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1 **Sectoral Dynamics and Technological Convergence: an evolutionary analysis of** 2 **eco-innovation in the automotive sector**

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

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

25

26 **1. Introduction**

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

33 This paper seeks to explore an evolutionary economic perspective on the greening of the
34 economy built upon behavioral theory of the firm (Faber & Frenken, 2009) and sectoral patterns of
35 innovation, both of which, we argue, are key dimensions to understand green industrial dynamics.
36 The overall research question investigates to what degree the economy is greening horizontally
37 (sector-wise) as opposed to vertically (chain wise) (Andersen & Faria, 2015). Many evolutionary

38 scholars have demonstrated that firms in the same sector could be subject to some convergence in
39 their innovation strategies and performance, forming sector-specific technological trajectories (
40 Pavitt, 1984; Breschi & Malerba, 1996; Klevorick et al., 1995; Malerba, 2002;). While this is a strong
41 and well recognized argument in evolutionary research, it is also been contested since the strength
42 and range of sectoral patterns of innovation is relative and other dimensions may also affect
43 innovative activities (Peneder, 2010a).

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

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

61 Using patent data, the paper analyses eco-innovation activities in the automotive sector from
62 1965 to 2012, allowing us to cover the main period of its greening process to date. The eco-
63 innovations are restricted to the core automotive innovation, the powertrain. This is partly to delimit
64 the analysis, which is quite comprehensive by nature, and partly to allow for an interesting
65 comparison between the mature dominant design, the combustion engine, and the upcoming
66 competing green trajectories (related to respectively hybrid/electric cars and fuel cell based cars). We
67 use the firms’ patent portfolios and two specialization indexes (Herfindahl-Hirshman index and
68 Relative Technological Specialization Index) to identify patterns of convergence/divergence in the

69 firms' green technological strategies, and argue that these may be seen as a proxy for the overall main
70 greening trend of the sector.

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

78 In recent years, however, many important transformations on technological regimes and
79 institutions in the automotive sector are taking place. Some of these transformations carry the
80 potential to challenge the current dominant design. Examples of these transformations include the
81 incorporation of microelectronics and information and communication technologies¹ (Seidel et al.,
82 2005), the growing pressures to generate energy efficient products, as governments and users are
83 increasingly aware² of the negative externalities in terms of environment harm and intensive use of
84 non-renewable resources associated with automobiles.

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

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

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/>.

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

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

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

117

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

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

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

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

141 [FIGURE 1 HERE]

142

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

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

155 related to the co-evolution of technologies, organizations and institutions over time (Lundvall,
156 1992a).

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

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

173 On the other hand, some scholars believe that there is in fact a broad "technology
174 fragmentation" movement with multiple and semi-conflicting pathways over time, with most
175 manufacturers progressively adopting active positions in alternative technologies development (Oltra
176 & Saint Jean, 2009; Wells & Nieuwenhuis, 2012; Sierzechula et al., 2012), acknowledging the
177 importance of gradual improvements that can take decades and are above the "hypes" (Patel & Pavitt,
178 1997).

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

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

186 This convergence is analyzed in terms of 1) reductions in the concentration of patenting activity
187 for each technology, and 2) the degree of homogeneity among the firms' patent portfolios. The
188 opposite situation is a divergence in their strategies, signaling that other factors may be stronger,
189 including firm-specific and geographic-specific elements or even rules of thumb (Patel & Pavitt,
190 1997). In this case we would also observe heterogeneous combinations in firms' patent portfolios.

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

198 [FIGURE 2 HERE]

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

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

207 **3. Methodology**

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

213 Despite its general limitations as an innovation indicator (Pakes, 1986; Pavitt, 1985), the rate
214 of growth in patenting in a certain technologic field can be used as *proxy* of its importance and
215 maturity degree (Chang, 2012; Nesta & Patel, 2005), and patent applications are considered indicators
216 of firms' technological competences as they show that the firm has sufficient competences to produce
217 knowledge pieces that are on the technological frontier in a given technological field (Breschi et al.,
218 2003). Moreover, patents are strongly correlated with R&D expenditures and therefore make a good
219 proxy for innovative activity (Griliches, 1990).

220 3.1. Data collection

221 First, we selected a group of major automakers in order to represent the innovative activity in
222 the sector and build a picture of important aspects of eco-innovation activity (Ernst, 2001). The
223 sample of firms was chosen based on two requirements: 1) the automaker must be listed on the
224 OICA's (International Organization of Motor Vehicle Manufacturers) World Motor Vehicle
225 Production ranking 2012³; and 2) the number of patents filled on the selected patent offices must be
226 of at least 500 up to 2013. Based on these criteria, we selected 17 car manufacturers as follows: BMW,
227 Daimler, Fiat, Ford, Fuji Heavy Industries (Subaru), General Motors, Honda, Hyundai, Isuzu, Mazda,
228 Mitsubishi, Nissan, Porsche, PSA (Peugeot-Citroën), Renault, Toyota, and Volkswagen.

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

237 Instead of using keywords (e.g. Frenken et al., 2004; Oltra & Saint-Jean, 2009a, 2009b), we
238 adopted selected International Patent Classification (IPC) codes in order to collect the patents
239 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.

240 developed IPC Green Inventory⁵ and the OECD's list of Environmentally-sound technologies (EST)⁶.
241 Therefore, for each technologic group, we selected a number of IPC codes to represent the patenting
242 activity in their respective areas. The groups of codes are presented in the Annex. By using these
243 application-based codes, we aim to minimize the risk of including irrelevant patents and excluding
244 relevant ones (Veefkind et al., 2012)⁷.

