, it is often argued that most automakers shifted their R&D activities from battery-electric to fuel cell technologies during the 2000s – leading to an hydrogen or fuel cell hype – and shifted again towards hybrid and battery electric technologies by the end of the decade.

On the other hand, some scholars believe that there is in fact a broad "technology fragmentation" movement with multiple and semi-conflicting pathways over time, with most manufacturers progressively adopting active positions in alternative technologies development (Oltra & Saint Jean, 2009; Wells & Nieuwenhuis, 2012; Sierzchula et al., 2012), acknowledging the importance of gradual improvements that can take decades and are above the "hypes" (Patel & Pavitt, 1997).

Given this theoretical framework, we aim to investigate the emergence and diffusion of eco-innovative activities within the automotive sector over time to understand how the overall greening of the economy is reflected in these firms' technological strategies. Our objective is to test the existence of a converging movement of automakers' strategies over time as indicative of possible emerging sectoral patterns of eco-innovation. Our first working hypothesis is therefore:

H1: Regarding powertrain technologies, the main firms of the automotive sector present a convergence in their technological strategies over the past decades.

This convergence is analyzed in terms of 1) reductions in the concentration of patenting activity for each technology, and 2) the degree of homogeneity among the firms' patent portfolios. The opposite situation is a divergence in their strategies, signaling that other factors may be stronger, including firm-specific and geographic-specific elements or even rules of thumb (Patel & Pavitt, 1997). In this case we would also observe heterogeneous combinations in firms' patent portfolios.

The convergence/divergence of firms' green technological strategies within a sector can be understood as part of a broad movement of greening of the economy in which agents integrate environmental issues in the economic processes and heuristics that are then reflected in the technological strategies (Andersen, 2009). Such integration of environmental issues is marked by phases, starting with a reactive phase (to environmental regulations, scandals or market preferences) and following the development of green markets up to the point that the green market becomes the standard (see Figure 2).

[FIGURE 2 HERE]

A very high degree of strategic convergence amongst heterogeneous companies within a sector, to some degree subjected to different national and firm-specific characteristics, might be an indicator of the gradual consolidation of a green market. In this sense, we also test a hypothesis related with the breath of the greening of the automotive sector, i.e. the importance of alternative technological trajectories (i.e. fuel cells, electric motors) to the overall green patenting activity in the sector. Accordingly, our second hypothesis is:

H2: Alternative trajectories (in relation to the dominant design) are becoming increasingly responsible for the growing of green patenting activity within the sector.

3. Methodology

Statistics on eco-innovation are scarce and firms in general do not disclose much quantitative data about the eco-innovation efforts as would be desirable to construct comprehensive sectoral analyzes (Fukasaku, 2005; Oltra et al., 2010). Although patent-based studies are only emerging in eco-innovation research, some scholars hold they are one of the best available sources of quantitative data for sectoral eco-innovation analyzes (Dechezlepretre et al., 2011; Oltra et al., 2010; Popp, 2005).

Despite its general limitations as an innovation indicator (Pakes, 1986; Pavitt, 1985), the rate of growth in patenting in a certain technologic field can be used as *proxy* of its importance and maturity degree (Chang, 2012; Nesta & Patel, 2005), and patent applications are considered indicators of firms' technological competences as they show 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). Moreover, patents are strongly correlated with R&D expenditures and therefore make a good proxy for innovative activity (Griliches, 1990).

3.1. Data collection

First, we selected a group of major automakers in order to represent the innovative activity in the sector and build a picture of important aspects of eco-innovation activity (Ernst, 2001). The sample of firms was chosen based on two requirements: 1) the automaker must be listed on the OICA's (International Organization of Motor Vehicle Manufacturers) World Motor Vehicle Production ranking 2012[3]; and 2) the number of patents filled on the selected patent offices must be of at least 500 up to 2013. Based on these criteria, we selected 17 car manufacturers as follows: BMW, Daimler, Fiat, Ford, Fuji Heavy Industries (Subaru), General Motors, Honda, Hyundai, Isuzu, Mazda, Mitsubishi, Nissan, Porsche, PSA (Peugeot-Citroën), Renault, Toyota, and Volkswagen.

We collected all patents from our selected group of major automakers at the Derwent World Patent Index database (Thomson Reuters) from 1965 to 2012, allowing us to analyze from the initial phase of eco-innovation emergence to recent years. This database can distinguish patent families, avoiding counting the same invention multiple times, and compiles all variations of the assignee's names, including secondary brands, research centers, and subsidiaries, into single codes, thus improving the coverage of the global patenting activity related to each firm. To avoid low-quality patents, we selected only granted patents deposited at the European Patent Office (EPO), the US Patent Office (USPTO), and the World Intellectual Property Organization (WIPO)[4].

Instead of using keywords (e.g. Frenken et al., 2004; Oltra & Saint-Jean, 2009a, 2009b), we adopted selected International Patent Classification (IPC) codes in order to collect the patents associated with each technologic group (Bointner, 2014; Johnstone et al., 2010), using the recently

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

[4] Since the aim of the patent data collected is to represent the knowledge produced by the automakers (and not the market value of the patents), we do not restrict the data to the Triadic patents, i.e. those patented at the EPO, USPTO and Japanese patent office (JPO), therefore considering the patents filled in each of these offices separately.

developed IPC Green Inventory[5] and the OECD's list of Environmentally-sound technologies (EST)[6]. Therefore, for each technologic group, we selected a number of IPC codes to represent the patenting activity in their respective areas. The groups of codes are presented in the Annex. By using these application-based codes, we aim to minimize the risk of including irrelevant patents and excluding relevant ones (Veefkind et al., 2012)[7].

We selected three main technological areas related with the powertrain, the main system in the automobile and the responsible for most of the environmental harm associated with their use: Internal Combustion Engines' (ICE) green technologies; Hybrid and Electric propulsion systems; and Fuel cells' electric propulsion systems. The former group represents basically the incremental innovations associated with the dominant design, while the other two groups represent more radical technologies that require more complex changes in the main components to function. We also included a group of what we called *complex patents*. Every patent can be attributed with two or more IPC codes representing different technological domains, and many patents have codes associated with more than one of the three groups of technologies we selected (e.g. fuel cells and electric/hybrid, fuel cells and ICE green, electric/hybrid and ICE green etc.). Therefore, a complex patent represents the "cross-fertilization" between two or more different technologies (Figure 3).

