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Theoretical considerations and a study case in the automotive sector

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Sectoral Patterns of Eco-innovation
Theoretical considerations and a study case in the automotive sector

PhD thesis
Technical University of Denmark

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CHAPTER 1
OUTLINE OF THE THESIS: CONCEPTUAL FRAMING, RESEARCH GAP AND DATA

1.1 Introduction

There goes almost thirty years since the World Commission on Environment and Development released the *Our Common Future* report, more than four decades since the Jay W. Forrester's Institute at MIT launched *Limits to Growth*, and more than two centuries since Thomas Malthus first published *An Essay on the Principle of Population*, all calling attention to the limits of natural resources, but the humanity – and particularly the *Homo economicus* – still struggle to acknowledge the limitations of our planet and act upon it. We appear to be locked in a primitive, tribal-oriented mindset, unable to effectively think and act globally.

In this perspective, the academic community is still taking the first steps towards the understanding of what a "green" economy - or more widely, a green society - truly means and how to move our whole industries, our habits, and our mindsets in that direction.

For instance, the relationship between technological advancement and the environment, in particular, is complex and paradoxical. On the one hand, much of the damage to the environment can be attributed to modern technologies, which were gradually developed and improved over decades without, however, take into account the environmental issues. On the other hand, the development of more efficient technologies is certainly one of the greatest allies in efforts to reduce environmental impacts.

We know, however, that the transition from one paradigm to the other is not straightforward, given the complexity of our productive, economic, and institutional foundations, as well as the multiplicity of interests involved, many of which in the opposite direction.

This thesis aims to contribute to the understanding of this transition between "dirty" and "green" technologies, as well as some structural characteristics of a green economy. We deal with the dynamics of the greening process in an evolutionary perspective and more specifically with the sector-specific patterns that arise in this process.

Overall, the thesis draws upon evolutionary economics' main hypothesis: the link between the dynamics of economic growth, market structures, and technological change (Nelson and Winter, 1982; Perez, 1983; Schumpeter, 1942; Utterback and Suarez, 1993), which we use as background to understand both why eco-innovation, by being a process of technological and economic change, is essential to the greening of the economy, and if there are regularities in this process similarly to the regularities that are reported in the "traditional" innovation literature.

The thesis is based in five articles that are here represented in chapters (Chapter 2 to 6). The discussion starts with two papers that are centered in the critical discussion of eco-innovation concept and its development and narrows to the ultimate focus of discussing empirically and theoretically sectoral patterns of eco-innovation.

During the first stages of my research, I had to effectively define the eco-innovation concept to conduct the data collection and analysis, as well as the literature review, necessary to study the sectoral patterns of eco-innovation. In this process, after discussing with my main supervisor and several colleagues, and reading the most relevant papers in this topic, I realized how the definition and scope of what can effectively be considered an eco-innovation is fuzzy and poorly discussed, although some authors disagree with this conclusion (for example, Berkhout, 2011). Likewise, defining eco-innovations is just as complex and challenging as analyzing the phenomenon itself. This topic is summarized in the first two papers of the thesis (Chapter 2 and 3).

The role of firms strategies and differences in market structures in the dynamics of the greening process is still under investigated, as most analyzes of eco-innovation are centered in broad policy issues (Berrone et al., 2013; Kemp and Oltra, 2011). In the second part of the thesis, I investigate the existence and strength of sectoral patterns versus fundamental heterogeneity in eco-innovation activities using the automotive sector as a case study. The core assumption is that the observation of patterns in firms' green technological strategies reflect the formation of sectoral patterns of eco-innovation. Accordingly, the thesis is centered in the following research question:

- Can we observe the rise of sector-specific patterns of eco-innovation in the automotive sector?

We chose the automotive sector as case study, first of all, because of its importance in the greening of the economy: while it is essential for the functioning of our actual society, the automobile also imposes enormous costs in terms of environment harm and intensive use of nonrenewable resources and, in order to reduce such environmental impact, new dynamics are introduced in the technological regime of the sector, traditionally characterized by the introduction of incremental innovations in product and process upon a dominant design (the internal combustion engine).

Secondly, because of the oligopolistic nature of the sector, a relatively small number of firms might be use as a representative of the trajectory of innovative activity in the sector, especially considering that our main data source is patents. Moreover, it presents distinguishable product technologies that can be observed using classifications of patent codes.

This first chapter consists of an introduction to 1) the conceptual framing utilized along the thesis, which include the evolutionary view on the dynamics of innovation and the formation of sectoral-specific patterns, as well as the literature on environmental innovation. 2) The research gaps that inspired our main research questions, the lack of micro foundations' and sector-specific analyzes of eco-innovation in general and in the automotive sector; 3) the outline of the thesis, with a brief explanation about the content of each chapter; and finally 4) a brief explanation on the sources and methods utilized to gather the data necessary to conduct the research.

1.2 Conceptual framing

1.2.1 The evolutionary approach on the dynamics and sectoral patterns of innovation

According to the evolutionary perspective of technological change, agents are capable of introducing behavioral and technological novelties into the production system using new knowledge and/or new combinations of existent knowledge (Dosi & Nelson, 1994) that can eventually change entire socio-economic structures (Perez, 1983). This *creation mechanism* is equivalent to the biological notion of genetic mutation that leads to the emergence of new species with different features in a specific environment but, unlike its biological parallel, the technological diversity is not created just by random mutations, but can also be a response to changes on the environmental characteristics (Nelson and Winter, 1982).

The *environment*, as defined here according to the evolutionary framework, is a complex structure of specific technological, socio-economic and institutional configurations (or regimes) and tend to be characterized by relatively invariant and path-dependent *routines*[1] that arise as a response to persistent uncertainty, risk, learning patterns, and technological characteristics that are inherent to innovative activities (Arthur, 1989; Dosi and Nelson, 1994; Dosi, 1988, 1982; Leonard-Barton, 1998; Nelson and Winter, 1982, 1977), therefore acting as *selection*

[1] Such routines are expressed in terms of, for example, dominant designs, basic heuristics used on R&D processes, general consumption preferences and prejudices - the "common sense", firms' common behaviors, political institutions, and sectoral standards. As agents (firms, consumers, policymakers) have imperfect information about the potential opportunities and risks related with new technologies, organizational methods or research agendas, they tend to adopt well-known, routinized behaviors (Leonard-Barton, 1998; Winter, 1984).

mechanisms that systematically winnow on extant diversity in market level (Nelson & Winter, 1982).

The creation and selection mechanisms are not static over time, but follows cycles in which their influence varies according to the characteristics of the environment (Utterback and Abernathy, 1975). Following Abernathy & Clark (1985), during the initial phases of *technologic life cycles*, the rate of experimentation is high and there is great diversity among products and processes, thus firms have more freedom to innovate, and therefore the influence of selection mechanisms is weaker. As a technology goes through its "maturation" phase and knowledge about the technology is increasingly accumulated (i.e. on potential applications, production costs, performance optimization, user preferences, environmental impacts), opportunities and risks start to be commonly perceived by firms, which align their individual technological trajectories.

The more a technology is explored, the higher its utility tends to become for users and producers (David, 1985; C. Perez, 2009). New infra-structures and complementary technologies can emerge to support it, and agents start to associate essential activities with them – new routines are set. At the same time, products become fully standardized and productive processes are so integrated that it becomes very difficult to implement changes since, given their systemic nature, even small changes in the process may require replacement of several components (Utterback & Abernathy, 1975).

Accordingly, selection mechanisms tend to be increasingly stronger over time, implying in a hardness degree that can difficult or even hamper the diffusion of further radical innovations - those that do not "fit" into existent environment and requires new routines and structures. This "hardness" is usually referred in the evolutionary literature as technological paradigms (Dosi, 1982, 1988), natural trajectories (Nelson & Winter, 1977; Nelson & Winter, 1982), technology systems (Freeman, 1994a), techno-economic paradigms (Perez, 2009), technological avenues (Sahal, 1985), dominant designs (Utterback and Suarez, 1993) and technological landscapes (Geels, 2002). All these concepts share central elements, dealing with the regularities of evolutionary processes of technological change caused by the emergence and strengthening of routines reflected in selection mechanisms and their consequences on market structures and socio-technical evolution (Niosi et al., 1993).

The evolutionary perspective recognizes the role of firms as primary instruments of economic change and key actors in technological change (Chandler, 1992; Malerba, 2002a; Nelson, 1991; Schumpeter, 1942). That said, we do not ignore the importance of other agents (universities, consumers, policymakers), but rather acknowledge that firms' behavior reflect the interactions and co-evolution between the elements within an innovation system (Freeman, 1988; Lundvall, 1992) and can indicate structural and systemic changes at the meso level. Hence, the dynamics of technological change as described above can be reflected in firms' *technological strategies*.

A technological strategy can be defined as the continuous alignments between firms' internal capabilities/competences and external conditions in unique arrangements in order to generate and sustain competitive advantages (Christensen *et al.*, 1987, Porter, 1996). Since firms in the same sector or region often share internal characteristics and are subject to similar external conditions (i.e. regulations, competition), collective perceptions about technologies' risks and opportunities might arise, causing their technological strategies to converge or diverge to specific trajectories (Patel and Pavitt, 1997).

A number of scholars point out to the existence of *sectoral patterns of innovation* based on the sector-specific characteristics that firms share (Breschi & Malerba, 1997; Klevorick et al., 1995; Malerba & Orsenigo, 1993, 1997; Malerba, 2002; Nelson & Winter, 1982; Pavitt, 1984; Winter, 1984, Dosi, 1988). Firms are usually classified into sectors by their main activities (products, services, production processes), as in ISIC and NACE classifications. As the number of technologies available for incorporation to a product or production process is usually very limited (given the existence of limited resources, risk aversion, path dependent knowledge bases, imitation strategies, and the influence of common institutions), in general firms producing similar products are also using similar technologies to some extent, and therefore can be grouped under one or a few technological regimes (Malerba & Orsenigo, 1993; Malerba & Orsenigo, 1997; Nelson & Winter, 1982; Winter, 1984).

More recently, a series of works from Franco Malerba focused on sector-specific innovation systems, highlighting that some institutions (laws, regulations, standards, routines) are specific to a sector and can influence its firms' innovative activities (Malerba, 2002, 2005). These systemic differences also contribute to explain why some sectors are protagonists in major technological revolutions while others lag behind, and why even the opportunities of application of general purpose technologies are unevenly distributed among sectors.

Nevertheless, there is no consensus in the literature about the strength and range of sectoral patterns of innovation. The strategic management literature highlights that intra-sectoral, firm-specific heterogeneity may overlap the sector-specific elements due to differences in firms' cognitive abilities, competences, learning and assets that influence their perceptions about opportunity conditions (e.g. innovation returns) and risks related with each technology, leading to different strategic choices. Likewise, country- and region-specific elements may also overlap and reduce the effect of sector specific elements (Barney, 1991; Clausen, 2013; Cohen and Levinthal, 1990; Dosi et al., 1997; Fagerberg, 2003; Leiponen and Drejer, 2007; Peneder, 2010; Teece and Pisano, 1994; Teece, 1980). The Chapters 5 and 6 of the present thesis deal fundamentally with the effect of these two opposite forces, namely sectoral patterns versus firm heterogeneity, in the eco-innovation dynamics using as case the recent technological trajectory in the automotive sector.

1.2.2 The environmental innovation and the greening of the economy under the evolutionary perspective

During the 1970s and 1980s, a critical debate was initiated about the relationship between technology, economic growth, and environmental impacts (Ehrlich and Holdren, 1972; Freeman, 1984; Holdren and Ehrlich, 1974; Meadows et al., 1972). It was argued that uncontrolled growth of production and population would eventually lead the planet to reach its limits in terms of natural resource availability and contamination of natural systems.