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

256 [FIGURE 3 HERE]

257 Our data sample presents some drawbacks. First, it does not include some relevant actors,
258 including new automakers and those from developing countries – particularly from China and India,
259 but also suppliers, universities and research centers. We argue, however, that in the specific time and
260 sectoral dimensions adopted in this paper, the major incumbents still have a crucial role in defining
261 the technological strategies of the sector, influencing all the other important actors in their decision
262 processes (Malerba & Orsenigo, 1997; Pavitt, 1984), and the group of selected firms is responsible
263 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](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).

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

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

276 [TABLE 1 HERE]

277

278 *3.2. Methodological procedures*

279 To check the sectoral convergence, we first analyze the trajectory of green patenting in our
280 sample over time. We use a measure of convergence typically used in industrial economics and
281 international trade literature to measure market concentration and specialization, the Herfindahl-
282 Hirshman index (HHI) (Herfindahl, 1950; Hirschman, 1964), as suggested by Malerba & Orsenigo
283 (1997). The index is described as:

$$284 \quad HHI = \sum_{i=1}^I b_i^\alpha$$

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

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

$$296 \quad RTSI_{ij} = \frac{(P_{ij}/\sum_i P_{ij})}{(\sum_j P_{ij}/\sum_i \sum_j P_{ij})}$$

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

$$302 \quad RTSIn_{ij} = \frac{(RTSI_{ij} - 1)}{(RTSI_{ij} + 1)}$$

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

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

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

317

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

319 *4.1 Evolution of green patenting in the automotive sector*

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

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

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

336 The first phase is marked by the introduction of the first comprehensive vehicle pollution
337 control and fuel economy standards and regulations, including the Clean Air Act of 1970 and the
338 1975 Corporate Average Fuel Economy (CAFE) in U.S., the Japanese Air Pollution Control Law of
339 1973, and the Economic Commission for Europe (ECE) Regulation 15-01 in 1974 that was the base
340 for many European countries’ regulations, as well as many other national regulations along the 1970s
341 and 1980s. According to Faiz et al. (1996), “compliance with these standards (...) provided the
342 impetus for major advances in automotive technology worldwide” (p. 3).

343 [FIGURE 4 HERE]

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

353 The relative participation of green patents in firms' portfolios decreased over the 1980s since
354 main regulations' requirements remained stable over the decade and governmental support was
355 subject to major budget fluctuations which have made it impossible to sustain a coherent development
356 program on alternative powertrain technologies. According to a report to U.S. Congress, "(...) after
357 an initial flurry of activity on hybrid vehicles at DOE [U.S. Department of Energy] from 1978 to
358 1980, the hybrid effort was shelved until 1992" (U.S. Congress, 1995, p. 229).

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

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

⁸ See <http://ec.europa.eu/environment/air/transport/road.htm>

373 Vehicles (ZEV I) Program⁹ recognized that ICE-related emissions tend to deteriorate rapidly with
374 time and could never be reduced to zero.

375 These regulations were followed by the establishment of joint research programs and
376 partnerships among automakers and other stakeholders, such as the U.S.-based Advanced Battery
377 Consortium (1991) and the Partnership for a New Generation of Vehicles (PNGV) (1993), the
378 Automotive Research and Technological Development Master Plan (1994) and the “Car of
379 Tomorrow” task force (1995) in Europe. However, the relative growth of green patents was still very
380 much dependent on the behavior of ICE-related patenting (Figure 4), since most automakers remained
381 reluctant to invest heavily in such risky alternative technologies¹⁰.

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

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

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 constraints, 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>

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

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

413 *4.2 Technological convergence/divergence towards eco-innovation activities*

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

419 [FIGURE 5 HERE]

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

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

433 [FIGURE 6 HERE]

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

440 [FIGURE 7 HERE]

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

444
$$\overline{RTSI}_{n_t} = \frac{1}{n} \times \sum_{j=1}^n RTSI_{ij}$$

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

449 [FIGURE 8 HERE]

450 The evolution of the average aggregated RTSI over time corroborates the results of the previous
451 analysis. In the first period, the RTSI for most firms was close to -1 for Fuel Cells and Complex
452 patents - indicating that only a few firms presented relative specialization in this technologies - and
453 higher for Electric Hybrid and ICE. Over time, the RTSI gets closer to 0 for all technologies, which

454 is another indicator of convergence – since they are all getting to the point where their share of these
455 technologies is equal to the share of the whole sample. It is worth mentioning, however, that fuel cell
456 technologies remain less spread among the firms when compared with the other technologies even in
457 the last period.

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

463 [FIGURE 9 HERE]

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

469 5. Discussion of the findings – signs of sectoral greening

470 The data analysis indicates a substantial reduction in concentration of all green technologies as
471 technological opportunities are being collectively perceived and risks are shared. A decrease in the
472 concentration levels of all technologies over time as measured by the HHI index demonstrate that
473 even (or especially) the technologies which are more distant from the existing technological are being
474 developed by an increasing number of firms, approaching the level of diversification of the overall
475 patent activity in the sector, with substantial shifts observed during the mid-1990s and notably after
476 the 2008 crisis. Moreover, the specialization index indicates a strong convergence in the automakers’
477 strategies in green ICE, Hybrid/Electric and Complex portfolios, which also finds support in the
478 literature using other datasets and methods (e.g. Frenken et al., 2004; Oltra & Saint-Jean, 2009a;
479 2009b; Sierzychula et al., 2012).