[FIGURE 3 HERE]

Our data sample presents some drawbacks. First, it does not include some relevant actors, including new automakers and those from developing countries – particularly from China and India, but also suppliers, universities and research centers. We argue, however, that in the specific time and sectoral dimensions adopted in this paper, the major incumbents still have a crucial role in defining the technological strategies of the sector, influencing all the other important actors in their decision processes (Malerba & Orsenigo, 1997; Pavitt, 1984), and the group of selected firms is responsible for more than 90% of passenger car sales (2012) according to OICA. Additionally, any major

[5] See www.wipo.int/classifications/ipc/en/est/

[6] Although this list also presents Cooperative Patent Classification (CPC) codes related with the technological areas chosen for this study, we were not able to use them due to the limitations of the database which does not support such tagging scheme. However, since the technologies selected for our study are well defined within the original (non-CPC) IPC codes, this limitation does not compromise the validity of our methodology. See http://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV/EPOC/WPEI(2014)6/FINAL&docLanguage=En

[7] For instance, patents without keywords such as "fuel cell*" can be still related with Fuel cells technologies, perhaps using specific technical terms for subcomponents. Likewise, patents with keywords like "electric motor*" might be related with other systems than the powertrain (e.g. motors for windows and other moving parts).

innovation from other actors will likely be reflected (albeit indirectly) in the automakers' technological strategies. Last, because the list of suppliers for this sector is very comprehensive and most of them are specialized in different components, it is difficult to gather and compare their data with the same level of simplicity and clarity as of the automakers that supposedly produce the same product.

A second drawback relates to the fact that our sample does not include other technologies that are also important to reduce the environmental impacts of the sector, including streamlining design, recycling, and painting, among others. We focused on the main competing powertrain technologies because they represent the core of the eco-innovation in the sector and the most important component of the automobile. This methodological choice is commonly used in papers working with green technologies in the automotive sector (e.g. Frenken et al., 2004; Oltra & Saint-Jean, 2009a). The Table 1 summarizes the data collected for each automaker and technologic group.

[TABLE 1 HERE]

3.2.Methodological procedures

To check the sectoral convergence, we first analyze the trajectory of green patenting in our sample over time. We use a measure of convergence typically used in industrial economics and international trade literature to measure market concentration and specialization, the Herfindahl-Hirshman index (HHI) (Herfindahl, 1950; Hirschman, 1964), as suggested by Malerba & Orsenigo (1997). The index is described as:

$$HHI = \sum_{i=1}^{I} {b_i}^{\alpha}$$

Where *b* is the share of each firm *i* in the overall patent portfolio (for each technology) and α represents the weight given to larger firms, which is α = 2 as standard. The index can also be used as a measure of diversification (Palan, 2010a), since specialization = 1 – diversification. Therefore, the closer to 0, the more diversified is a given portfolio, meaning that a given technology is better distributed among the firms in the sample.

The HHI fulfills all criteria of a favorable specialization index (Palan, 2010), however, it may be biased downwards for small samples (Hall, 2005). To increase the reliability of the results, we also adopted a normalized Relative Technologic Specialization Index derived from Relative Specialization index (Nesta & Patel, 2005; Pavitt, 1998), in order to measure the evolution of firms' trajectories on the specified green technological areas and the convergence among the firms' strategies. Its formula is given as follows:

$$RTSI_{ij} = \frac{\left(P_{ij}/\sum_i P_{ij}\right)}{\left(\sum_j P_{ij}/\sum_i \sum_j P_{ij}\right)}$$

where P_{ij} represents the number of patents from technology *i* on the patent portfolio of firm *j*. Thus, this Relative Specialization index compares the share of a given technology *i* within the portfolio of firm *j* with the share of the same technology for the whole sample of firms as a measure of relative technologic specialization. We normalized the index in order to simplify and compare symmetrically the results (Nesta & Patel, 2005):

$$RTSIn_{ij} = \frac{\left(RTSI_{ij} - 1\right)}{\left(RTSI_{ij} + 1\right)}$$

In order to linearize and attenuate the effects of the largest patentees in our sample (such as Toyota, Honda, and General Motors, see Table 1) on the average portfolio, we transformed each P_{ij} using natural logarithms, thus $P_{ij} = \ln\left(1 + P_{ij}\right)$.

The RTSI is able to reveal how firms develop and change their technology portfolios - and consequently their strategies - over time. Accordingly, if [-1 < RTSI < 0], the firm *j* has a smaller share of patents on technology *i* than the sector average and the closer to -1, the less specialized is the firm on such technology. In contrast, if [0 < RTSI < 1], a firm is more specialized on the technology than the average. A RTSI = 0 indicates that the firm *j* follows the average patenting activity of the sector for technology *j*.

The RTSI is also able to capture changes in opportunities and persistence in firms' strategies. If, for instance, the index is moving away from -1 and stabilizes around 0, it indicates that the firm is in a process of *technological catching up*. If the index is consistently over 0 (and especially around and over 0.3), it indicates that such firm has a persistent relative specialization on the technology analyzed (Nesta & Patel, 2005).

4. Data analysis - Eco-innovation dynamics in the automotive sector

4.1 Evolution of green patenting in the automotive sector

The evolution of green patenting as a share of total patenting in our sample (Figure 1) demonstrates the cumulative nature of the greening process in the automotive sector. From the early, slow emergence of eco-innovative activities in the late 1960s, an increasing number of companies have being involved in eco-innovative activities.

Our data shows that around 35-40% of all patents produced by the firms in our sample are related with the selected green technologies in the past years, with increasing participation of alternative propulsion technologies (Figure 4). Since automakers typically have substantial patenting efforts in other areas such as security, safety, suspension, brakes, entertainment, steering and navigation systems (Thomson Reuters, 2015), this share is a indicative that the automotive industry is in the middle of a strong greening process, at least from the point of view of technological development.