Technology has a paradoxical role in this process: the technological development has been responsible to increase the environmental impacts dramatically during the industrial revolutions (Georgescu-Roegen, 1971; Commoner et al., 1971), but technological change could also be beneficial if new technologies reduce or neutralize the harmful effects of human economic activities (Freeman, 1984). It is essentially under this narrative that the concept of eco-innovation arises.

Eco-innovations differ from other innovations by their environmental goals. They are often defined as innovations (new or significantly improved products and processes, marketing techniques, organizational strategies) which contribute to significantly decrease environmental impacts (for example, reduce the use of natural resources, including materials, energy, water and land, and/or decrease the release of harmful substances across the whole life-cycle) when compared with existing alternatives (Fussler and James, 1996), although this definition is somehow problematic (See Chapter 1).

The characteristics and dynamics of eco-innovative activity have been subject of study in diverse scientific disciplines, including design, sociology, business management, and economics (See Chapter 2). Within the last group, Rennings (2000) argues that the two most relevant approaches are neoclassical and evolutionary economics, although he and others acknowledges that neoclassical modeling might be too narrow to understand the complexity of the broad and systematic changes required to reduce the impacts of the whole economy in the long run: “Market prices (…) reflect short- and medium-term change in supply and demand rather than those factors that may affect the global environment in the longer term” (Freeman, 1996a, p. 35).

Evolutionary economics, on the other hand, engages in understanding the “black box” of complex and systemic relationships that characterize innovation processes, and many of its main concepts are of paramount importance to the greening of the economy through technological change (Freeman, 1996; Rennings, 2000). The notion of heterogeneous agents with limited information and bounded rationality, for example, illustrate why many agents in the economy ignore the effects of environmental problems in the long term (van den Bergh and Bergh, 2007)

The framework considers that technological development is path-dependent, in the sense that new technological developments share elements (knowledge, routines, institutions, components) with technologies developed in the past (Dosi, 1982), creating lock-in mechanisms that inhibit radical shifts in the techno-economic paradigms, as we explain in details in the subsection 1.2.1. This narrative suits well to explain why we perceive strong inertia in the process of greening of the industry, as green technologies might require radical changes in knowledge, institutions, and demand, calling for a better understanding of the transition process from one paradigm to another (Oltra and Saint Jean, 2005).

Moreover, the systemic approaches to innovation that have been developed along with evolutionary frameworks clarify how the wide range of heterogeneous agents might be grouped according to shared characteristics that affect their eco-innovation activities (Andersen, 2004; Foxon and Andersen, 2009; Lundvall, 1992; Malerba and Orsenigo, 1997; Malerba, 2002a; Oltra and Saint Jean, 2009a). Accordingly,

> Environmental innovations involve many changes at different levels, in particular in infrastructure able to receive the new technology. Environmental innovations are thus said to be part of system innovations. The differentiated development of each sub-system can create bottlenecks that can hinder technological development and diffusion. (Saint-Jean, 2006, p. 63)

1.3 Research gap:

1.3.1 The lack of microeconomic analysis of eco-innovation

To date, most analyzes of eco-innovation grounded on evolutionary principles have targeted policy issues as main objects of analysis, including new approaches such as socio-technical systems and niche management (Geels, 2004; Nill and Kemp, 2009; Schot and Geels, 2008). Given the specific problems that these innovations face (Rennings, 2000), it is indeed necessary and comprehensible to approach policy as key instruments to promote the greening of the economy.

That said, however, the literature barely touches on the role of firms' agency, and therefore the role of corporate strategies and its relation with eco-innovation dynamics (Berrone et al., 2013). Because of its complexity and multiplicity of objectives,

> (…) the analysis of environmental innovations should focus more on the complex relationships between competitiveness and environmental performances of firms, as well as on the integration of environment within the overall innovative strategy of firms. It implies to go further in the microeconomic analysis of environmental innovation process. (Oltra, 2008, p. 6)

The role of firms strategies in the greening process gains further importance with the ongoing economic downturn, which brought attention to the creation of new competitive advantages based on green performance, including eco-innovations, as a powerful mechanism to escape from the current downturn and foster economic growth through the greening of the economy (Andersen, 2008a; EU Commission, 2011b; 2011c; OECD, 2009).

1.3.2 The lack of sectoral eco-innovation analyzes

One of the core assumptions in the evolutionary literature is that the innovation activities present sector-specific regularities. However, little is known about the existence and strength of sectoral patterns for eco-innovation activities. In a recent review of eco-innovation determinants, del Río et al. (2016) exposed very clearly the extent of this gap:

> The degree of "eco-innovativeness" can be expected to differ across sectors (Díaz-Lopez, 2008; Montalvo, 2008). The innovativeness of a particular sector depends on factors such as the maturity of the dominant technology, scale, capital intensity, R&D intensity of the industry and competitiveness (Norberg-Bohm, 2000, p.198). Relevant sector-specific features influencing eco-innovation include the existence of technological opportunities, the properties of innovative processes, the market structure, the maturity of the sector, the environmental impact and the exposure to societal pressures (Del Río et al., 2013). Sectoral differences and their influence on eco-innovation

> have been addressed in a superficial manner, however, only through the inclusion of a sectoral dummy variable. (…) An analysis on the distinct drivers and barriers to eco-innovation in different sectors has not been performed. (del Río et al., 2016, pp. 2167–2168).

The only hypothesis regarding sector-specific patterns that has been extensively discussed and empirically tested so far, they argue, is that of more polluting sectors being associated with higher eco-innovation efforts due to stricter environmental regulations (Arora and Cason, 1996; Cainelli et al., 2012; De Marchi, 2012; del Río et al., 2015; Fukasaku, 2005; Hitchens et al., 1998; Lopez and Montalvo, 2012; Mazzanti and Zoboli, 2006), in line with Malaman's (1996) notion of *environmental sensitivity* of a sector.

As the greening of the economy moves gradually to more mature stages, one would expect that research also expands in scope and complexity. Other factors might be equally or more important to explain why firms engage into eco-innovation, some of which may also be sector-specific, including the role of differences and similarities in technological regimes, sectoral institutions, demand, and market structures (Oltra, 2008). For instance, the "fit" between existing technological competences and environmental goals might be subject to sectoral specificities, and such fit might well to be unstable over time, since both industrial characteristics and environmental sensitivity are in constant change (see Chapter 4).

One of the major limitations towards sectoral innovation analysis is data availability, and this issue is even more evident for eco-innovations (del Río et al., 2016). 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). For instance, as one of the most commonly used indicator of innovation activities, firms' R&D expenditures usually do not differentiate between green and non-green investments.

By analyzing the micro foundations of sectoral innovation activity, we argue that the observation of *convergence* among firms' green technological strategies over time might reflect commonly perceived opportunities and risks which are derived from sector-specific patterns of innovation (See Chapters 5 and 6). We therefore would be able to capture indirect evidence of sector-specific elements influencing eco-innovation.

1.3.3 The eco-innovation dynamics in the automotive sector

In Chapters 5 and 6, we chose the automotive sector as a case to discuss the formation of sectoral patterns of eco-innovation due to its role in modern societies, but positively as main transportation choice and negatively due to its enormous costs in terms of environment harm and intensive use of nonrenewable resources (MacKenzie and Walsh, 1990). Moreover, the green product innovations are related mainly to powertrain components that are easily distinguishable from "non-green" ones.

The automotive sector traditionally has been pointed out as one of the clearest examples of a mature industry, as well as a "successful" case of co-evolution between technologies, routines and structure. Albernathy & Clark (1984), among others, used the evolution of automotive technologies to illustrate the transition between the phases of technologic life cycles until their maturity.

The automotive value-chain has been dominated by relatively few Original Equipment Manufacturers (OEM), and the technological regime was introduction of incremental innovations (*creative accumulation*) based on a dominant-design characterized by three fundamental features: internal combustion engines (ICE), all-steel car bodies, multi-purpose character, and fully integrated productive processes (Orsato and Wells, 2007a). The automobile based on this dominant design became an essential part of modern society, not only because its transportation function but also economically (Dosi and Nelson, 1994).

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

Additionally, organizational frameworks were established within firms and networks were built between OEMs and suppliers. The integration of the subsystems in an all-steel body improved the design of automobiles and reduced its time and costs of production (Nieuwenhuis and Wells, 2007).

Over the past three decades, the combination of new technological opportunities from information and communication technologies (ICT) and microelectronics, and the strengthening of pollution regulations and consumer awareness about the impact of current road transport technologies in the environment[2] introduced new elements in the dynamics of innovation of the sector (Achtnicht, 2012; Bohnsack et al., 2015). As a consequence, governments and automakers have been searching for technological solutions to reduce the environmental impacts of automobiles.

Given the nature of ICE engines, it is virtually impossible to reduce their emissions to zero, and increasing marginal costs mean that the technology might be close to reach its peak of performance and efficiency (NRC, 2010b). Investing in technologies related with ICE is important to reduce the automobile environmental impact in the short-term, but it is not the long term solution to the problem.

The alternative to incremental ICE innovation is the development of more radical, disruptive alternatives and includes technologies such as Battery Electric-, Hybrid-, and Fuel cells-based engines, which may require major changes in routines and structures and present technical "bottlenecks" that have prevented further developments and diffusion to the market.

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[2] According to data from OICA (*Organisation Internationale des Constructeurs d'Automobiles*), fossil-fueled motor vehicles are responsible for about 16% of anthropogenic emissions of carbon dioxide (CO2) each year.

The role of institutional stimuli, including national and regional regulations and standards, in influencing the timing and direction of eco-innovation has been widely acknowledged in the literature (Budde et al., 2012; Dijk and Yarime, 2010; Frenken et al., 2004; Penna and Geels, 2014; Schlie and Yip, 2000; Sierzchula et al., 2012; van den Hoed, 2007), even under increasingly harsh competitive conditions, when is expected that firms adopt a short-term mentality and avoid technological experimentation (Aldrich, 1979; Rothenberg and Zyglidopoulos, 2003).

Previous studies highlighted how automakers respond to these stimuli. In an aggregated level, the technological variety in the sector seems to be increasing over time (Frenken et al., 2004; Oltra and Saint Jean, 2009b), although some argue that most automakers successively and collectively shifted their R&D activities towards specific green technologies (for example, from electric vehicles to fuel cells) in a way that these technologies would 'compete' with each other and the outcome would be the dominance of one technology over the others (Bakker et al., 2012; Bakker, 2010b; Penna & Geels, 2015; van den Hoed, 2005). Finally, analyzes of automakers prototyping activities seems to indicate that some automakers are specializing in distinct green technologies: "From a firm-level perspective, some incumbents focused on specific technologies e.g., Nissan with EV [electric vehicles] and Toyota with HEV [hybrid-electric vehicles]" (Sierzchula et al., 2012, p. 219).

Without discarding the importance of these findings, the analysis of the eco-innovative dynamics under an evolutionary perspective in this sector remains fragmented, and while having good evidence of the role of policymaking in the overall eco-innovative activity, the literature is unable to answer if the overall greening of the sector represents the emergence of new sectoral patterns or such greening is marked by firm heterogeneous strategies, and in this case why some firms would engage in more or less (and also similar or dissimilar) environmental innovation activities even when exposed to the same regulations.

1.4 Outline of the thesis

Besides this introductory Chapter and the conclusions in Chapter 7, the thesis is composed by five papers. The papers are organized according to its generalization in relation to the overall eco-innovation literature, starting from a general discussion on the eco-innovation concept towards the sectoral innovation analysis, and ultimately focusing in the automotive sector as case study.

In Chapter 2, a single-authored discussion paper, I discuss some of the main problems related with the conceptualization of eco-innovation as an evolutionary concept using a literature review, bibliometrics and an historical analysis. I argue that, rather than identify the innovations that have actual reduced impacts, researchers should be looking at how firms change their technological strategies and business models towards the greening of the economy.