480 Therefore, our findings suggest that the hypothesis H1 is valid: we indeed observe an increase
481 in the convergence of firms’ strategies for the green powertrain technologies, which reflect common
482 perceptions of risks and opportunities among the firms in the sample. However, the portfolio of

483 patents related with Fuel cells continues to be relatively more concentrated than the other
484 technologies. It suggests that innovations that are further away technologically from the dominant
485 design present greater levels of uncertainty – and thus variation (Anderson & Tushman, 1990). It also
486 suggests that other factors, such as country- and firm-specific characteristics, may have a stronger
487 influence in such complex technologies. Nevertheless, these hypotheses require further research to
488 be validated.

489 As a counterpoint to the findings of Sierzechula et al. (2012) that the number of hydrogen-based
490 announced models decreased rapidly during the 2000s, the rise and breakdown of expectations about
491 a hydrogen-based economy, usually referred as a “hype” in the literature (Bakker, 2010), did not
492 translate into a large reduction of fuel cell patenting, but into a stabilization of such activities of about
493 5% of the total patenting in the sector (taking off the complex patents related with fuel cells). This is
494 an indicator that the effects of frustrated expectations might be smaller in a context of technological
495 uncertainty, high competition and strong pressures to change.

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

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

514 6. Final considerations

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

526 It can, off course be debated how high the greening level is we are witnessing with these data;
527 we know from other studies that the automotive sector, as other sectors, is still facing a number of
528 serious eco-innovation challenges, compare the recent “dieselgate” scandal (Blackwelder et al.,
529 2016). We propose none the less that we may interpret our findings as robust indications that most if
530 not all the main players in the industry are in fact greening to quite some degree and in a global
531 perspective which has not been analyzed before. Tentatively we propose that we may interpret this
532 as a sign that we have reached a certain level of global market driven green economic evolution,
533 though more research is needed, e.g. including studies into the increasingly important Asian
534 economies and integration with other types of data analysis. We can, in other words, mainly say
535 something about the direction of the greening trend than the level of greening with the current study.

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

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

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551 **References**

- 552 Abernathy, W. J., & Clark, K. B. (1985). Innovation: Mapping the winds of creative destruction. *Research*
553 *Policy*, 14(1), 3–22. doi:10.1016/0048-7333(85)90021-6
- 554 Andersen, M. M. (2008). Eco-innovation. Towards a taxonomy and a theory. In *DRUID Conference 2008 -*
555 *Entrepreneurship and innovation - organizations, institutions, systems and regions.*
- 556 Andersen, M. M. (2009). Combating Climate Change through Eco-innovation - Towards the Green Innovation
557 System. In *Innovative Economic Policies for Climate Change Mitigation* (1st ed., pp. 37–58).
- 558 Andersen, M. M., & Faria, L. (2015). Eco-innovation Dynamics and Green Economic Change: the role of
559 sectoral-specific patterns. In *R&D Management Conference 2015.*
- 560 Arundel, A., & Kemp, R. (2009). Measuring eco-innovation. *Accounting Finance* (Vol. 20). United Nations
561 University - Maastricht Economic and social Research and training centre on Innovation and Technology.
562 doi:10.1111/j.1467-629X.1980.tb00220.x
- 563 Bakker, S. (2010). The car industry and the blow-out of the hydrogen hype. *Energy Policy*, 38(11), 6540–
564 6544.
- 565 Barney, J. (1991). Firm resources and sustained competitive advantage. *Journal of Management*, 17(1), 99–
566 120.
- 567 Blackwelder, B., Coleman, K., Colunga-Santoyo, S., Harrison, J., & Wozniak, D. (2016). *The Volkswagen*
568 *Scandal*. University of Richmond
- 569 Bointner, R. (2014). Innovation in the energy sector: Lessons learnt from R&D expenditures and patents in
570 selected IEA countries. *Energy Policy*, 73, 733–747. doi:10.1016/j.enpol.2014.06.001
- 571 Breschi, S., Lissoni, F., & Malerba, F. (2003). Knowledge-relatedness in firm technological diversification.
572 *Research Policy*, 32(January 2001), 69–87.
- 573 Breschi, S., & Malerba, F. (1996). Sectoral innovation systems: technological regimes, Schumpeterian
574 dynamics and spatial boundaries. In C. Edquist (Ed.), *Systems of innovation: Technologies, institutions and*
575 *organizations* (pp. 130–156). London: Routledge.
- 576 Chang, S.-B. (2012). Using patent analysis to establish technological position: Two different strategic
577 approaches. *Technological Forecasting and Social Change*, 79(1), 3–15. doi:10.1016/j.techfore.2011.07.002

578 Cooke, P., Gomez Uranga, M., & Etxebarria, G. (1997). Regional innovation systems: Institutional and
579 organisational dimensions. *Research Policy*, 26(4-5), 475–491. doi:10.1016/S0048-7333(97)00025-5

580 Dechezleprêtre, A., Glachant, M., Haščič, I., Johnstone, N., & Meniere, Y. (2011). Invention and Transfer of
581 Climate Change-Mitigation Technologies: A Global Analysis. *Review of Environmental Economics and*
582 *Policy*, 5(1), 109–130. doi:10.1093/reep/req023

583 Ernst, H. (2001). Patent applications and subsequent changes of performance: evidence from time-series cross-
584 section analyses on the firm level. *Research Policy*, 30(1), 143–157. doi:10.1016/S0048-7333(99)00098-0

585 Faber, A., & Frenken, K. (2009). Models in evolutionary economics and environmental policy: Towards an
586 evolutionary environmental economics. *Technological Forecasting and Social Change*, 76(4), 462–470.
587 doi:10.1016/j.techfore.2008.04.009

588 Faiz, A., Weaver, C. S., & Walsh, M. P. (1996). Air pollution from motor vehicles: standards and technologies
589 for controlling emissions. World Bank Publications.