To contextualize the evolution of green patenting in the automotive sector, we combined our findings with a review of major institutional, socio-economic, and competitive changes that happened along the last 50 years and affected the sector. We divided the analysis in four distinctive "phases": Phase 1, from 1965 to 1986 (A-B); Phase 2, from 1987 to 1996 (B-C); Phase 3, from 1997 to 2007 (C-D); Phase 4, from 2008 to 2012 (D-E).

The first phase is marked by the introduction of the first comprehensive vehicle pollution control and fuel economy standards and regulations, including the Clean Air Act of 1970 and the 1975 Corporate Average Fuel Economy (CAFE) in U.S., the Japanese Air Pollution Control Law of 1973, and the Economic Commission for Europe (ECE) Regulation 15-01 in 1974 that was the base for many European countries' regulations, as well as many other national regulations along the 1970s and 1980s. According to Faiz et al. (1996), "compliance with these standards (…) provided the impetus for major advances in automotive technology worldwide" (p. 3).

[FIGURE 4 HERE]

This phase is characterized by the emergence of internal combustion engines' (ICE) patents related primarily to pollution control, incorporation of new systems to these engines (i.e. electronic fuel injection and catalytic converters) and adaptation to alternative fuels (i.e. ethanol, natural gas) which reaches up to 16% of the patenting activity in the sample. Despite some early governmental initiatives to foster the development of alternative propulsion technologies in U.S., such as The Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976, and the Automotive Propulsion Research and Development Act of 1978, only a small amount of electric/hybrid patents and very few fuel cells patents were produced, demonstrating the experimental nature of these initiatives.

The relative participation of green patents in firms' portfolios decreased over the 1980s since main regulations' requirements remained stable over the decade and governmental support was subject to major budget fluctuations which have made it impossible to sustain a coherent development program on alternative powertrain technologies. According to a report to U.S. Congress, "(…) after an initial flurry of activity on hybrid vehicles at DOE [U.S. Department of Energy] from 1978 to 1980, the hybrid effort was shelved until 1992" (U.S. Congress, 1995, p. 229).

The timing of the eco-innovative upswing in the *phase 2* (B-C) coincides with the emergence of a new discourse on sustainability following efforts of the World Commission on Environment and Development – also known as Brundtland Commission - in 1987, whose mission was to call policymakers, civil society and firms to pursue sustainable development goals (WCED, 1987). In U.S. the James Hansen's testimony before the U.S. House Energy Committee in June 1988 is considered "the catalyst that catapulted climate change onto corporate radar screens, gaining attention of the mass media and senior management" (Levy & Rothenberg, 2002, p. 180-181), while for European firms, the 1992 UNCED conference in Rio was "the crucial event that spurred corporate attention" (*Ibid*, p. 181).

New sets of regulations and major revisions also emerged during this phase. Among them, it is worth mentioning the Californian Air Board regulations and the Clean Air Act amendments in 1990, as well as the first tier of the European Emission Standards in 1993 (Euro 1)[8]. While the latter two were mainly focused on gradual improvements in ICE performance, the former also included specific elements to foster the development of alternative powertrain technologies: the Zero Emission

[8] See http://ec.europa.eu/environment/air/transport/road.htm

Vehicles (ZEV I) Program[9] recognized that ICE-related emissions tend to deteriorate rapidly with time and could never be reduced to zero.

These regulations were followed by the establishment of joint research programs and partnerships among automakers and other stakeholders, such as the U.S.-based Advanced Battery Consortium (1991) and the Partnership for a New Generation of Vehicles (PNGV) (1993), the Automotive Research and Technological Development Master Plan (1994) and the "Car of Tomorrow" task force (1995) in Europe. However, the relative growth of green patents was still very much dependent on the behavior of ICE-related patenting (Figure 4), since most automakers remained reluctant to invest heavily in such risky alternative technologies[10].

The subsequent actions following the abovementioned events had major impacts over the dynamics of green patenting in the sector, as it is evident in Phase 3. Despite the revision of CARB ZEV I in 1996 and 1998 - which relieved automakers acting in the state to invest in zero emission vehicles up to 2003, the failure of General Motors' electric vehicle leasing program (EV1), and the tightening of emissions regulations targeted to ICE vehicles worldwide (which could otherwise foster further investments in ICE technologies), *the growth of green patenting in this phase was caused solely by the growth of patenting in alternative technologies*, such as electric/hybrid and fuel cells (Figure 4).

The successful introduction of the first mass market hybrid/electric vehicles, Toyota Prius and Honda Insight, to the Japanese market in 1997 and 1998, respectively, might have been the decisive factor to encourage other automakers to invest in this technologies. The initiative of U.S. President George W. Bush to allocate US$ 1.2 billion to finance hydrogen research in 2003, as well as DaimlerChrysler's announcement of bringing 100,000 Fuel Cell vehicles to the streets by 2006 definitely contributed to foster the investments in hydrogen and fuel cells (Bakker et al., 2012). Especially interesting is that, during this period, firms also started to produce a significant amount of complex patents, denoting an *increased cross fertilization between the different technologies*, e.g. fuel cells and electric/hybrid, electric/hybrid and ICE and so on.

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[9] At that time, the program required that in 1998, 2% of the vehicles that large manufacturers produced for sale in California had to be ZEVs, increasing to 5% in 2001 and 10% in 2003. Due to cost, lead-time, and technical constrains, it presented major changes in 1996, 1998 and 2001, relaxing most objectives.
Source: http://www.arb.ca.gov/msprog/zevprog/zevregs/zevregs.htm

[10] Source: http://www.arb.ca.gov/regact/zev/fsor3.pdf

Finally, the last phase (2008-2012) consists of the immediate effects of the crisis (e.g. profit reduction, cost cutting), the reduction of financing to hydrogen-based fuel cell program in U.S., and the introduction of advanced hybrid and electric vehicles, such as Nissan Leaf, Tesla Roadster and Model S. Overall, these events had a negative effect on alternative technologies' patenting and a positive effect over ICE green patents in a first moment, but the former recovered quickly while the latter started to fall rapidly again. Unfortunately, the more recent dramatic events in electric vehicles market development boosted by Tesla cannot be captured by the current data and will have to be analyzed at a later stage.