The alternative to the consensual definition might be difficult and problematic (del Río et al., 2016), but it is important that future research keep in mind that a single eco-innovation *definition* cannot be easily applied in range of heterogeneous sectors, technologies, and countries because the role of environmental impacts is different to each sector (Malaman, 1996). The chapter also serves as basis to the idea of eco-innovation that is used in the whole thesis.

The discussion on the concept of eco-innovation continues in Chapter 3, where I analyze, together with two colleagues, Simone Franceschini and Roman Jurowetzki, the differences and similarities in the usage of different terms usually referred as synonymous to the same phenomenon, including eco-innovation, environmental innovation, sustainable innovation, and green innovation.

We argue that differences in the use of these terms can shape meanings and belong to different scientific communities. Therefore, the comparison between them may help to access the intellectual structure of the eco-innovation as a scientific field, to access the influence and scientific impact of different journals, authors and geographic locations to each concept, and to suggest future paths for the development. The paper conducts a bibliometric analysis aiming to disentangle similar or distinct meanings and identify scientific communities associated with the four terms, using the data discussed in the Section 1.5.

In Chapter 4, we narrow the analysis to discuss theoretically the existence of sectoral patterns of eco-innovation. This and the next chapters are co-authored with my main supervisor, Maj Munch Andersen. As for innovations in general, we believe that it is possible to identify sectoral eco-innovation patterns (Pavitt, 1984). Our starting assumption is the assumption that the green economic change can be described as a new techno-economic paradigm that may affect all companies and industries and cause structural change of the global economic system, although different industries and countries may be affected in different ways and intensities (Andersen, 2012).

Additionally, we argue, because green technologies may have different characteristics from existing ("dirty") ones, the innovation processes associated with them may be distinct and generate novel innovation patterns. The paper identifies eight specific characteristics of eco-innovations which form the basis for four core hypotheses that may explain sectoral heterogeneity.

Chapters 5 and 6 narrow even further by focusing in the automotive sector as case study to investigate the formation of such novel innovation patterns. The core assumption is that the observation of patterns in firms' green technological strategies reflect the formation of sectoral patterns of eco-innovation. Both papers use the patent data presented in Section 1.5.

In Chapter 5, we conduct an analysis of the breadth and strength of the greening in the automotive sector from 1965 to 2012, focusing on changes in three specific aspects: 1) the concentration of green patenting; 2) the convergence/divergence of firms' strategies; and 3) the participation of alternative technologies on the total patenting activity of the sector. As suggested by Malerba & Orsenigo (1997) and others, we calculate the Herfindahl-Hirshman index (Herfindahl, 1950; Hirschman, 1964), to measure the concentration of green patenting, and a a normalized Relative Technologic Specialization Index (Balassa, 1963; Brusoni & Geuna, 2005; Debackere & Luwel, 2005; Nesta & Patel, 2005; Pavitt, 1998; Soete, 1987) to measure the evolution of firms' trajectories on the specified green technological areas.

The data analysis indicates a substantial reduction in concentration of all green technologies as technological opportunities are being collectively perceived and risks are shared, albeit the group of patents representing fuel cells technologies is relatively more concentrated than the other technologies among the share.

Finally, in the Chapter 6, we expand these findings in two fronts: data, and why the fuel cell trajectory differs from the others. First, we use the relative technological specialization index at firm level to understand we investigate if the aggregate reduction in patenting concentration is reflected in the firm-level, using descriptive and cluster analysis. The results show that even at this micro level, firms have been converging to similar trajectories over time in all technologies but fuel cells, for which we find two divergent trajectories.

In the second part, we propose that these divergences might be explained by firms' internal and external characteristics. We then conduct an econometric analysis to isolate the effect of some of the main characteristics that may affect such decisions, namely: a) the effect of internal assets that might affect firms' propensity to develop fuel cell technologies; b) the country-specific determinants; and c) the effects of external shocks. The econometric analysis indicates that the general economic situation and firms' financial conditions are indeed important determinants of the divergence between the firms in the sector regarding fuel cells.

All papers are in an advanced stage. Some presented in leading innovation and evolutionary conferences and were already submitted to publication, as seen in the Table 1.1.

Table 1.1 – Status of articles

Chapter (Article)	Title	Publication Status
2	The devil is in the details: a critical discussion on the definition of eco-innovation	Advanced draft
3	Unveiling scientific communities about sustainability and innovation: a bibliometric journey around sustainable terms	Submitted to Journal of Cleaner Production
4	Eco-innovation Dynamics and Green Economic Change: the role of sectoral-specific patterns	Presented at the R&D Management Conference 2015
5	Sectoral Dynamics and Technological Convergence: an evolutionary analysis of eco-innovation in the automotive sector	Presented at the Globelics International Conference 2015; Submitted to Industry and Innovation
6	Sectoral Patterns versus Firm-level Heterogeneity - the dynamics of eco-innovation strategies in the automotive sector	Presented at the Druid Conference 2014; Submitted to Technological Forecasting and Social Change

1.5 Data sources

Besides systematic literature review, the thesis draws upon two main data sources. In Chapter 2, we extracted bibliometric data consisting of full records (title, abstract, keywords, year of publication, journal, authors' names and addresses, and references) for scientific papers containing "eco-innovation" and related terms as topics[3]. The data was extracted from Thomson Reuters' Web of Science (WoS) in

[3] The search consisted in the following code: (TS=("eco innovation*" OR "eco-innovation*" OR "ecological innovation*" OR "sustainable innovation*" OR "green

December 2013. The dataset has been updated in 2015 to include the year of 2014 and complemented with data extraction from Scopus for Chapter 1.

Restricting the analysis to WoS data in Chapter 2 limited the number of analyzed articles, as the number of publication records is significantly larger in other bibliographic databases, such as Scopus and Google Scholar (GS). However, only the WoS data has the high level of curation necessary to conduct our analysis (i.e. proper normalization of the cited references). We also avoided including non-peer-reviewed literature that is commonly found in Google Scholar searches. (Bornmann et al., 2009; Delgado López-Cózar et al., 2014; Giustini & Boulos, 2013; Lasda Bergman, 2012).

As mentioned, the biggest challenge for sectoral eco-innovation analysis is the data (del Río et al., 2016). For Chapters 5 and 6, we had to define an indicator to represent the green technological strategies and eco-innovation activities of the automotive sector. There are remarkable efforts to create robust quantitative eco-innovation indicators, including the iGrowGreen framework[4] and the Eco-Innovation Scoreboard[5] (both from European Union). Using these indicators in a sectoral eco-innovation analysis, however, is problematic as they use mostly country-level data, which cannot be used to discriminate sectoral patterns. Second, as these indicators are fairly new (and so is most of the data used to construct them), the time frame is very limited, usually covering the last decade or even less, limiting the dynamic analysis over time.

We followed the literature holding that the best available source of quantitative data for dynamic sectoral eco-innovation analyzes is patent data (Haščič and Migotto, 2015; Oltra and Saint Jean, 2009b; Oltra et al., 2010; Popp, 2005), but not without acknowledging that their use to measure innovative activity is far from perfect (Griliches, 1990; Pakes, 1986): they are only indirect indicators of

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innovation*" OR "environmental innovation*").) AND Document Types=(Article OR Abstract of Published Item).

[4] See http://ec.europa.eu/economy_finance/db_indicators/igrowgreen/index_en.htm.

[5]See http://www.eco-innovation.eu/

innovation activities, and are not the only way to protect an invention; many inventions simply cannot be patented and many are not patented because it is much easier – and safer - to restrict competitors' access to technical information about new industrial processes instead of disclosing the information required for filling a patent claim (Haščič and Migotto, 2015).

However, patent analysis reveals information about eco-innovation activities whereas other firm-level indicators cannot. So far, firms in general make no clear distinction between R&D expenditures on eco-innovation and on "traditional" innovation, and innovation surveys are not able to capture the dynamics over time.

The level of disaggregation and time coverage of patent data allows us to analyze the evolution of the green technologies - and the transformation of traditional technologies towards lower environmental-harm standards (Haščič and Migotto, 2015). Moreover, patent applications are considered a robust indicator of firms' technological competences, indicating that the firm has sufficient competences to produce knowledge pieces in the technological frontier for a given technological field (Breschi et al., 2003; Chang, 2012).

A remarkable challenge in sectoral analysis based on patent data is how to establish the link between patents and economic sectors. Patents are classified for administrative purposes according to their scientific and technical features following the International Patent Classification (IPC), so one subgroup (at 3 digits) can include patents from many sectors: "(…) the IPC grouping B05 includes all goods or processes involved in 'spraying or atomizing in general; applying liquids or other fluent materials to surfaces in general', and also so will include products and processes from a variety of different industries, from cosmetics atomizers to agricultural pesticide sprayers" (Johnson, 2002, p. 5).

There are important attempts to relate patents with industrial sectors, as those held by the Yale Technology Concordance and the OECD Technology Concordance (Johnson, 2002; Kortum and Putnam, 1997) translating International Patent Codes (IPC) into, respectively, IOM-SOU and ISIC codes. However, these attempts have many limitations: their application is limited, they are complex and become easily outdated as new technologies and applications arise (Schmoch et al., 2003).

To overcome this challenge, we adopted a mixed search method involving IPC classifications and keywords related with a sample of main firms in the automotive sector. We chose keywords related with 18 car manufacturers - corresponding to 90% of global sales of passenger vehicles in 2012 - to represent the sector. Moreover, instead of relying on keywords such as "fuel cell*" or "electric vehicle*" to identify green patents like most existing studies (Oltra and Saint Jean, 2009b; Rizzi et al., 2014; Sierzchula et al., 2012; Wesseling et al., 2014), we used two new classifications of green technologies provided by OECD[6] and IPO[7]. These classifications use specialists in different fields to classify IPC codes related with "environmentally-sound" technologies at very high disaggregation level (often 7 to 9 digits).

By using the IPC green classifications instead of keywords, we are able to have a more accurate sample of green patents, avoiding not including relevant green patents that do not present any of the keywords related with green technologies (Haščič and Migotto, 2015; Veefkind et al., 2012). Nevertheless, this method is not accurate for sectors in which: 1) green technologies are not so easily distinguishable from the "grey" ones; 2) firms are dependent of specialized suppliers to incorporate innovations (Pavitt, 1984); 3) it is not possible to select a group of main firms to represent the sectoral activity.

[6] See Haščič and Migotto (2015).
[7] See http://www.wipo.int/classifications/ipc/en/est/

CHAPTER 2

THE DEVIL IS IN THE DETAILS: A CRITICAL DISCUSSION ON THE DEFINITION OF ECO-INNOVATION

by

Lourenço Galvão Diniz Faria

ABSTRACT

In this review paper, we discuss how some imprecisions in the widely accepted concept of eco-innovation may affect the green economy dynamics. Conceptualizing eco-innovation is a useful tool to promote the greening of the economy and requires a closer look to the context which the innovation is generated and implemented, including issues related with technologic, sectoral, and institutional dynamics, as well as timing and the nature of the environmental impacts. Our methodology is based on a literature review and bibliometrics. Based on evolutionary economic thinking, we argue that, beyond their individual environmental impacts, the scope of eco-innovation activity should be defined based on the role of such innovations in the overall greening of the economy. We highlight and discuss some of the main problems of the present eco-innovation conceptualization and its consequences to empirical and conceptual research. The paper is relevant methodologically and also as a tool for policy making, since the concept of eco-innovation has been used to define the scope of technologies to be addressed by policies target at promote the greening of the economy.

2.1 Introduction

Eco-innovation research is still in its earlier phases, and both conceptual and empirical studies in this field are scarce and divergent, generating a lack of theoretical consistency and analytical rigor (Andersen, 2008; Kemp, 2010). After more than two decades of research in the field, there is a relative consensus on the actual concept of eco-innovation: the common denominator is the measurable reduction of actual environmental impacts of the technology compared with existing alternatives, even if such reduction is unintended (Carrillo-Hermosilla, del Río, & Könnölä, 2010; René Kemp & Pearson, 2007; OECD, 2009; Rennings, 2000; EU Commission, 2004).