590 Frenken, K., Hekkert, M. P., & Godfroij, P. (2004). R&D portfolios in environmentally friendly automotive
591 propulsion: Variety, competition and policy implications. *Technological Forecasting and Social Change*,
592 71(5), 485–507. doi:10.1016/S0040-1625(03)00010-6

593 Fukasaku, Y. (1998). Revitalising mature industries. *The OECD Observer* 213.

594 Fukasaku, Y. (2005). The need for environmental innovation indicators and data from a policy perspective. In
595 *Towards environmental innovation systems* (pp. 251-267). Springer Berlin Heidelberg.

596 Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level
597 perspective and a case-study. *Research policy*, 31(8), 1257-1274.

598 Griliches, Z. (1990). Patent statistics as economic indicators: a survey. *Journal of Economic Literature*, 28(4),
599 1661–1707.

600 Hall, B. H. (2005). A Note on the Bias in Herfindahl-Type Measures Based on Count Data. *Revue d'economie*
601 *industrielle*, (110), 149-156

602 Herfindahl, O. C. (1950). Concentration in the steel industry (Doctoral dissertation, Columbia University).

603 Hirschman, A. O. (1964). The paternity of an index. *The American Economic Review*, 761-762.

604 Horbach, J., Rammer, C., & Rennings, K. (2012). Determinants of eco-innovations by type of environmental
605 impact — The role of regulatory push/pull, technology push and market pull. *Ecological Economics*, 78, 112–
606 122. doi:10.1016/j.ecolecon.2012.04.005

607 Johnstone, N., Haščič, I., & Popp, D. (2010). Renewable Energy Policies and Technological Innovation:
608 Evidence Based on Patent Counts. *Environmental and Resource Economics*, 45(1), 133–155.
609 doi:10.1007/s10640-009-9309-1

610 Kemp, R., & Soete, L. (1992). The Greening of Technological-Progress - an Evolutionary Perspective. *Futures*,
611 24(5), 437–457. doi:10.1016/0016-3287(92)90015-8

612 Klevorick, A. K., Levin, R. C., Nelson, R. R., & Winter, S. G. (1995). On the sources and significance of
613 interindustry differences in technological opportunities. *Research Policy*, 24(2), 185–205. doi:10.1016/0048-
614 7333(93)00762-I

615 Levy, D., & Rothenberg, S. (2002). Heterogeneity and change in environmental strategy: technological and
616 political responses to climate change in the global automobile industry. In A. Hoffman & M. Ventresca (Eds.),

617 Organizations, policy and the natural environment: institutional and strategic perspectives (pp. 173–193).
618 Stanford University Press: Stanford.

619 Lundvall, B.-Å. (1992a). National Systems of Innovation: Toward a Theory of Innovation and Interactive
620 Learning. London: Anthem Press.

621 Malerba, F. (2002a). Sectoral systems of innovation and production. *Research Policy*, 31(2), 247–264.
622 doi:10.1016/S0048-7333(01)00139-1

623 Malerba, F., & Orsenigo, L. (1997). Technological Regimes and Sectoral Patterns of Innovative Activities.
624 *Industrial and Corporate Change*, 6(1), 83–118. doi:10.1093/icc/6.1.83

625 Nelson, R. R. (1991). Why do firms differ, and how does it matter? *Strategic Management Journal*, 12(1 991),
626 61–74.

627 Nesta, L., & Patel, P. (2005). National patterns of technology accumulation: Use of patent statistics. In H. F.
628 Moed, W. Glänzel, & U. Schmoch (Eds.), *Handbook of Quantitative Science and Technology Research* (pp.
629 531–551). London: Kluwer Academic Publishers.

630 Oltra, V., Kemp, R., & Vries, F. De. (2010). Patents as a measure for eco-innovation. *International Journal of*
631 *Environmental Technology*, 13(2), 130–148. doi:http://dx.doi.org/10.1504/IJETM.2010.034303

632 Oltra, V., & Saint-Jean, M. (2009a). Sectoral systems of environmental innovation: An application to the
633 French automotive industry. *Technological Forecasting and Social Change*, 76(4), 567–583.
634 doi:10.1016/j.techfore.2008.03.025

635 Oltra, V., & Saint-Jean, M. (2009b). Variety of technological trajectories in low emission vehicles (LEVs): A
636 patent data analysis. *Journal of Cleaner Production*, 17(2), 201–213. doi:10.1016/j.jclepro.2008.04.023

637 Orsato, R., & Wells, P. E. (2007). The automobile industry & sustainability. *Journal of Cleaner Production*,
638 15(11), 989–993. doi:doi:10.1016/j.jclepro.2006.05.035

639 Pakes, A. (1986). Patents as options: Some estimates of the value of holding European patent stocks.
640 *Econometrica*, 54(4), 755–784. doi:10.2307/1912835

641 Palan, N. (2010a). Measurement of Specialization -The Choice of Indices. FIW – Working Paper,
642 62(December), 2–38.