So far, the net effects of these events under green patenting activities have been the further decline of ICE patenting and the strengthening of alternative technologies. In 2012, for the first time, the number of patents in HEV/BEV was almost the same as the number of green ICE patents. Even the patenting activity related with fuel cells, presumably under decline after the frustration of initial expectations, presented a rather stable behavior after the crisis, leveling at about 5% of the total patenting in the sector (not considering the complex patents related with fuel cells).

4.2 Technological convergence/divergence towards eco-innovation activities

In this subsection we will look into the details of the evolution of eco-innovation activities in the automotive sector over time. To understand how this evolution affected the convergence (or divergence) of automakers strategies towards new patterns of eco-innovation, we calculated the HHI for each technology and also for the whole sample of patents (Figure 5). We used 3-year moving averages to avoid the effects of seasonal fluctuations in patenting activity.

[FIGURE 5 HERE]

The results show that the different alternative technologies have been following very different paths of specialization: the ICE green technologies and electric-hybrid present a quite stable path since the 1970s, more or less following the trajectory of the overall portfolio. This indicates that these technologies were developed by a broader group of automakers from the beginning and quite simultaneously and therefore were not an isolated strategy. These technologies and the capabilities they build on are closer to the existent dominant design, and this has certainly an impact on the perceived opportunities, costs and risks of firms.

The fuel cells and complex patents, on the other side, have been quite concentrated in one or few automakers until the beginning of the 1990s. One explanation for such behavior can be that these technologies are more complex, demanding more resources and capabilities and offering greater risks than the others (Singh, 1997). The Figure 6 shows that, in average, these two sets of technologies present a higher number of inventors per patent than the others, an indication that they require bigger R&D teams to be developed.

[FIGURE 6 HERE]

Likewise, the higher average number of assignees per patent in our sample reveals that the willingness of the firms to cooperate with other agents in order to solve complex problems related with these technologies (Figure 7), since "(…) the automobile network features learning, capabilities, and assets outside what would appear to be core fields. In other words, the automobile network has capabilities in a broader range of technological fields than would be assumed from its major product lines."(Rycroft & Kash, 2004, p. 192–193).

[FIGURE 7 HERE]

Regarding the Relative Technological Specialization Index, after calculating the four technology-specific indexes for each firm and for each year, we aggregated them using the average of all firms' indexes for each technology:

$$\overline{RTSIn_\iota} = \frac{1}{n} \times \sum_{j=1}^{n} RTSI_{ij}$$

In order to simplify the data visualization, we then made a second aggregation using the average for the four phases mentioned earlier (1965-1986; 1987-1995; 1996-2007; 2008-2012), although we missed the first two years (1965 and 1966) by applying the 3 year moving average to the patent data. Therefore, we ended up with 16 aggregated RTSI values as shown in Figure 8.

[FIGURE 8 HERE]

The evolution of the average aggregated RTSI over time corroborates the results of the previous analysis. In the first period, the RTSI for most firms was close to -1 for Fuel Cells and Complex patents - indicating that only a few firms presented relative specialization in this technologies - and higher for Electric Hybrid and ICE. Over time, the RTSI gets closer to 0 for all technologies, which is another indicator of convergence – since they are all getting to the point where their share of these technologies is equal to the share of the whole sample. It is worth mentioning, however, that fuel cell technologies remain less spread among the firms when compared with the other technologies even in the last period.

We also calculated the average standard deviation from the $\overline{RTSIn_i}$ for each technology and time period (Figure 9). Except for the first period, when most firms were not developing alternative technologies (therefore the RTSI was always close to -1), average standard deviations are in general much smaller for ICE technologies, as it is closer to the dominant design and therefore a "safer" trajectory, and higher for more radical technologies.

[FIGURE 9 HERE]

In a sectoral perspective, standard deviations has also been decreasing considerably over time, indicating that they are converging to a more homogeneous pattern of green technological specialization – that is, with fewer variations over the period. Therefore, the development of these technologies as measured by patenting activity is becoming more stable rather than uncertain and turbulent as some argue (e.g. Sierzchula et al., 2012).

5. Discussion of the findings – signs of sectoral greening

The data analysis indicates a substantial reduction in concentration of all green technologies as technological opportunities are being collectively perceived and risks are shared. A decrease in the concentration levels of all technologies over time as measured by the HHI index demonstrate that even (or especially) the technologies which are more distant from the existing technological are being developed by an increasing number of firms, approaching the level of diversification of the overall patent activity in the sector, with substantial shifts observed during the mid-1990s and notably after the 2008 crisis. Moreover, the specialization index indicates a strong convergence in the automakers' strategies in green ICE, Hybrid/Electric and Complex portfolios, which also finds support in the literature using other datasets and methods (e.g. Frenken et al., 2004; Oltra & Saint-Jean, 2009a; 2009b; Sierzchula et al., 2012).

Therefore, our findings suggest that the hypothesis H1 is valid: we indeed observe an increase in the convergence of firms' strategies for the green powertrain technologies, which reflect common perceptions of risks and opportunities among the firms in the sample. However, the portfolio of patents related with Fuel cells continues to be relatively more concentrated than the other technologies. It suggests that innovations that are further away technologically from the dominant design present greater levels of uncertainty – and thus variation (Anderson & Tushman, 1990). It also suggests that other factors, such as country- and firm-specific characteristics, may have a stronger influence in such complex technologies. Nevertheless, these hypotheses require further research to be validated.

As a counterpoint to the findings of Sierzchula et al. (2012) that the number of hydrogen-based announced models decreased rapidly during the 2000s, the rise and breakdown of expectations about a hydrogen-based economy, usually referred as a “hype” in the literature (Bakker, 2010), did not translate into a large reduction of fuel cell patenting, but into a stabilization of such activities of about 5% of the total patenting in the sector (taking off the complex patents related with fuel cells). This is an indicator that the effects of frustrated expectations might be smaller in a context of technological uncertainty, high competition and strong pressures to change.