Facing this scenario, some claim that "(…) the question 'What is an eco-innovation?' no longer generates heated academic debate. It has for practical purposes been settled" (Berkhout, 2011, p. 192), and researchers could therefore focus on empirical analysis and theorization. Most conceptualization efforts aim to formulate a concept as general and applicable as possible, similarly to what has been made with the innovation concept through manuals (OECD, 2005), to operationalize the idea of sustainable innovation via technological and organizational change (K Rennings, 2000).

By defining eco-innovation only by their individual environmental impacts, researchers are subject to many imprecisions that may lock the green technological development in inefficient trajectories. The exact measurement of environmental impacts is still controversial, especially for innovations whose impacts are dependent on systemic interactions with other technologies. It also neglects the fact that innovative change is a gradual process in which technologies not always present superior characteristics – such as economic and environmental gains - when implemented, but often require a long process of incremental adaptation in order to prove their value (Rosenberg, 1976). Moreover, since many regulations related with environmental impacts are becoming stricter, it is expected that most innovations could be considered green compared with existing ones – since their impact is lower - even though they are based on (and therefore reinforce) "dirty" technologic paradigms.

In this paper, we discuss how some imprecisions in the widely accepted and policy important concept of eco-innovation may affect green economy dynamics. Based on evolutionary economic thinking we argue that, beyond their individual environmental impacts, the scope of eco-innovation activity should be defined based on the role of such innovations for the overall greening of the economy. Conceptualizing eco-innovation is useful to promote the greening of the economy and requires a closer look at the context in which the innovation is generated and implemented, including issues related with technologic, sectoral, and institutional dynamics, as well as timing and the nature of the environmental impacts.

Innovations have been studied not only because of their individual impacts on the economy, but also to formulate policies and guide firms' strategies so that they can address systemic problems and achieve socio-economic development through changes in technological trajectories and paradigms (Dosi, 1982; Edquist, 2011). This role is especially important for eco-innovations, which are confronted by issues such as the double externality problem and the "unfair" competition with existing technologies that are "dirty" but well adapted to existing institutional arrangements, demand requirements, and market characteristics (Acemoglu et al., 2009; Cleff & Rennings, 1999; Kemp & Pontoglio, 2011; Veugelers, 2012), but have a crucial role in the greening of the economy (OECD, 2009).

From an evolutionary economic perspective, the economy is greening when it is moving in a green direction, in the sense that environmental issues becomes such an important driver of economic development and competitive advantage that the economic activities move in a sustainable direction at aggregate levels. The economy is green[8] when the selection environment favours environmentally-friendly technologies to such a degree that they become - or are becoming - the "easy and natural" way of innovating (Andersen, 2012). In this context, it is worth questioning what would be the adequate boundaries between eco-innovations and

[8] However, it is worth noting that this process is not deterministic but gradual and evolutionary in nature, thus there is not a single point in time where we can observe the transition (Rennings, 2000).

"ordinary" innovations so that former would be a tool to achieve and sustain green growth (OECD, 2009).

We therefore argue that, beyond their individual environmental impacts, the scope of eco-innovation activity should be defined based on the role of such innovations in the overall greening of the economy. We highlight and discuss some of the main problems of the present eco-innovation conceptualization and its consequences to empirical and conceptual research. The paper is relevant for theoretical clarification and hence as a basis for more rigorous empirical research as well as for policy making, since the concept of eco-innovation has been used to define the scope of technologies to be addressed by policies targeted at promoting the greening of the economy (Inderst et al., 2012; OECD, 2011a; 2009; EU Commision, 2004).

The paper first discusses from a historical perspective the relationship between the environment and technological change in section 2.2 as a basis for the critical analysis of the conceptualization of eco-innovation that is made in the section 2.3. A discussion and final remarks are made in section 2.4

2.2 The relationship environment-technological innovation over the last decades

From the 1970's onwards, many researchers shed light on the relationship between technology, economic growth and environmental resources. Perhaps the most famous is *Limits to growth* (Meadows et al., 1972): based on system analyzes conducted by Jay W. Forrester's Institute at MIT, they presented the idea of a global "overshoot" - or overutilization of natural resources - providing a rather pessimistic scenario given the future prospects on population and economic growth. Despite its importance by calling attention on environmental issues hitherto neglected, in the following years many scholars questioned some of the assumptions of their model, especially concerning the passive role of technology attributed in their scenario. Accordingly, Freeman (1984), one of the first evolutionary scholars to address environmental issues, argued that

> (…) the basic environmentalist argument that there are physical limits on this planet to the growth of population and of social artefacts is irrefutable. So too is the argument that if growth were to continue indefinitely on a particular materials-intensive, energy-intensive, and capital-intensive path, physical limits of resource availability would sooner or later be encountered. The ecological movement of the 1970s and its reflection in the computer-based doom models of that period served a valuable purpose in drawing public attention to these ultimate limits. It was also valuable in highlighting the long-term global consequences of air and water pollution, associated with the reckless disregard of the social costs of a particular form of industrialization. Although energy did not figure as such in the early MIT models, much the same points can be made with respect to nuclear power. The critique of the MIT models is, however, related not to these fundamental limitations of the 'room to grow', nor to the gravity of the environmental hazards associated with a particular pattern of growth, nor yet to the global nature of the problems. It is related to the possibilities open to human societies to make intelligent use of technical change over the next century and so to modify the pattern of growth, that living standards could still be vastly improved throughout the world *whilst the gravest environmental hazards were averted*. (p. 495; emphasis added).

Also in the 1970's, Commoner *et al.* (1971) discussed the relationship between nature, men, and technology, and how these three elements should be considered as interdependent. They argued that capitalist technologies were responsible for increased environmental problems, as technological innovations at that time had usually greater environmental impact than their predecessors. Ehrlich & Holdren (1972), on the other side, emphasized the role of population growth rather than technologic development to explain such problems: "(…) if there are too many people, even the most wisely managed technology will not keep the environment from being overstressed" (p. 376). One of the most important outcomes that emerged from this debate is the IPAT equation:

$$I = PAT$$

where I stands for the anthropogenic environmental impact, P is the population size, A is affluence (production per capita), and T represents the current impact of technologies (environmental impact/product). According to Chertow (2000), the equation was originally formulated to measure which variables could be responsible for the bigger impact on environment, but latter it was converted in an "(…) expression of the profound importance of technological development in Earth's environmental future" (p. 14). It makes sense to focus on technology, since the population growth is difficult to influence and its reduction may be associated with a decrease in socio-economic development, as it means an aging population with increased health and pension funds costs combined with decreased young workforce. Since we live in a capitalist society where economic growth is the main indicator of development — and physical production is still necessary to achieve such growth, a reduction on production per capita seems also unlikely to happen (Holdren and Ehrlich, 1974; Wackernagel and Rees, 1998).

On the other side, the optimism and hope regarding the power of technological change to reduce environmental impact has been particularly influential in the last decades. The Report of the World Commission on Environment and Development, "Our common future" (WCED, 1987), was very successful in spreading around the idea that environment and economic development could be mutually compatible. The idea received further attention from policy makers after the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 and the implementation of the Kyoto Protocol[9] in 1997.

Also in the 1990s, some scholars began to discuss how to conduct the operationalization of the sustainable development principles and objectives within social science's theories and methods, including economic (Freeman, 1996; Kemp & Soete, 1992; Rennings, 2000), business and management (Barrett, 1991; Elkington, 1994; Gladwin et al., 1995; Madsen et al., 1997; Porter & van den Linde, 1995) and sociological perspectives (Christoff, 1996; Cohen, 1997; Mol, 1996). Accordingly, the eco-innovation concept arises as an effort to highlight the role of some innovations as agents of change towards sustainable development.

[9] See https://treaties.un.org/pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-7-a&chapter=27&lang=en

Although Rennings (2000) and others attribute the introduction of the term “environmental innovation” to Klemmer et al. (1999) and the OECD (2009) attributes it to Fussler & James (1996), it appears in several precedent works. In fact, the concept appeared in two relatively unknown papers from the late 1970s which were never credited in literature reviews (for example, in Carrillo-Hermosilla et al., 2010; and Schiederig et al., 2012): Pampel & van Es (1977) and Taylor & Miller (1978) discuss the adoption of environmental innovations in agriculture from a sociological point of view. The former defines environmental innovation as those which “(…) have as a first objective the preservation of existing resources” (Pampel and van Es, 1977, p. 58).

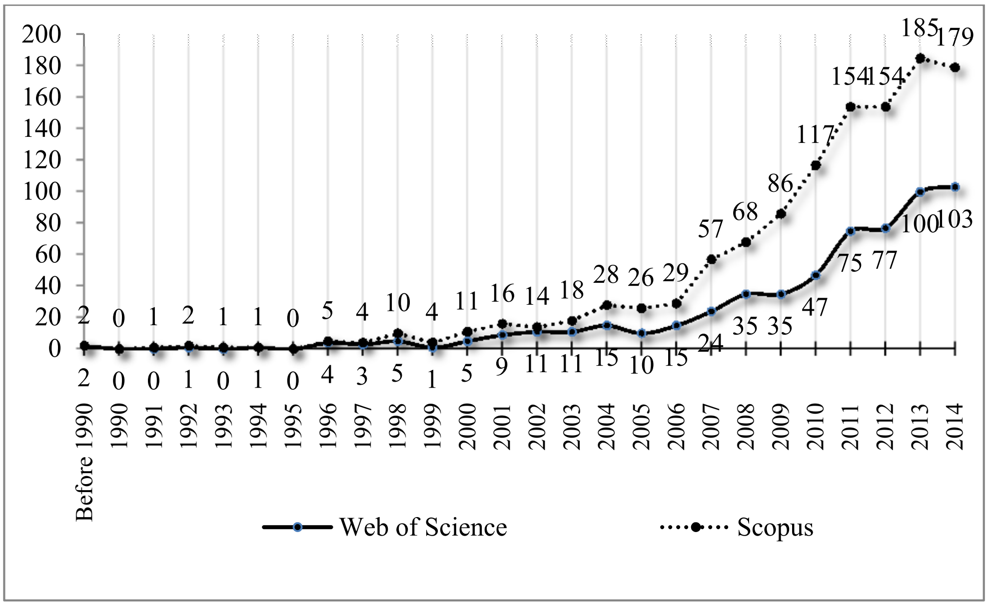
The concept then remained in disuse until the 1990s, when it reappears in many business, economics, design, and sociologic papers and books. Some of the earlier applications of the concept are found in Carraro & Siniscalco (1992), Barrett (1992), Green et al. (1994), Schwendner (1995), Brezet et al. (1995), Fussler & James (1996), Laffont & Tirole (1996), Lanjouw & Mody (1996), Johansson & Magnusson (1998), Azzone & Noci (1998), Conway & Steward (1998), Andersen (1999), and later in Rennings (2000), which became one of the most cited references for the theme.

In the 2000s, the publication of the Assessment reports from Intergovernmental Panel on Climate Change (IPCC)[10] provided scientific evidence for the human-driven process of climate change (Oreskes, 2004). After the financial and economic crisis in 2008, regional policymakers and international organizations emphasized the development of eco-innovations and environmental goods and services has been presented as a way to overcome the low growth rates and start a new period of socio-economic growth based on the “greening” of the economy, a competitive restructuring based on lower environmental impacts while also including elements from the ICT economy and the knowledge economy, influencing policymakers and international agencies (EU Commission, 2011b; OECD, 2011a; World Bank, 2012).