643 Palan, N. (2010b). Measurement of Specialization–The Choice of Indices. Retrieved from
644 <https://ideas.repec.org/p/wsr/wpaper/y2010i062.html>

645 Patel, P., & Pavitt, K. (1997). The technological competencies of the world's largest firms: complex and path-
646 dependent, but not much variety. *Research Policy*, 26(2), 141–156.

647 Patel, P., & Vega, M. (1999). Patterns of internationalisation of corporate technology: location vs. home
648 country advantages. *Research Policy*, 28(2-3), 145–155. doi:10.1016/S0048-7333(98)00117-6

649 Pavitt, K. (1984). Sectoral patterns of technical change: Towards a taxonomy and a theory. *Research Policy*,
650 13(6), 343–373. doi:10.1016/0048-7333(84)90018-0

651 Pavitt, K. (1985). Patent statistics as indicators of innovative activities: possibilities and problems.
652 *Scientometrics*, 7, 77–99.

653 Pavitt, K. (1998). Technologies, products and organization in the innovating firm: what Adam Smith tells us
654 and Joseph Schumpeter doesn't. *Industrial and Corporate Change*, 433–452. Retrieved from
655 <http://icc.oxfordjournals.org/content/7/3/433.short>

656 Peneder, M. (2010). Technological regimes and the variety of innovation behaviour: Creating integrated
657 taxonomies of firms and sectors. *Research Policy*, 39(3), 323–334. doi:10.1016/j.respol.2010.01.010

658 Penna, C. C. R., & Geels, F. W. (2014). Climate change and the slow reorientation of the American car industry
659 (1979–2012): An application and extension of the Dialectic Issue LifeCycle (DILC) model. *Research Policy*,
660 44(5), 1029–1048. doi:10.1016/j.respol.2014.11.010

661 Popp, D. (2005). Lessons from patents: Using patents to measure technological change in environmental
662 models. *Ecological Economics*, 54(2-3), 209–226. doi:10.1016/j.ecolecon.2005.01.001

663 Reid, A., & Miedzinski, M. (2008). Eco-innovation: final report for sectoral innovation watch. SYSTEMATIC
664 Eco-Innovation Report. Retrieved from
665 https://scholar.google.dk/scholar?q=Reid+%26+Miedzinski%2C+2008&btnG=&hl=en&as_sdt=0%2C5#0

666 Rycroft, R. W., & Kash, D. E. (2004). Self-organizing innovation networks: implications for globalization.
667 *Technovation*, 24(3), 187–197. doi:10.1016/S0166-4972(03)00092-0

668 Seidel, M., Loch, C. H., & Chahil, S. (2005). Quo Vadis, Automotive Industry? A Vision of Possible Industry
669 Transformations. *European Management Journal*, 23(4), 439–449. doi:10.1016/j.emj.2005.06.005

670 Sierczula, W., Bakker, S., Maat, K., & van Wee, B. (2012). Technological diversity of emerging eco-
671 innovations: a case study of the automobile industry. *Journal of Cleaner Production*, 37, 211–220.
672 doi:10.1016/j.jclepro.2012.07.011

673 Singh, K. (1997). The impact of technological complexity and interfirm cooperation on business survival.
674 *Academy of Management Journal*, 40(2), 339–367. doi:10.2307/256886

675 U.S. Congress (1995). *Advanced Automotive Technology: Visions of a Super-Efficient Family Car*. US
676 Government Printing Office: Washington DC.

677 Van den Hoed, R. (2005). Commitment to fuel cell technology? *Journal of Power Sources*, 141(2), 265–271.
678 doi:10.1016/j.jpowsour.2004.09.017

679 Veefkind, V., Hurtado-Albir, J., Angelucci, S., Karachalios, K., & Thumm, N. (2012). A new EPO
680 classification scheme for climate change mitigation technologies. *World Patent Information*, 34(2), 106–111.
681 doi:10.1016/j.wpi.2011.12.004

682 WCED (1987). *Our Common Future*. Assessment report for the World Commission on Environmental
683 Development. Oxford University Press, Oxford, UK.

684 Wells, P. E., & Nieuwenhuis, P. (2012). Transition failure: Understanding continuity in the automotive
685 industry. *Technological Forecasting and Social Change*, 79(9), 1681–1692.
686 doi:10.1016/j.techfore.2012.06.008

687 Wesseling, J. H., Faber, J., & Hekkert, M. P. (2014). How competitive forces sustain electric vehicle
688 development. *Technological Forecasting and Social Change*, 81, 154–164.

693 **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/*			

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695 **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
<i>Total</i>	<i>144931</i>	<i>20879</i>	<i>9138</i>	<i>5669</i>	<i>4609</i>