We propose that the automotive sector case presented, despite its limitation to the powertrain case and patent data only, could be seen as a strong indication of a high degree of sectoral greening and accordingly a rapidly maturing global green economy. Our data demonstrate that the evolution of relative green patenting has followed a positive, linear growth over the last decades, culminating with around 35-40% of all patents produced by the firms in our sample related with the selected green technologies over the last phase (2008-2012), with increasing participation of alternative propulsion technologies. This conclusion is also supported by scholars using different data and methodologies (Oltra & Saint-Jean, 2009b; Sierzchula et al., 2012) and it challenges the idea that the attempts of going green remain marginal to the sector as argued by e.g. Wells & Nieuwenhuis (2012). Based on these findings, we confirm the hypothesis H2 that alternative green trajectories (in relation to the dominant design) are increasingly responsible for the growing of innovative activity within the sector.

The substantial increase in the relative number of complex patents indicates not only a diversified portfolio, but also a process of cross fertilization between the different technologies, e.g. fuel cells and electric/hybrid, electric/hybrid and ICE and so on. In other words, these technologies share a number of components that suggest a considerable degree of complementarity among them, with components that can be used for two or more of these technologies. Further research into this special group of patents might give more insights on how knowledge is shared among different technologies.

6. Final considerations

This paper has provided longitudinal evidence of sectoral eco-innovation trends and proven that the automotive industry is in fact greening to a very high degree. We recognize that this is only one sectoral case which could be elaborated on with more data and which needs to be succeeded by many more similar studies as well as cross-sectoral studies of eco-innovation in order to understand the influence of sectoral eco-innovation patterns. Nonetheless, we argue that the paper contributes to a relatively new research agenda in inquiring into to what degree an (important) industry is greening and hence to what degree the increasingly global economy is greening sector wise. In this sense, our findings show signs of high levels of sectoral green convergence among the main automotive incumbents. The evolution of relative green patenting has followed a positive, linear growth over the last decades with increasing participation of alternative propulsion technologies and increasing convergence of automakers' strategies towards a diversified portfolio.

It can, off course be debated how high the greening level is we are witnessing with these data; we know from other studies that the automotive sector, as other sectors, is still facing a number of serious eco-innovation challenges, compare the recent "dieselgate" scandal (Blackwelder et al., 2016). We propose none the less that we may interpret our findings as robust indications that most if not all the main players in the industry are in fact greening to quite some degree and in a global perspective which has not been analyzed before. Tentatively we propose that we may interpret this as a sign that we have reached a certain level of global market driven green economic evolution, though more research is needed, e.g. including studies into the increasingly important Asian economies and integration with other types of data analysis. We can, in other words, mainly say something about the direction of the greening trend than the level of greening with the current study.

There are, overall, some first indications that horizontal greening is an important feature in the greening of the economy. We need, however, to expand this research into more sectoral cases as well as cross–sectoral studies of eco-innovation in order to identify possible patterns of sectoral eco-innovation. We need more research into green industrial dynamics, in order to understand better the scope of horizontal, versus vertical, versus regional greening trends, as well as the role of the big incumbents versus the small upstarts for the greening of the economy. Only when such studies have been made can we begin to discuss what role the automotive industry, and other industries, has for the overall green economic evolution.

We further argue that the methodology we have used (including the choices of the IPC codes and the two indexes) for the sectoral case study is applicable to other research oriented industries (albeit not the less research intensive). The methodology may be used to undertake comparable studies in a number of industries and allow for important cross- sectoral eco-innovation studies too.

Acknowledgements

The authors would like to thank Lars Alkaersig, Franco Malerba and Ju Liu for their valuable feedbacks and suggestions. The usual disclaimers apply.

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Annex – List of IPC (International Patent Codes) for each technologic group

ICE Green patents		Electric/Hybrid patents		Fuel Cells
F01N-011/00	B01D-041/*	B60K-001/*	B60K-006/*	H01M-012/*
F01N-009/00	B01D-046/*	B60K-016/00	B60L-007/16	H01M-002/*
F02B-047/06	B01D-053/92	B60L-011/*	B60W-020/00	H01M-004/86
F02D-041/*	B01D-053/94	B60L-015/*	F16H-003/*	H01M-004/88
F02D-043/*	B01D-053/96	B60L-007/1*	F16H-048/00	H01M-004/9*
F02D-045/00	B01J-023/38	B60L-007/20	F16H-048/05	H01M-008/*
F02M-023/*	B01J-023/40	B60L-008/00	F16H-048/06	B60L-011/18
F02M-025/00	B01J-023/42	B60R-016/033	F16H-048/08	
F02M-025/02*	B01J-023/44	B60R-016/04	F16H-048/10	
F02M-025/03*	B01J-023/46	B60S-005/06	F16H-048/11	
F02M-025/06	F01M-013/02	B60W-010/08	F16H-048/12	
F02M-025/08	F01M-013/04	B60W-010/26	F16H-048/14	
F02M-025/10	F01N-011/00	B60W-010/28	F16H-048/16	
F02M-025/12	F01N-003/01	H02J-015/00	F16H-048/18	
F02M-025/14	F01N-003/02*	H02J-003/28	F16H-048/19	
F02M-027/*	F01N-003/03*	H02J-003/30	F16H-048/20	
F02M-003/02	F01N-003/04	H02J-003/32	F16H-048/22	
F02M-003/04*	F01N-003/05	H02J-007/00	F16H-048/24	
F02M-003/05*	F01N-003/06	H01M-010/44	F16H-048/26	
F02M-003/06	F01N-003/08	H01M-010/46	F16H-048/27	
F02M-003/07	F01N-003/10	H01G-011/00	F16H-048/28*	
F02M-003/08	F01N-003/18	H02J-007/00	F16H-048/29*	
F02M-003/09	F01N-003/20	H01M-10/0525	F16H-048/30	
F02M-003/10	F01N-003/22	H01M-10/50		
F02M-003/12	F01N-003/24	H01M-010/04		
F02M-003/14	F01N-003/26			
F02M-031/02	F01N-003/28			
F02M-031/04	F01N-003/30			
F02M-031/06	F01N-003/32			
F02M-031/07	F01N-003/34			
F02M-031/08*	F01N-005/*			
F02M-031/093	F02B-047/08			
F02M-031/10	F02B-047/10			
F02M-031/12*	F02D-021/06			
F02M-031/13*	F02D-021/08			
F02M-031/14	F02D-021/10			
F02M-031/16	F02M-025/07			
F02M-031/18	G01M-015/10			
F02M-039/*	F02M-053/*			
F02M-041/*	F02M-055/*			
F02M-043/*	F02M-057/*			
F02M-045/*	F02M-059/*			
F02M-047/*	F02M-061/*			
F02M-049/*	F02M-063/*			
F02M-051/*	F02M-065/*			
F02M-071/*	F02M-067/*			
F02P-005/*	F02M-069/*			