[10] See https://www.ipcc.ch/publications_and_data/publications_and_data_reports.shtml

The use of eco-innovation as a concept spread rapidly and generated whole new theoretical frameworks concerned with not only the environmental impacts but also the processes of technological change (Andersen, 2008; del Río et al., 2016; Ekins, 2010; Kemp & Oltra, 2011; Schiederig et al., 2012; Smith et al., 2010). The Figure 2.1 shows the evolution in number of papers and books with eco-innovation[11] as topic in two scientific databases, Web of Science and Scopus.

Figure 2.1 Use of eco-innovation and related terms in the academic literature



Source: own elaboration.

The figure resumes the evolution of the concept in three distinct phases: up to 1995, the mentions to eco-innovation were restricted to few publications and there was no major effort to define the concept properly. The second phase, from 1995 to 2006, represents the concept's gradual diffusion among scholars aiming to define

[11] We used the following keywords to conduct the search into the databases: "eco innovation*", "eco-innovation*", "ecological innovation*", "sustainable innovation*", "green innovation*", and "environmental innovation*".

and operationalize the concept. The third phase, from 2007 to 2014 is marked by a fast growth in the terms' utilization, representing the consolidation of the concept in different fields and attesting its growing relevance in the literature as a framework to conduct empirical studies on, for instance, the drivers of eco-innovation activities (del Río et al., 2016; Hojnik and Ruzzier, 2015).

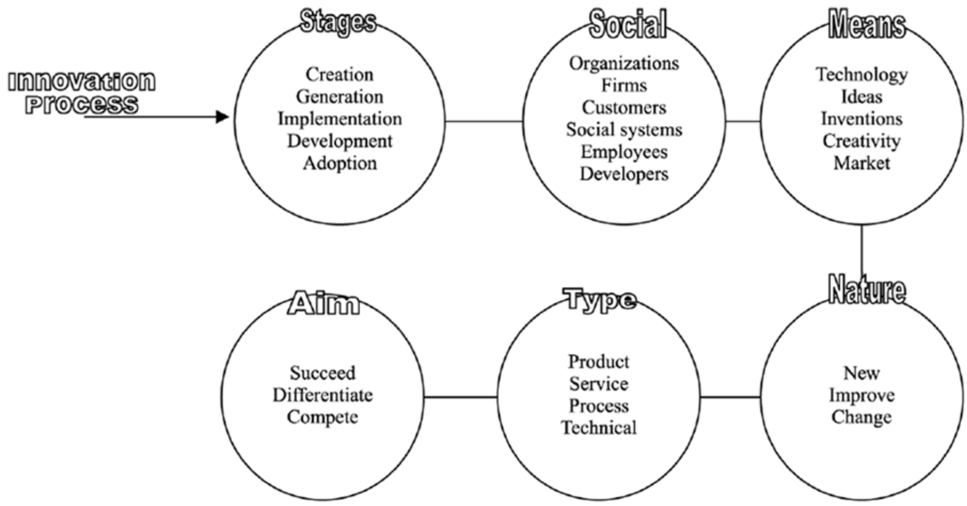
2.3 The conceptualization of eco-innovation: a critical review

Gathering sixty distinct definitions of "innovation" in different fields such as economics, business and management, marketing, among others, (Baregheh et al. (2009) conclude that the concept is as dynamic as the innovative activity itself, changing over time to include new activities, as well as gaining new meanings as its use advances in different knowledge fields. As common denominator, they suggest, "(…) innovation is the multi-stage process whereby organizations transform ideas into new/improved products, service or processes, in order to advance, compete and differentiate themselves successfully in their marketplace" (p. 1334). This definition may sounds limited or simplistic for those who had contact with the vast literature on innovation, and it is natural to be so, as it reflects the fact that no single discipline or knowledge field can deal with all aspects of innovation (Fagerberg, 2012).

In fact, innovation as a phenomenon can be analyzed through many different angles. It encompasses different phenomena (from simple, discrete items such as products and processes to complex organizational attributes impossible to be reduced to a single event) developed using different processes (formal and informal R&D, machinery acquisition, learning-by-doing, learning-by-using, knowledge acquisition, etc.), different degrees of novelty (radical, incremental, architectural, diffusion), conducted by a wide range of actors (inventors, firms, governments, universities, networks, users etc.) with distinct objectives (social, economic, environmental, individual).

It can be understood as the first application of an idea or knowledge, as well as recombination of existent knowledge or even existent innovations applied in a new context. Sometimes it is difficult even to classify them by identifying product and process innovations in a macro level (the same artifact can be considered a product innovation for the supplier or a process innovation for the user firm) and defining the boundaries between invention and innovation (when the time lag between the idea and the market implementation is too small or unclear) (Fagerberg, 2012). The Figure 2.2 below, made by Baregheh *et al.* (2009), is an attempt to summarize most of these dimensions.

Figure 2.2 A diagrammatic definition of innovation



Source: Baregheh *et al.* (2009).

One can extend this analysis to the subgroup of eco-innovation by narrowing down the scheme to understand what really differentiates eco-innovation from innovation to the point that the former would require specific theoretical and empirical considerations. The Table 2.1 represents an effort to put in place the most relevant definitions of the eco-innovation concept to date, based on an extensive bibliometric search at Google Scholar, Scopus, and Web of Science.

Keeping in mind the angles defined in the Figure 2.2, one can identify different stages, social actors, means, aims, types, and nature within the eco-innovation concepts presented. Although some are more subjective than others, the common denominator is that eco-innovations necessarily include some reduction (relative or absolute) of environmental impacts compared with existing technologies and organizational methods.

Table 2.1 Eco-innovation concept – a literature review

Reference	Definition
Pampel & van Es (1977)	Environmental innovations have as a first objective the preservation of existing resouces.
Klemmer et al. (1999); Rennings (2000);	Eco-innovations are all measures of relevant actors (firms, politicians, unions, associations, churches, private households) which develop new ideas, behavior, products and processes, apply or introduce them and which contribute to a reduction of environmental burdens or to ecologically specified sustainability targets. Eco-innovation represents innovation that results in a reduction of environmental impact, whether such an effect is intended or not. The scope of eco-innovation may go beyond the conventional organisational boundaries of the innovating organisation and involve broader social arrangements that trigger changes in existing socio-cultural norms and institutional structures.
OECD (2009)	Eco-innovation can be described as the implementation of new, or significantly improved, products (goods and services), processes, marketing methods, organisational structures and institutional arrangements which, with or without intent, lead to environmental improvements compared to relevant alternatives
Beise & Rennings (2005)	Environmental innovations consist of new or modified processes, techniques, practices, systems and products to avoid or reduce environmental harms. Environmental innovations may be developed with or without the explicit aim of reducing environmental harm. They may also be motivated by typical business objectives such as profitability or the enhancement of product quality. Many environmental innovations combine environmental benefits with corporate or user benefits.
Kemp & Foxon (2007); Horbach et al. (2012)	Eco-innovation is the production, application or exploitation of a good, service, production process, organizational structure, or management or business method that is novel to the firm or user and which results, throughout its life cycle, in a reduction of environmental risk, pollution and the negative impacts of

	resource use (including energy use) compared to relevant alternatives.
Carrillo-Hermosilla et al. (2010)	Eco-innovation is an innovation that improves environmental performance, in line with the idea that the reduction in environmental impacts (whether intentional or not) is the main distinguishing feature of eco-innovation. From the social point of view, it does not matter very much if the initial motivation for the uptake of eco-innovation is purely an environmental one.
EU Comission (2004)	Eco-innovations are all technologies whose use is less environmentally harmful than relevant alternatives. They include technologies to manage pollution (e.g. air pollution control, waste management), less polluting and less resource-intensive products and services (e.g. fuel cells) and ways to manage resources more efficiently (e.g. water supply, energy-saving technologies). Other more environmentally-sound techniques are process-integrated technologies in all sectors and soil remediation techniques.
EU Comission (2006; 2011)	Eco-Innovation is any form of innovation resulting in or aiming at significant and demonstrable progress towards the goal of sustainable development, through reducing impacts on the environment, enhancing resilience to environmental pressures, or achieving a more efficient and responsible use of natural resources.
Oltra & Saint Jean (2009b)	In a broad sense, environmental innovations can be defined as innovations that consist of new or modified processes, practices, systems and products which benefit the environment and so contribute to environmental sustainability.
Fussler & James (1996)	New products and processes which provide customer and business value but significantly decrease environmental impacts
Andersen (2008)	Eco-innovation is defined as innovations which are able to attract green rents on the market. The concept is closely related to competitiveness and makes no claim on the "greenness" of varies innovations. The focus of eco-innovation research should be on the degree to which environmental issues are becoming integrated into the economic process.

Reid & Miedzinski (2008)	Eco-innovation is the creation of novel and competitively priced goods, processes, systems, services, and procedures designed to satisfy human needs and provide a better quality of life for everyone with a whole-life-cycle minimal use of natural resources (materials including energy and surface area) per unit output, and a minimal release of toxic substances.
METI (2007)	A new field of techno-social innovations that focuses less on products' functions and more on environment and people.
Huppes et al. (2008)	Eco-innovation as the combined improvement of economic and environmental performance of society. Eco-innovation is a subclass of innovation. Innovations not being eco-innovations, are characterized by environmental improvements with economic deterioration or economic improvements with environmental deterioration.
Lanjouw & Mody (1996)	Environmental innovation includes pollution abatement (end-of-pipe) innovation and new technologies which lower the production of pollutants
Pickman (1998)	An environmental innovation is a technology that embodies pollution control, pollution remediation or pollution avoidance. Pollution control and remediation technologies solve existing pollution problems and pollution avoidance technologies address the deeper issue of how to prevent pollution.
Jones et al. (2001)	Eco-innovation aims to develop new products and processes, which meet the needs of customers in the most Eco-efficient way.
Chen et al. (2006)	This study defined ''green innovation'' as hardware or software innovation that is related to green products or processes, including the innovation in technologies that are involved in energy-saving, pollution-prevention, waste recycling, green product designs, or corporate environmental management

Because the reduction of anthropogenic impacts on the environment is required in the entire production and consumption complex system that shape the global economy, eco-innovations are expected to appear as products, services, processes, techniques, and organizational methods implemented by a wide range of social actors in different stages (with emphasis on the diffusion) with different aims and means. Roughly, one could define eco-innovation as all innovations that have a decreased environmental impact compared with the relevant alternatives, but even this definition can be problematic and inaccurate. In the next subsections we focus on some of these issues and how they might affect empirical analysis and policymaking in the field.

2.3.1 Economic gains

There are many differences among the concepts presented: first, some definitions emphasize the economic gains (including competitiveness, differentiation, value creation etc.) as essential components of an eco-innovation (Andersen, 2008; Fussler & James, 1996; Reid & Miedzinski, 2008; Huppes *et al.*, 2008), while others cite only the environmental gains (Kemp & Foxon, 2007; Horbach *et al.* 2012; EU Commission, 2004; OECD, 2009).

For the second group, the boundaries of what is actually an eco-innovation can go far beyond the ones that define "traditional" innovation for Baregheh *et al.* (2009) by including also technologies, artifacts and organizational methods that *do not necessarily bring overall superior economic value* for the actors (firms, organizations) that implement them (K Rennings, 2000). Without the economic incentives that are core to innovation theories, it may be necessary to reevaluate if this specific group of technologies without any economic gain could be even considered innovations as defined in evolutionary and economics approaches (Ekins, 2010).

On the other hand, many technologies with environmental improvements may not offer immediate or even potential economic advantages compared with existing technologies. Eco-innovative agents have to deal with specific institutional and technological challenges while maintaining an acceptable degree of efficiency compared with "traditional" technologies in order to generate some economic value.