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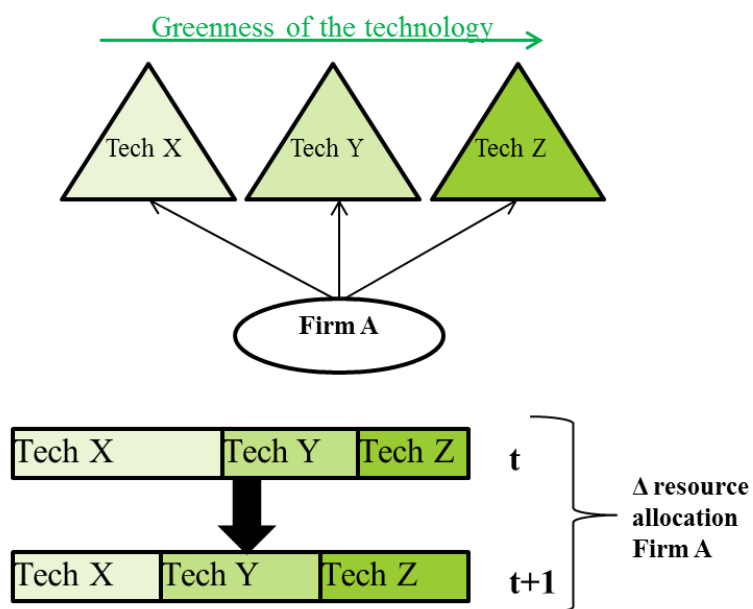
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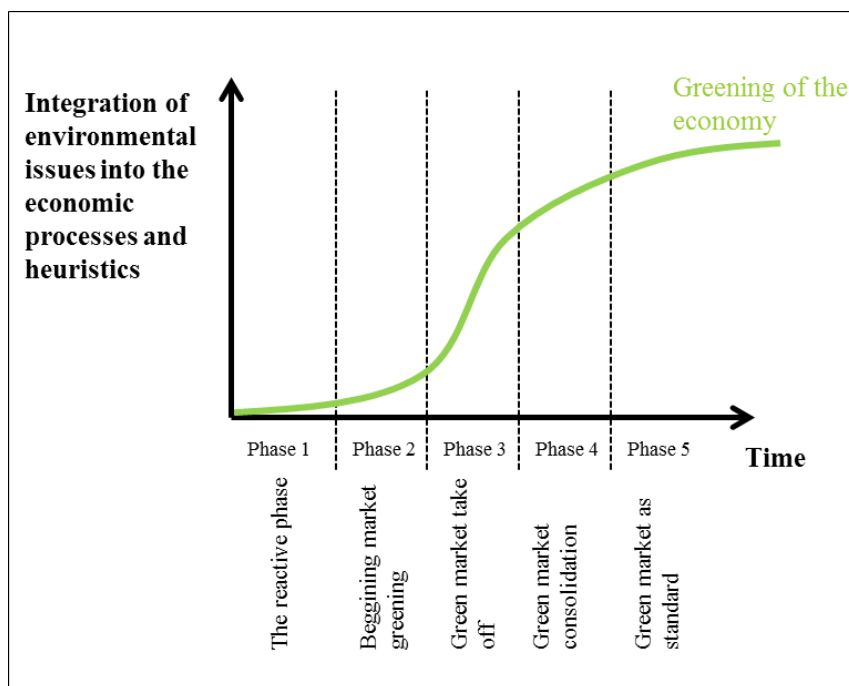
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712 **Figure 1. Technological strategies as resource allocation in different technologies**



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714 **Figure 2. The green learning curve**