Table 1. Descriptive data (1965-2012)

	Total Patents	ICE green	Electric/Hybrid	Fuel cells	Complex patents (1+ categories)
BMW	5020	393	246	56	95
Daimler	7579	768	353	385	160
Fiat	2082	257	81	6	14
Ford	15823	2722	910	278	259
Fuji	1313	144	113	32	50
GM	23644	2472	2010	1313	472
Honda	21961	2622	1063	1085	672
Hyundai	5728	556	550	237	287
Izusu	1283	440	41	0	4
Mazda	3105	606	58	2	23
Mitsubishi	1680	448	95	6	66
Nissan	12831	2001	603	612	423
Porsche	2410	166	130	5	54
PSA	2977	478	254	30	88
Renault	3349	684	243	32	134
Suzuki	1351	197	130	10	84
Toyota	26769	5152	2028	1526	1605
Volkswagen	6026	773	230	54	119
Total	*144931*	*20879*	*9138*	*5669*	*4609*

Figure 1. Technological strategies as resource allocation in different technologies

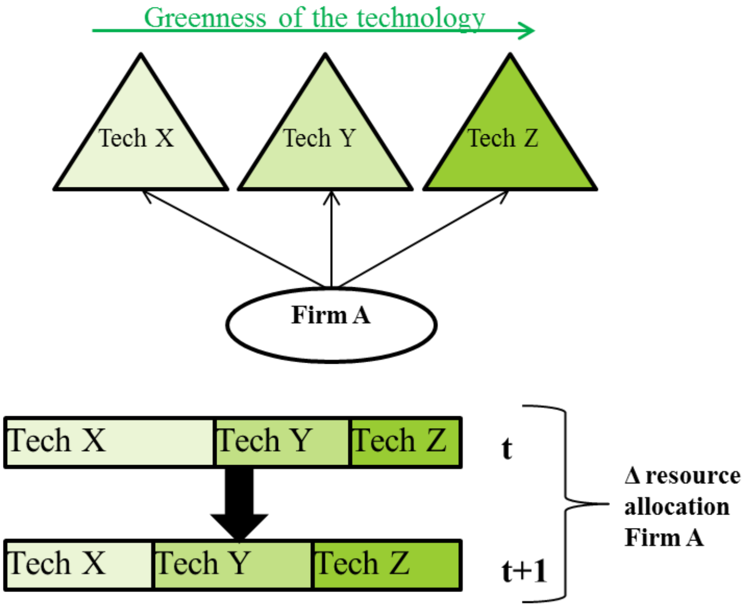

Figure 2. The green learning curve

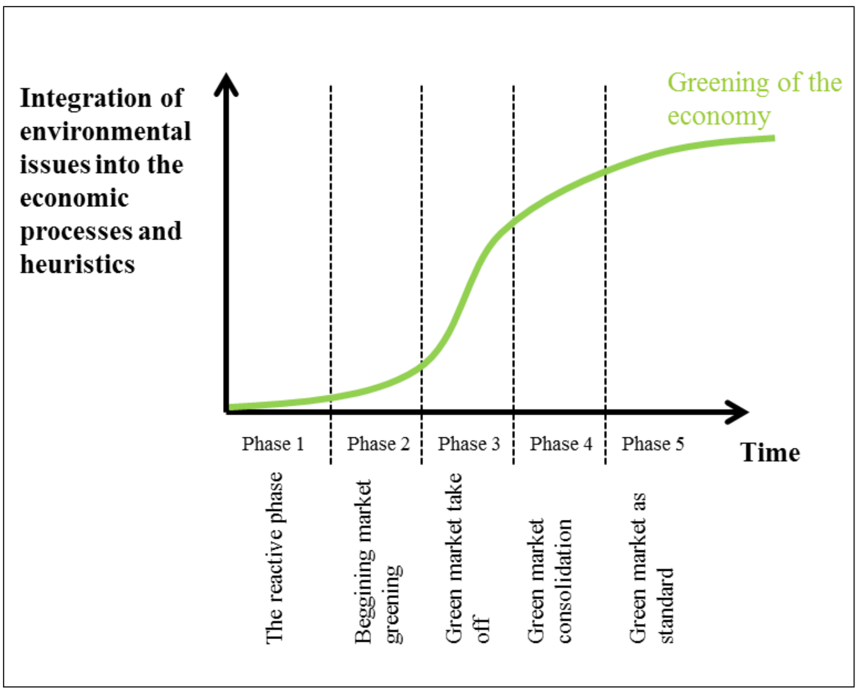

Figure 3 – The four selected technological groups

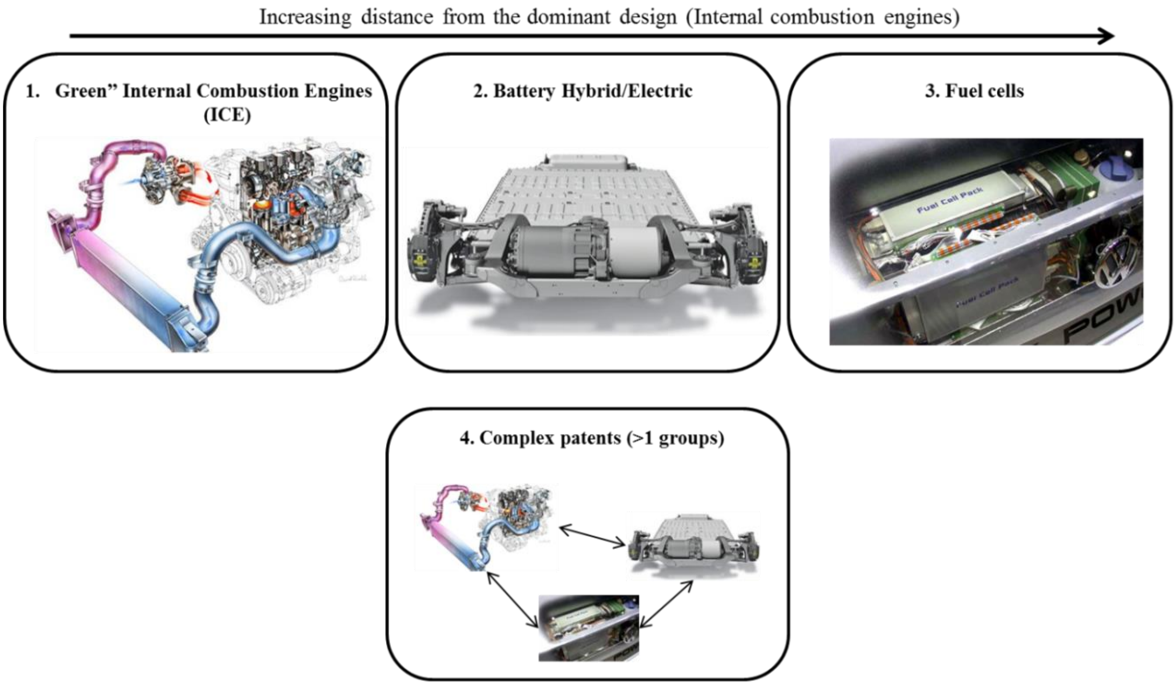

Figure 4. Green patents' production as % of total patenting activity in the sample

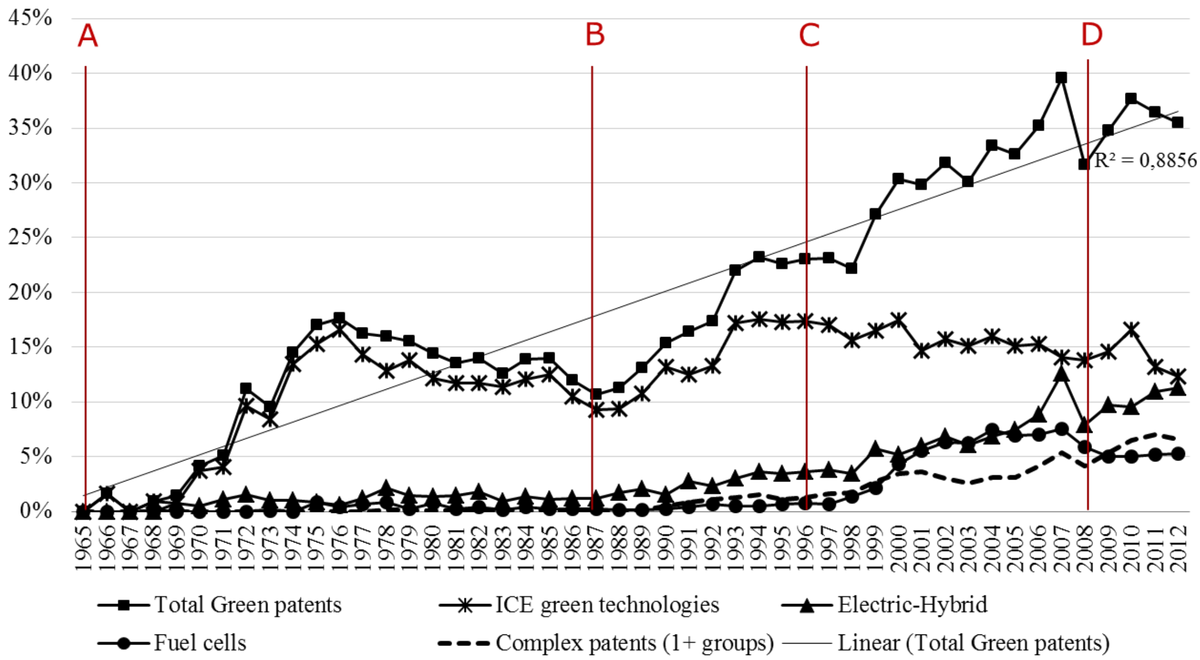

Figure 5. Herfindal-Hirschman index (HHI), 3-year moving average (1965-2012)

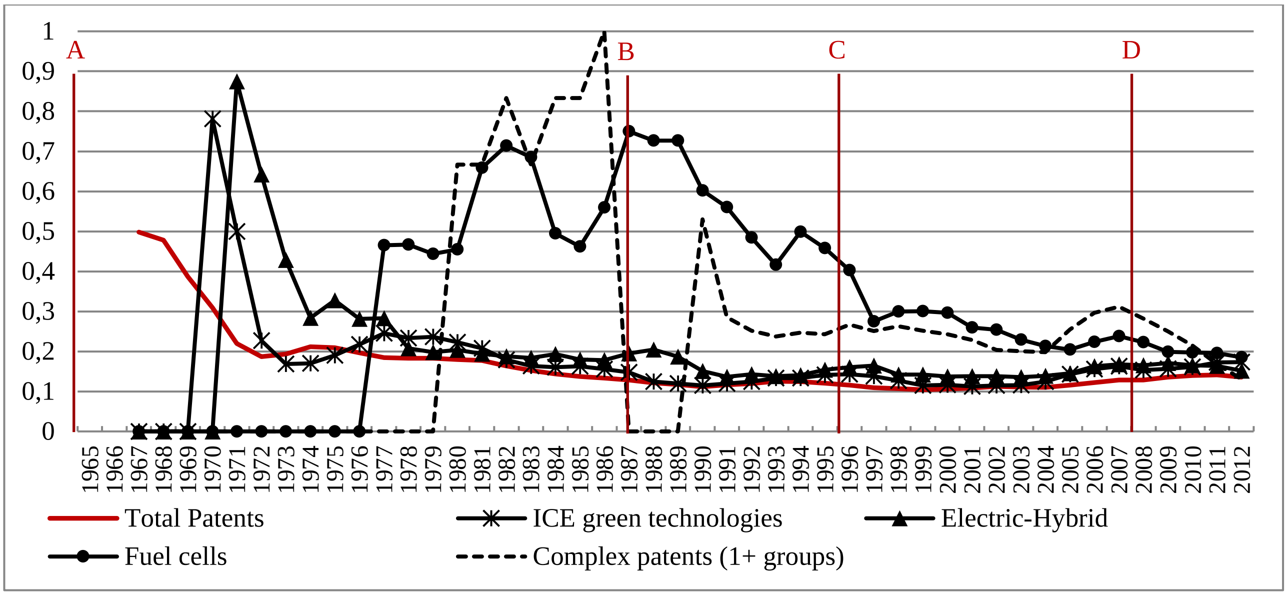

Figure 6. Average number of inventors per patent (1965-2012)