The mature technologies of today have generally undergone a continuous, long period of adaptation and incremental innovation by which the focusing devices (Fagerberg, 2012; Rosenberg, 1976; Dosi 1988) were influenced by heuristics such as cost efficiency, performance, consumer preferences, existing infra-structures and quality (individual advantages) rather than environmental issues, making them more attractive in many aspects compared with the new "clean" technologies.

Moreover, technologies are not "neutral tools", but elements that gradually alter our perceptions, behavior patterns and institutions, creating adapted laws and regulations, dominant designs, basic heuristics used on R&D processes, general consumption preferences and prejudices - the “common sense”, firms’ common behaviors, political institutions, sectoral standards, and so on (Geels, 2004). The diffusion of fossil fuel powered automobiles, for example, transformed the behavior of society and institutions throughout the twentieth century, but by creating solid behavior patterns and perceptions, it prevents the adoption of alternative technologies that result in major changes in infrastructure and consumer behavior (Faria & Andersen, 2014; 2015). As pointed by Perez (2010), “(…) organisational inertia is a well-known phenomenon of human and social resistance to change” (pp. 198) and, once established, routines “(…) give rise to intense resistance and require bringing forth even stronger change-inducing mechanisms” (pp. 199).

Technologies and institutions influence each other over time in a co-evolutionary process (Lündvall, 1992), implying in a hardness degree that can hamper the development and diffusion of innovations that do not “fit” into existent technological and institutional frameworks (Nelson & Winter, 1982). These “selective mechanisms” also play an important role in defining market structures: while in emerging industries innovative activities rely on grasping opportunities external to the firm (as non-explored technological opportunities, for example), in mature industries they depend rather on the capabilities and knowledge of firms, reflecting a higher degree of incrementalism (Dosi & Nelson, 1994; Faber & Frenken, 2009).

Nevertheless, there is always some room for new business models and technologies that compete with existent ones, even when there is no initial economic gain. They do not necessarily present immediate economic and performance gains, though it should not be regarded as a signal of failure (Foster, 1986; Dosi, 1982; Rosenberg, 1976). As Christensen & Rosenbloom (1995) explains,

> When viewed in terms of the preferences of established markets, these challenging technologies often display inferior characteristics, and therefore find their earliest application in new or remote market segments where preferences are more closely aligned with the capabilities of the new technology. As normal advances are made in the new technology in its initial market, the new paradigm may return to overtake and surpass established paradigms in the original market as well. (p. 236).

Environmentally-friendly technologies and organizational models have features that are currently valued by specific groups of users. The concept of "value" of a technology depends on stakeholders' preferences[12] (Dosi, 1988): some features are universally valued (cost efficiency, quality and other individual benefits) while others are not (for example, reduced environmental impacts and other collective, socialized benefits). Many eco-innovations still cannot compete with existing technologies in terms of those universally valued features.

In a given population of users with distinct preferences, some may accept to give up individual benefits on behalf of collective (for example, to give support to these technologies), making room for the creation of market niches (Schot and Geels, 2007). Eco-innovations, as any other radical innovations, can exist even generating lower individual benefits than existing technologies, as they can be (and have been) initially restricted to specific niches before going (if they go) mainstream. The generation of economic advantages and improved performance is, however, crucial to the *diffusion* of these technologies towards mainstream markets (Andersen, 2008).

2.3.2 Environmental gains

The second controversial point regarding the concept relates to the level of "greenness" of eco-innovation. There is a general consensus among the definitions presented at the Table 2.1 that the concept of eco-innovation must include

[12] Including firms, users, governments.

innovations that are *intentionally and unintentionally* designed to have less environmental impacts than existing technologies, as long as they effectively present such advantages (i.e. Klemmer *et al.,* 1999*;* Rennings, 2000; OECD, 2009; Beise & Rennings, 2005; Carrillo-Hermosilla *et al.,* 2010). In this subsection, we address the main problems with this definition that might affect the scope of eco-innovation activity and its role in the greening of the economy.

Firstly, many eco-innovations are systemic by nature and depend on other related innovations and technologies to be considered green *de facto* (Andersen, 2004; Nill & Kemp, 2009; Oltra & Saint Jean, 2009b). To evaluate the greenness of an electric vehicle, for instance, one should include the impact of its production processes, battery deployment regulations and energy production structure. While the former can be somehow tracked by the manufacturer, the latter relies on country- or region-specific institutions and infra-structures. Thus adopting the strict environmental impact rule, the same electric vehicle could be considered an eco-innovation or not depending on the market where it is sold and the metrics used. Additionally, many components aiming at improving green technologies' attributes (for example safety, comfort, noise level, durability, compatibility with other technologies etc.) do not present any environmental gain, although they might be crucial to improve performance and contribute to their diffusion.

As already discussed, technologies usually need some time to improve its characteristics before reach an acceptable performance degree, and that includes their environmental impacts. Some technologies can display potential environmental gains, but they may require a certain period of experimentation to reach this point, and of course there is always the risk that they never reach it due to technological/economic barriers, or they can also be surpassed by a better technology.

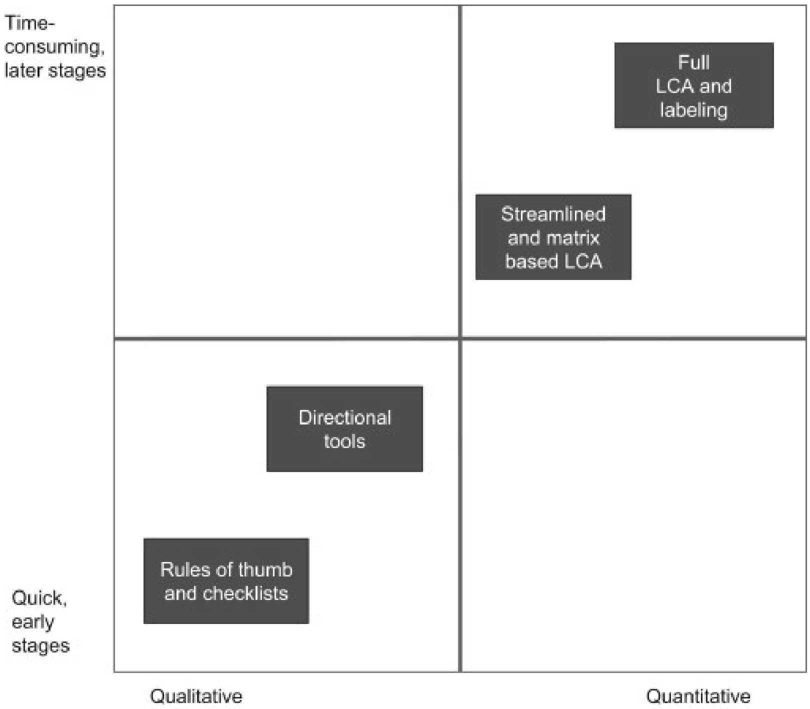
From the social value creation and environmental impact perspectives, innovations with *unintended* environmental gains are as important as the ones with intended gains. However, considering the former as eco-innovations would imply in including a huge amount technologies produced so far, even some of those that are regarded as "polluting" technologies. Moreover, eco-innovations are distinct from innovations because they can be used as tools to guide and understand the greening of the economy, not because they provide individual environmental gains *per se* (Andersen, 2008).

Unintended environmental gains are the *random side of the greening process* and are *exogenous*, thus difficult to predict, manage and influence by policy mechanisms usually described in the traditional innovation literature (Lundvall and Borrás, 2005). One firm may be considered as an eco-innovator because it is producing innovations that have unintended environmental gains, but future generations of the same product may not offer such gains. On the other hand, firms producing innovations that have intended environmental gains demonstrate commitment to the greening of the economy by having technological strategies that take environmental issues into account.

Finally, technologies designed to be environmentally-friendly but unable to provide immediate environmental advantages would not be considered as eco-innovations. The literature provides many different methods for evaluating the environmental impact of a new technology (Figure 2.3), from life-cycle assessment tools to rules of thumb and checklists. The most accurate methods (streamlined and full LCA) are time- and resource-consuming, especially for complex technologies and value chains. Different methods may also generate different, often contrasting results.

It remains almost impossible to assess the overall environmental impacts of some potentially green technologies and to compare them with existing technologies (Bocken *et al.,* 2012), especially when considering rebound effects and other issues that may not be predicted before the mass-market diffusion of a technology (Jänicke, 2012). Following and expanding the most accepted definition of innovation (OECD, 2005), most definitions, including Rennings (2000), emphasize the existence of eco-innovations that go beyond products and processes, including organizational, marketing and social eco-innovations. It remains very unclear how to measure their unintended and even intended environmental gains, as they often do not have direct impacts like technologies do (del Río et al., 2016).

Figure 2.3 Classification of different types of environmental impact assessment tools



Source: Bocken *et al.* (2012).

This may sound like a pure theoretical discussion, but it has important effects on policy making and ultimately on the direction of the greening process. One practical example is a series of regulations from the European Union (EU) regarding certification of eco-innovations in the automotive sector. According to the regulation (EC) No 443/2009, CO2 emissions from all new cars registered in the EU should not exceed an average of 130 gCO2/km in 2015, and the eco-innovation scheme would help manufacturers meet the target by implementing certified technologies in their products.

The regulations (EC) No. 510/2011, (EC) No. 725/2011, and (EC) No. 427/2014 establish a series of criteria for determining which technologies should be eligible as eco-innovations, including that:

- only those technologies should be eligible that are intrinsic to the transport function of the vehicle and *contribute significantly to improving the overall energy consumption of the vehicle*. Technologies that are accessory to that purpose or aim at enhancing the comfort of the driver or the passengers should not be eligible.
- it should be possible to measure the CO2 savings from an eco-innovation with a *satisfactory degree of accuracy*. That accuracy can only be achieved where the savings are 1g CO2/km or more.
- where the CO2 savings of a technology depends on the behavior of the driver or on other factors that are *outside the control of the applicant*, that technology should in principle not be eligible as an eco-innovation.

The criteria adopted in this regulation, which might effectively affect the eco-innovation activity in the sector, reflect the consensus around measurable environmental gains. In this case, it is strictly necessary that the technologies present a measurable environmental gain to be considered an eco-innovation in the first place. Although this is a short to medium term policy aiming to reduce CO2 emissions, it excludes the systemic effects and the potential gains from radical technologies that are not yet in their optimal performance levels.

The excessive focus on CO2 reduction as a metric to eco-innovation definition may divert automakers from investing in systemic solutions, including new business models, radical technologies, infrastructure changes etc., or in enhancing the performance of alternative propulsion systems. It does not contribute to the greening of these firms, because it stimulates the very incremental greening of dirty technologies (such as the internal combustion engines) rather than stimulating the radical changes that are required. It might even stimulate greenwashing practices, such as Volkswagen's recent "Dieselgate"[13].

2.4 Discussion and Final Considerations

This paper has critically assessed the concept of eco-innovation, its main drawbacks and different interpretations, and offered a new definition and interpretation based on insights from the innovation concept based on evolutionary theory, in order to help scholars, organizations and policymakers to improve the understanding of green industrial dynamics.

The "green economy" concept should not be considered green in any absolute sense. From an evolutionary economic perspective, the economy is greening when it is moving in a green direction (Andersen, 2012). This means that the environment has become such an important *driver* of economic development that innovation moves in a green direction at the aggregate level. The economy is green when the selection environment favors eco-innovation and green entrepreneurship to such a degree, that they become - or is close to becoming - the "easy and natural" way.

The central question is, then, not how green an innovation, an entrepreneurial activity, a firm or even a nation is at a given time or whether we have actually reached a green economy, but whether the economic process, as the most powerful existing coordination mechanism, overall is moving in a green direction and at what pace. Such a suggested dynamic perspective on environmental sustainability, eco-innovation and the green economy is often lacking in both research and policy making, none the least in a development context where static (neoclassical) macro perspectives tends to dominate whereas green industrial dynamics are neglected.