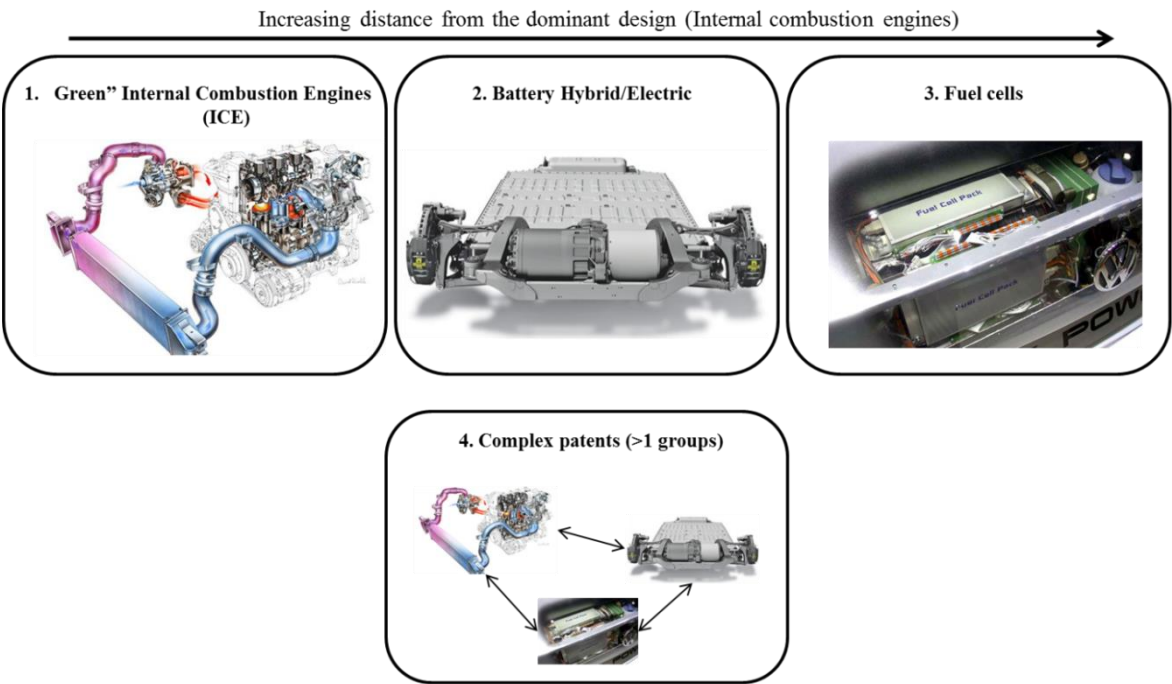


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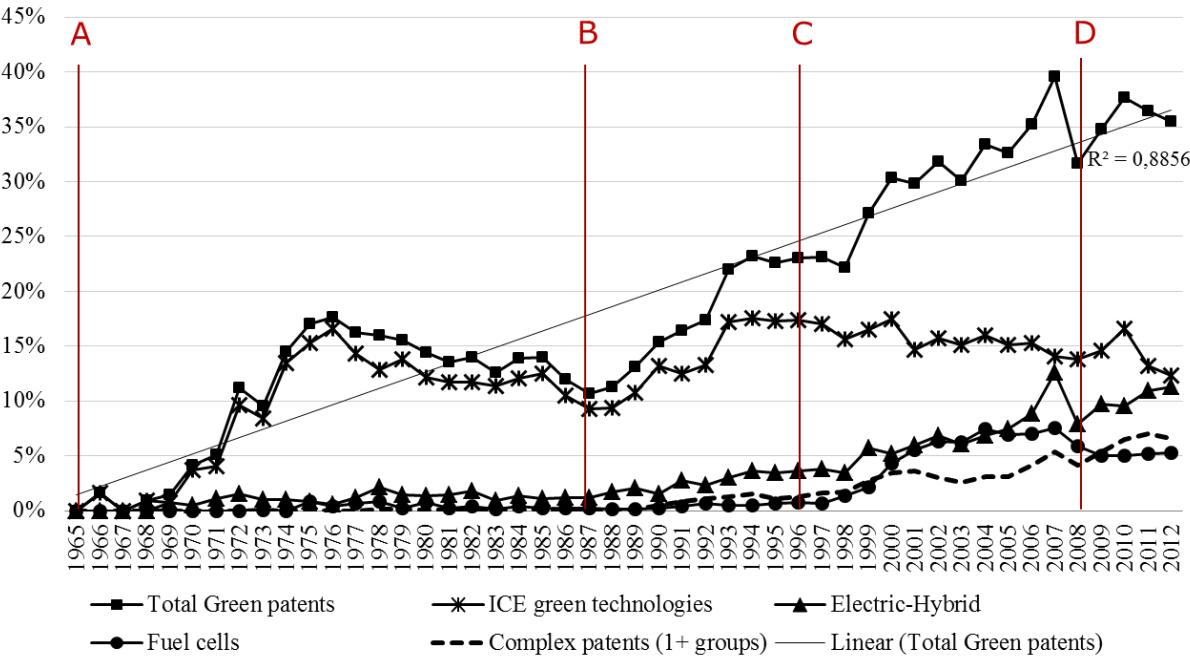
718 **Figure 3 – The four selected technological groups**



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721 **Figure 4. Green patents’ production as % of total patenting activity in the sample**