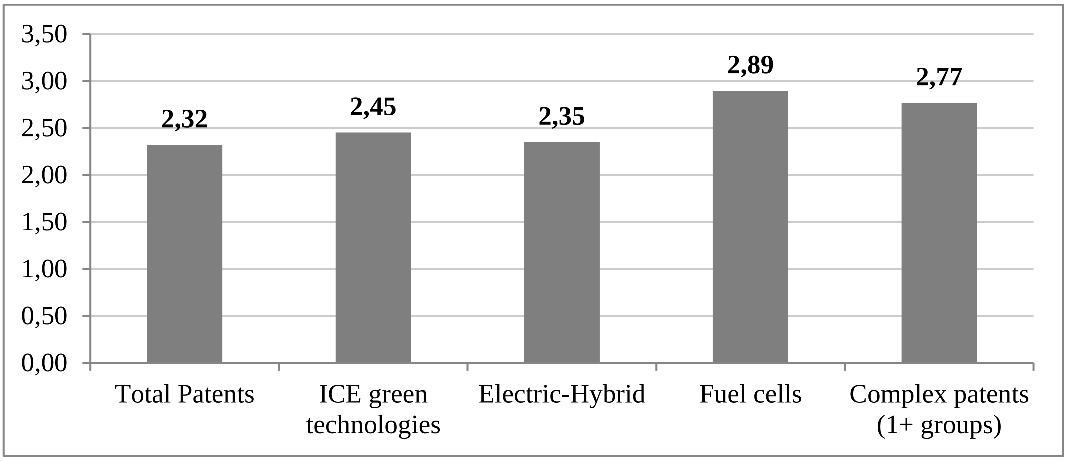

Figure 7. Average number of assignees per patent (1965-2012)

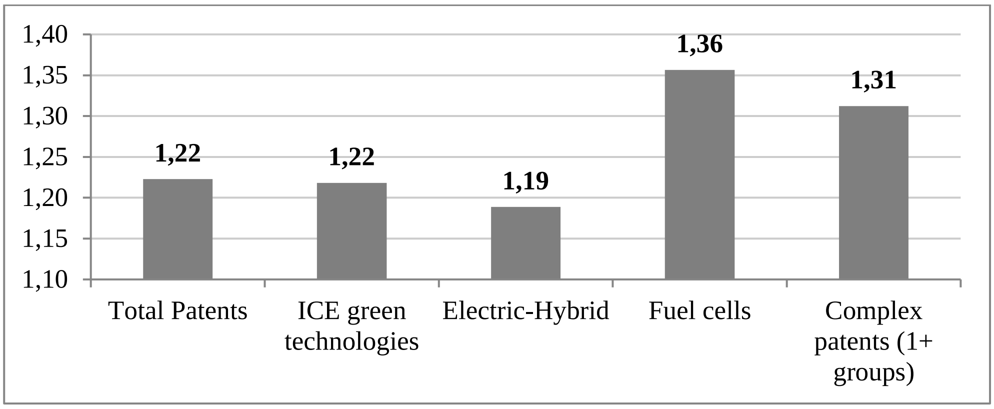

Figure 8. Average Aggregated RTSI

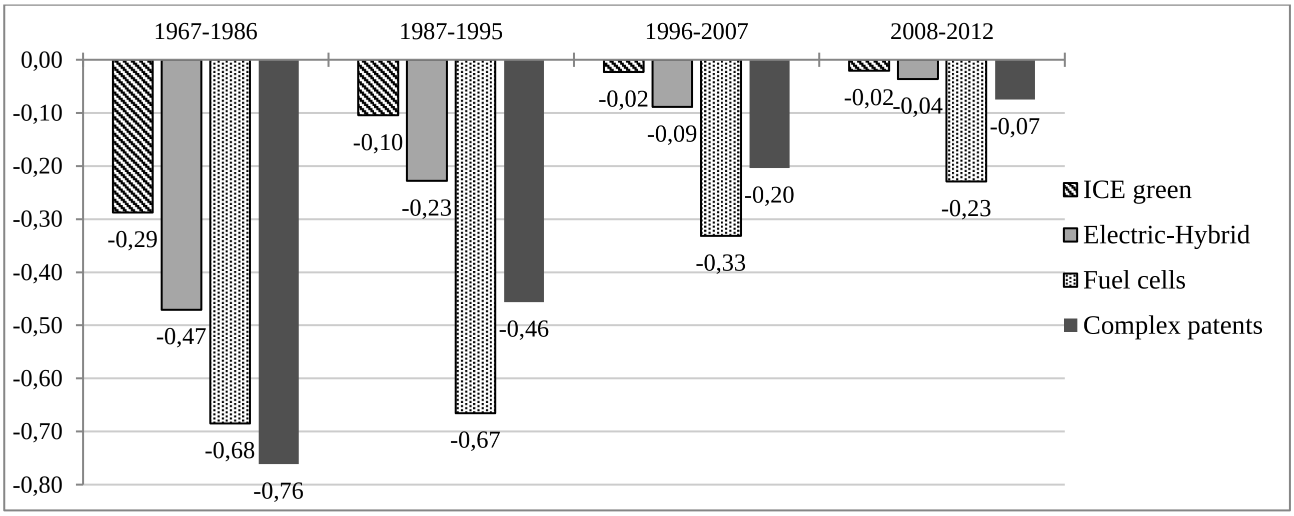

Figure 9. Aggregated RTSI – Average standard deviation