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[13] In 2015, Volkswagen admitted that it had deliberately equipped 11 million of its diesel vehicles with a "defeat device" to "cheat" at U.S. emissions testing (Blackwelder et al., 2016).

An innovation is not always the best known solution for a problem from economic, competitive, technical, and environmental perspectives, but is often the best available solution to solve the problem given all the path dependencies that the innovative processes are subject to, such as dominant designs, routines and regulations, existent knowledge bases (Arthur, 1989; David, 1985). These elements, on the other side, are continually influenced by historical events and technologic/organizational advances in a co-evolutionary dynamic (Nelson & Winter, 1982).

In this sense, why should scholars establish boundaries between eco-innovations and non-green innovations? Certainly it is because of the role that technologies and have on this greening process, not because of their individual environmental impacts. Innovations, for instance, have been studied not only because of their immediate impacts on the economy, institutions and wellbeing, but also to understand their determinants and to formulate proper policies in an appropriate context where they can act as tool to address systemic problems and promote socio-economic development (Edquist, 2011). Nevertheless, the concept of eco-innovations has been defined mainly in terms of their individual environmental impacts (even recognizing the difficulties in measuring such impacts) rather than the innovators' motivations and values, those that really drive the greening of the economy.

Defining eco-innovations is just as complex and challenging as analyzing them. The alternative to the consensual definition might be difficult and problematic (del Río et al., 2016), but it is important that future research keep in mind that eco-innovation definition cannot be easily generalized across sectors, technologies, and countries. It might be true that, for some sectors, defining specific environmental gains works just fine, but generalizing it to the economic activity as a whole might be dangerous.

Rather than identify the innovations that have actual reduced impacts, we should be looking at how firms change their technological strategies and business models towards the greening of the economy. As environmental impacts tend to be product or technology specific, meso-level analyzes are important tools to find differences between eco-innovation activities and characteristics among sectors in order to better define eco-innovation. For instance, identifying firms' investments in specific technologies that have great potential to reduce society's environmental impact and require considerable effort, resources and new capabilities (for example fuel cells, wind power, electric cars, solar energy) might be a good indicator of real greening in the sectors were the products are complex, dominant designs are present and markets are mature and competitive, while other sectors might require completely different metrics.

By redefining the concept in order to capture real technological change towards the greening of the economy, one is able to select only those innovations that really have a positive, endogenous impact on the greening of the economy, not only in terms of individual environmental footprint but mainly in terms of values and incentives.

CHAPTER 3
UNVEILING SCIENTIFIC COMMUNITIES ABOUT SUSTAINABILITY AND INNOVATION: A BIBLIOMETRIC JOURNEY AROUND SUSTAINABLE TERMS

by

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ABSTRACT

Literature about the relationship between innovation and sustainability has skyrocketed in the last two decades and new terms have appeared. However, only very few bibliometric analyses have reviewed some of these terms (*eco-innovation*, *environmental innovation*, *green innovation*, and *sustainable innovation*), and they concluded that such terms are mostly interchangeable. These findings surprise in light of the different positions shown in the innovation for sustainability debate. Our bibliometric analysis tracks meanings and communities associated with these four terms and indicates some overlaps, especially between *eco-innovation* and *environmental innovation*. However, we found relevant differences of meanings and communities that reflect the different positions in the innovation for sustainability debate.

3.1 Introduction

The relationship between technology, innovation, and environment is an example of a widely contested topic because technological change has been considered both the source and the solution for many environmental issues related to anthropogenic activities (Hekkert et al., 2007). The root of academic discovery in this field began in the 1970s, when several authors discussed the feasibility of endless economic growth on a finite planet (Beckerman, 1974; Cole et al., 1973; Georgescu-Roegen, 1971; Meadows et al., 1972; Solow, 1973). The well-known idea of sustainable development (SD) was a milestone in this debate. Linking economic growth to the actual state of technology gave innovation a central role -- as the way to stretch the limits of economic growth within the availability of finite resources. One consequence of the SD debate was to settle the scientific agenda. This resulted in more scholars analyzing innovation through the lens of sustainability (Freeman, 1996). The approach also finds important applications in policy contexts, as in recent reports and manuals written by regional, national, and international organizations (Dutz & Sharma, 2012; O'Hare et al., 2014; OECD, 2009, 2010, 2013a, 2013b; UNEP, 2014; World Bank, 2012), and even within co-funding calls[14], regulations and other policy instruments (EU Commission, 2011a, 2011b, 2009).

When contested positions exist, terms and languages may have a powerful role because they can be used to shape meanings and identify belongings to the different communities (Nicolini, 2012). Therefore, the comparison between concepts is crucial to define and explore the intellectual structure of a given scientific field, to access the influence and scientific impact of different journals, authors and geographic locations to each concept, to suggest future paths for the development. For this reason, we were surprised to find only few bibliometric analyses (Dias Angelo et al., 2012; Karakaya et al., 2014; Schiederig et al., 2012) that addressed the language dimension of the relationship between innovation and

[14] See http://ec.europa.eu/environment/eco-innovation/apply-funds/selection-criteria/index_en.htm

sustainability without finding relevant differences in the usage and meanings of different terms. More specifically, Dias Angelo et al. (2012) reviewed papers – over the last three years and only in the journals tied to organizational environmental management -- which contain the terms environmental innovation, green innovation and eco-innovation in titles or abstracts indexed in the ISI Web of Science (WoS) and Scopus. They found a predominance of environmental innovation, but not any difference in meanings. Karakaya et al. (2014) studied the diffusion of eco-innovation looking at eco-innovation, ecological innovation, green innovation, sustainable innovation and environmental innovation terms in Google Scholar. While the focus of Karakaya et al. is to identify the core disciplines and research streams of literature, they did not highlight any differences between these terms. Schiederig et al (2014) identified and analyzed four main sustainable innovation terms (*eco-innovation, environmental innovation, green innovation,* and *sustainable innovation*) and concluded that the terms "*can be used largely interchangeably*" (p. 182), even though "*sustainable innovation includes a social dimension as well as ecological dimension*" (p. 188).

Such non-conflictual view seems to stand in contrast with the richness of the positions in the sustainability debate. For instance, Rennings (2000) uses the terms eco-innovation and environmental innovations as synonymous, while Ekins (2010) makes a very clear distinction between them. In addition, these three bibliometric reviews seem not to define a clear methodology to identify meanings and communities, leaving room for more advanced and detailed bibliometric analyses.

We performed an alternative bibliometric analysis that explicitly aimed to (i) disentangle the meanings and (ii) identify associated scholarly communities and discussions behind these same four terms. We utilized bibliographic data from WoS and a methodology that combined keywords analyses -- as a way to track meanings -- with community detection based on shared references.

Differently from the cited reviews, our results indicate that these four terms focus on different topics and partially identify different scientific communities. For example, *sustainable innovation* is preferred by communities dealing with complex system-oriented approach, especially the transition school of UK and The

Netherlands. *Green innovation* is used by the management community, and it is very popular outside Europe. *Eco-innovation* has an important focus on eco-design and it has important overlaps with *environmental innovation* especially within specific communities – as for example – those studying evolutionary economics. We also found a correspondence between journals and communities, and – very interesting – the use of the Journal of Cleaner Production as common platform of the different communities.

In conclusion, we confirm that terms and language are important concepts to understand different positions and meanings within different scientific sub-communities. The different importance and popularity of the scientific sub-communities can influence future policies for sustainability. For example, the growing popularity of the *eco-innovation* term may result in policies which focus on eco-design and eco-labels, whilst the sustainable innovation perspective may focus on policies which purse wider societal changes (Franceschini & Pansera 2015).

The paper is organized as follows: Section Two briefly introduces the concepts of Kuhnian scientific communities and the discourse analysis approach to sustainability. Section Three presents the data and methodology used for our bibliometric analysis. Section Four presents the main results and discussions, and section Five outlines our main conclusions and potential future developments for this approach.

3.2 The Discourse Analysis about Innovation and Sustainability in a Kuhnian World

Before Kuhn, theorists of epistemology and science understood scientists as individual agents free from any social boundaries (Jacobs, 2006). Polanyi (1951), Royce (1968), and Fleck (1979) touched upon the notion of the scientific community, but it was Kuhn's seminal work *The Structure of Scientific Revolutions* (1962) that popularized this topic (Jacobs, 2002). In Kuhn's view, a scientific community consists of scientists who agree on specific paradigms about reality.

Paradigms are ways in which scientists look at the world, and each paradigm consists of specific theoretical frameworks, puzzles to be solved, methodological processes, and potential solutions. These paradigms are the "theoretical hard core" of scientists who shape research programs (Lakatos & Musgrave, 1970).

Different scientific communities seek to gain popularity and reproduce themselves as they attract new members through specific processes of education, initiation, and selection in which students have been similarly educated and are thought to use the same language (Jacobs, 2006). Consequently, paradigms evolve and compete at any time, representing the progress of scientific knowledge. Paradigms and scientific communities are found in all research topics in which different ideologies, approaches, and interests exist. The existence of different scientific communities is crucial to solve complex problems through the continuous exposition and confrontation of parallel theories (Kornfeld & Hewitt, 1981) and, therefore, the advance of scientific research is intrinsically dependent on diversity (Popper, 1963).

The use of a common language defines the existence of--and draws the boundaries between--different paradigms and scientific communities. The use of language is a specific subject of study, called *discourse analysis*, which has become popular to address the relationship between science, technology, and society (Hajer and Versteeg, 2005). As Nicolini argued, discourse is "*first and foremost a form of action*" (2012, p. 189) through which each community tries to attach meaning to topics and influence other communities. Consequently, any discourse is a way to sustain specific social group(s) and culture(s) (Gee, 2010). Therefore, discourse analysis can be applied to study the dominant ideologies and values in the scientific world.

The comparison between concepts is important to define and explore the intellectual structure of a given scientific field (Dobers et al., 2000; Hill and Carley, 1999; Ramos Rodríguez and Ruíz Navarro, 2004), to access the influence and scientific impact of different journals, authors and geographic locations to each concept (Baumgartner and Pieters, 2003; Ingwersen, 2000), and to suggest future paths for the development of the many different branches within a field. It has been used largely to define concept-based scientific communities in many fields such as Strategic and operational management (Charvet et al., 2008; Ramos Rodríguez and Ruíz Navarro, 2004; Vokurka, 1996), corporate social responsibility (Bakker et al., 2005), logistics and transportation (Kumar and Kwon, 2004), service innovation (Sakata et al., 2013), National Innovation systems (Teixeira, 2013) and even Innovation itself (Fagerberg et al, 2012).

Under the lens of discourse analysis, nature, innovation and sustainability are socially constructed and historically dependent concepts. As any social concepts, they are widely debated within scientific communities that carry different theoretical lenses, terms, and ideological values (Castro, 2004; Franceschini & Pansera, 2015; Garud & Gehman, 2012; Hopwood et al., 2005; Markard et al., 2012; Pansera, 2012; Rennings, 2000; Scoones, 2007).

The relationship between technological change and environment has been discussed at least since the early 1970s, when the first general discussions on the environmental impacts were conducted (Ehrlich & Holdren, 1972; Meadows et al., 1972). As the research field has evolved in the last decades, the scope of the innovation literature has widened in the last decades to include not only technical innovations (Freeman & Soete, 1997) but also organizational, marketing, institutional, and normative aspects (Fagerberg and Verspagen, 2009).

Such discussion was also incorporated in early evolutionary works (Freeman, 1984) and in the so-called Berlin school of environmental policy research, which came up with the related concept of ecological modernization (Christoff, 1996; Huber, 1985), focusing on a sociological, policy-oriented perspective. With the idea of sustainable development being formulated and presented in the late 1980s (WCED, 1987) and specific environmental targets being defined later through the Kyoto Protocol, many scholars from different backgrounds started to incorporate its premises in order orient their research fields towards the premises of the concept.