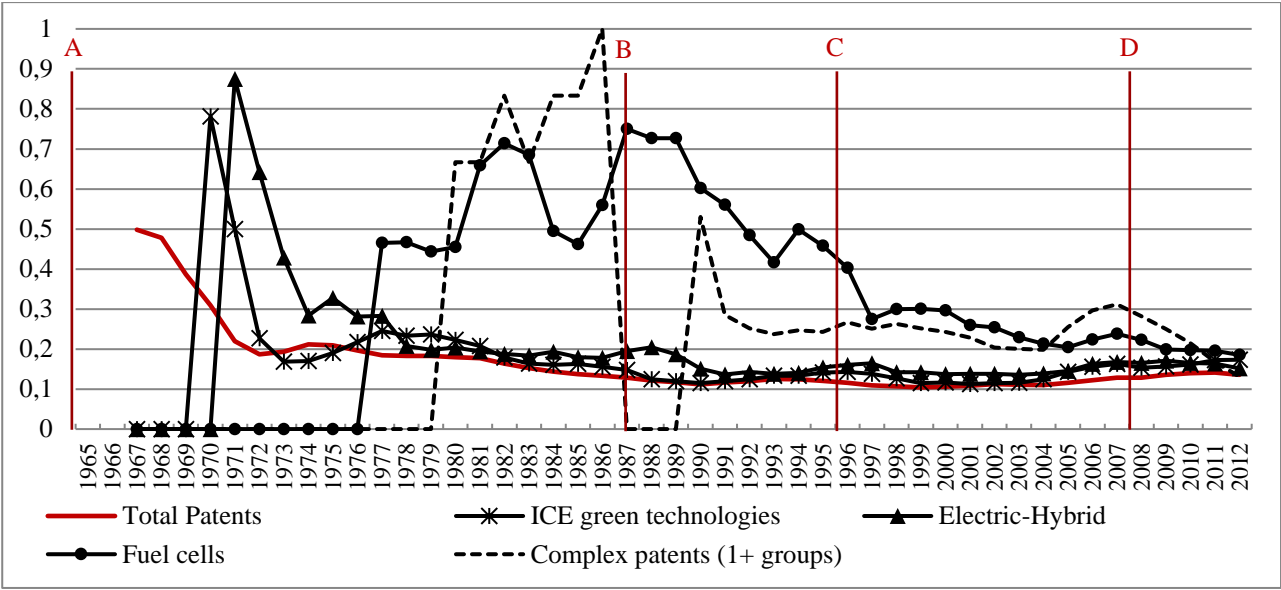


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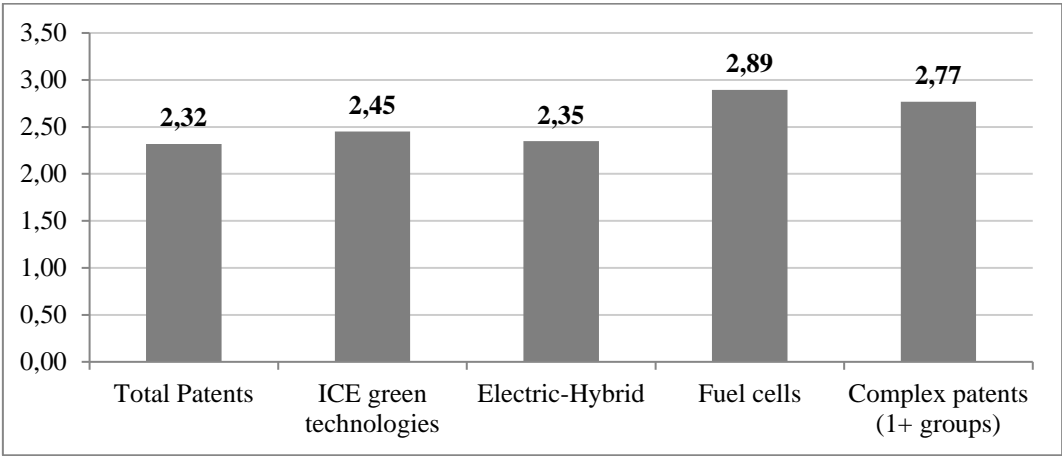
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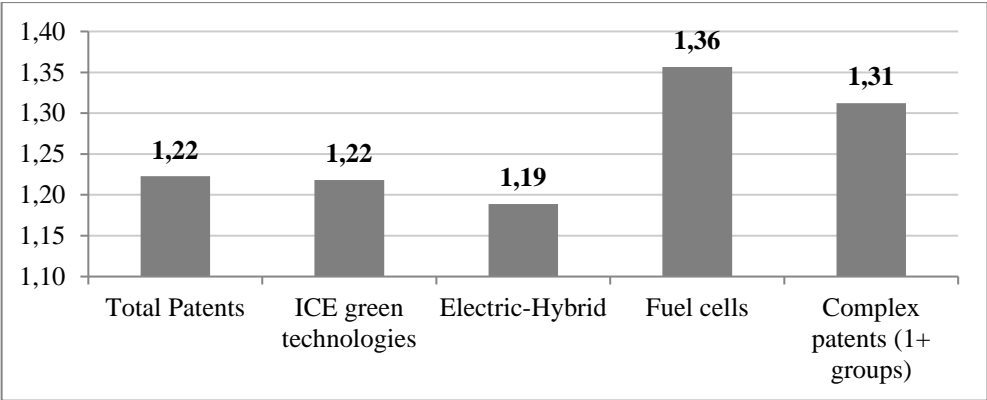
725 **Figure 5. Herfindal-Hirschman index (HHI), 3-year moving average (1965-2012)**
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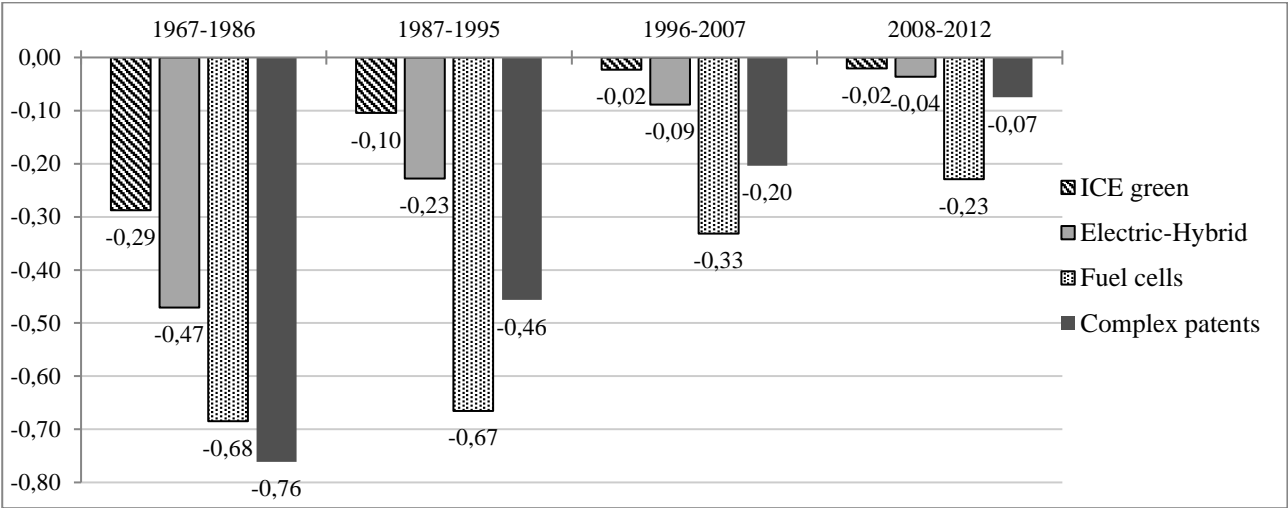
729 **Figure 6. Average number of inventors per patent (1965-2012)**



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



742 **Figure 8. Average Aggregated RTSI**



745 **Figure 9. Aggregated RTSI – Average standard deviation**