In the beginning of the 1990s the importance of sustainable development guidelines for technological change and growth was highlighted by business (e.g.

Barrett, 1991; Elkington, 1994; Gladwin et al., 1995; Porter & Linde, 1995; Repetto, 1995; Welford, 1995), economics (Jacobs, 1993; Jaffe and Peterson, 1995; Jaffe and Stavins, 1995; Jorgenson and Wilcoxen, 1990; Tietenberg, 1990), and design (Keoleian and Menerey, 1994) literatures.

With such diverse roots, the literature about the relationships between innovation and sustainability is expected to show branching terms with differentiated attached values. Likewise, we could assume to find scholars with different understandings of the four terms, in opposition to the findings of the already existing literature. In fact, we found cases in which the terms were used interchangeably, as synonyms, and cases in which they had contrasting meanings.

In the mid-1990s, the incipient literature on sustainable development and technological change started to use specific terms such as *eco-innovation* and *environmental innovation* to refer explicitly to the innovations aiming at reducing environmental impacts, in the attempt of operationalizing the sustainable development premises (Carraro & Siniscalco, 1992; Fussler & James, 1996; Green, McMeekin, & Irwin, 1994; A. B. Jaffe & Palmer, 1997; Johansson & Magnusson, 1998; Lanjouw & Mody, 1996; Pickman, 1998). The terms *green innovation* and *sustainable innovation* could also be found at this time, although their use was restricted to very few papers (e.g. Azzone & Noci, 1998).

Lately, Rennings (2000) stood out as one of the main references for the concept of *eco-innovation* and *environmental innovation*, using both interchangeably[15]. His definition was widely cited and influenced subsequent works, many of which also made no distinction between the two terms (for example Arundel & Kemp, 2009; Hojnik & Ruzzier, 2015; Horbach et al., 2013; Triguero et al., 2013; Oltra et al., 2008, De Marchi, 2012). In another influential project, "Measuring Eco-innovation" (MEI), Kemp & Foxon (2007) explicitly stated, citing Rennings, that "*often eco-innovation is used as a shorthand for environmental innovation*" (p. 2).

[15] In fact, the author also mentions the term "green innovation" sometimes when referring to the theme (Rennings, 2000).

In fact, many authors use two or more terms to refer to the same idea or concept: Hellström (2007) used *eco-innovation* as a synonym for "environmentally sustainable innovation" and also for *sustainable innovation*. Bernauer et al. (2007) stated, "*The terms eco-innovation and green innovation are used synonymously for environmental innovation*" (p. 3). Andersen (2010) and Pujari (2006) used *green innovation* and *eco-innovation* synonymously, and Halila and Rundquist (2011) used all four sustainable terms to refer to the same concept. Similarly and more recently, Hojnik and Ruzzier (2015) stated that *eco-innovation*, *ecological innovation*, *green innovation*, and *environmental innovation* are interchangeable.

On the other hand, many scholars made distinctions between these terms. For example, Kemp & Foxon (2007), Schiederig et al. (2012), Charter & Clark (2007) agreed that an explicit social positive aspect, besides economic and environmental gains, differentiates *sustainable innovation* from the other terms. Charter & Clark (2007) argue that, "*although the two terms are often used interchangeably, eco-innovation only addresses environmental and economic dimensions while sustainable innovation embraces these as well as the broader social and ethical dimensions*" (p.10).

Noteworthy, Ekins (2010) defined *environmental innovation* as "*changes that benefit the environment in some way,*" while *eco-innovation* is "*a sub-class of innovation, the intersection between economic and environmental innovation*" (p. 269). In other words, for him *eco-innovation* is related to both environmental *and* economic benefits, and *environmental innovation* is related only to the former. Therefore, the author made a clear, conceptual distinction between the two terms, contrasting with Rennings (2000) and subsequent works.

These examples demonstrate how complex it is to delineate these terms according to their existing, explicit definitions. This motivated us to define a methodology which allows to consistently identify the existence of different meanings and different communities.

3.3 Methodology

Our methodology is designed to disentangle the meanings and communities related to the different sustainable terms, as a way to understand the complexity involved in their use by scholars. We reviewed four sustainable terms (*eco-innovation*, *environmental innovation*, *green innovation*, and *sustainable innovation*) widely used in the literature and applied a combination of content analysis techniques--which draw meanings from the manifest content of language and communication (Baregheh et al.,2009)-- and community detection in networks (Blondel et al., 2008). We narrowed the analysis to peer-reviewed, English-written journal articles, gathered through WoS.

WoS data is considered the central source of information for extensive bibliometric exploration within the social sciences (Liu et al., 2014). In fact, only the WoS data has the high level of curation, essential to our analysis. To the best of our knowledge, WoS is the only bibliographic database that normalizes the cited references for each article record across the whole collection. This feature allowed us to calculate pairwise, bibliographic coupling and perform the community-level detection as explained in phase three of the analysis.

We extracted the full records for the analyzed articles, including cited references. The keywords at the center of our analysis were the original, author-provided keywords, which exposed a high level of linguistic variation. To prepare these terms for quantitative analysis, we applied a combination of manual consolidation and algorithmic stemming, explained below in more detail. While a certain level of linguistic normalization is essential to achieve comparability, we cannot completely exclude the possibility that changes in meanings were introduced in the course of data preparation.

The restriction to leading peer reviewed journals results in smaller samples which can be regarded as representative for the respective research areas (van Leeuwen 2006). The use of WoS limited the number of analyzed articles, as the number of publication records is significantly larger in other bibliographic databases, such as Scopus even using Google Scholar (GS) as for instance in (Schiederig et al., 2012) where several thousand publications constitute the basis of the analysis. While GS is an excellent choice for literature discovery, it contains all kinds of publications including working papers, conference papers, and even student assignments and forged documents (Bornmann et al., 2009; Delgado López-Cózar et al., 2014; Giustini & Boulos, 2013; Lasda Bergman, 2012). According to Kousha & Thelwall (2007), "*it is likely that a significant mass of non-refereed web documents which do not pass any 'qualitative' process are indexed by Google Scholar, although some may be postprints or preprints of subsequently accepted refereed articles*." (p. 290).

The over-time development of publications within the different areas (Figure 2.1) shows differences but no alarming signs of systematic bias of particular publication groups over time. Another indication for the validity of the sample is the relative number of search results with a similar query but using a different database. The results of this cross-check using the Scopus database resemble for the most the patterns found in the WoS data[16]. "Eco-innovation" and "environmental innovation" are similar in size and the two "larger groups" while there are less hits for "sustainable innovation" and "green innovation". In contrast to the WoS data, Scopus contains more records for "sustainable innovation" than "green innovation", which might indicate that our sample contains relatively little literature on the former term.

With this methodology, we are able to detect i) different meanings carried by the four sustainable terms; and ii) different scientific communities behind these terms. Meanings were detected by looking at co-occurrence patterns of keywords. More specifically, we analyzed the co-occurrence between each of the four sustainable terms when used as article keywords and other recurrent keywords. This technique was based on the idea that if a sustainable term is highly connected to specific

[16] Cross-check query on Scopus for each of the 4 sustainable terms, excluding hits for the three others. Results restricted to journal articles from lates 2014 in the subject matters "Business", "Engineering", "Energy", "Social Science", "Environmental Science", and "Economics". Eco-innovation (169), environmental innovation (223), green innovation (99), sustainable innovation (147)

keywords, these associations may be meaningful. In other words, if these sustainable terms are fully interchangeable, we would not expect to find any specific pattern of correlations because their use would be random. To evaluate the association of any of the keywords with each of the four sustainable terms, we used the term frequency inverse document frequency (*tf.idf*) statistic (Rajaraman and Ullman, 2011) which is often used as a weighting approach in information retrieval. The term frequency (TF_{ij}) measures the frequency (number of occurrences) f_{ij} of a term (keyword) i in a document j, normalized by the maximum number of occurrences of any term in the same document:

$$TF_{ij} = \frac{f_{ij}}{max_k f_{kj}} \quad (1)$$

If the term i is the most frequent term in a document j, then $TF_{ij} = 1$. The inverse document frequency (IDF_i) measures how frequently the term i occurs in a collection of documents, based on the total number of documents (N):

$$IDF_i = \log_2(N/n_i) \quad (2)$$

Combining (1) and (2)--the term frequency and the inverse document frequency returns the final *tf.idf* equation (3):

$$tf.idf_{ij} = \frac{f_{ij}}{max_k f_{kj}} \ x \ \log_2(N/n_i) \quad (3)$$

In our analysis, the "document" is comprised of keywords that appeared together with one of the four sustainable terms in the set of keywords in one article. The *tf.idf* counts the number of times a word occurs in a document, discounting for the overall generality of a keyword in the whole corpus. In this way, the importance of keywords (such as innovation) that are fairly general in the overall corpus is lowered, yet they are not excluded from the corpus as contextual stop words. In fact, having a keyword highly associated with all four sustainable terms did not indicate a specific association of the keyword with any of the sustainable terms. Using this relatively simple word co-occurrence and weighting approach, we were able to identify the keywords associated with each of the four terms and score them by their level of association.

Scientific communities were explored using the bibliographic information extracted during the analysis of meanings. For those articles, we focused on: i) the journal in which the paper was published, ii) the authors' countries of origin, and iii) the cited references.

The data preparation and analysis was divided into three phases: Phase 1 included the preparation of the database of journal articles. Phase 2 analyzed the meanings of the sustainable terms looking at a) the co-occurrences between these sustainable terms used as keywords and other keywords, and b) the content of titles and abstracts of journals articles. Phase 3 consisted of the analysis of the scientific communities, looking at citations, authors, and journals.

Phase 1 – We extracted a list of 473 items[17] from Web of Science that were matched by a "topic search" for one of the following terms: "eco-innovation", "environmental innovation", "green innovation", and "sustainable innovation". From this first list, we selected the 400 items that contained keywords and citations in the WoS record, and, finally, the 196 papers that used one or more of those terms as keywords. These 196 journal articles contained 788 unique keywords that were grouped, by stemming or conceptual similarity, in 321 unique keywords for a total of 1,216 hits.

Phase 2 – We applied the *tf.idf* analysis to the selected data to find patterns of correlation between the sustainable terms and the other keywords.

Phase 3 – We investigated the community-level dimension by looking at journals, authors, and citation statistics. To construct the network, we first calculate a variation of the bibliographic coupling (BC) between each pair of papers in our corpus of 196 articles. The traditional BC indicator is calculated as

[17] Extracted on the 13th August 2014.

$$w_{ij} = \frac{n_{ij}}{\sqrt{n_i \times n_j}} \tag{4}$$

where the number of shared references between paper i and j is discounted by the tendency of the papers to cite. We propose to extend this measure by accounting for the general popularity of literature to be cited. The argument behind this extension is the following: a shared reference to a seminal paper that stands in the beginning of a larger academic discussion is probably a weaker indicator for communality between paper i and j as compared to a shared reference to a more specific and less cited empirical study. We use Newman's (2001) collaboration index, which he developed to identify relationships between scholars from co-authorships. This index suggests that, for instance, the collaboration on a physics article with 10 authors is probably generating a weaker connection between the participating scientists than the joint authorship of a paper by 2 scholars. In order to include this extension, we changed the numerator from equation (4), assuming that

$$n_{ij} = \sum_k \frac{\delta_i^k \delta_j^k}{n_k - 1} \tag{5}$$

Where n_k is the number of citations that k receives and $\delta_i^k \delta_j^k = 1$ if papers *i* and *j* both cite *k*. The final BC equation is, therefore:

$$w_{ij} = \frac{\left(\sum_k \frac{\delta_i^k \delta_j^k}{n_k - 1}\right)}{\sqrt{n_i \times n_j}} \tag{6}$$

Finally, we apply the established Louvain algorithm in order to identify communities in the network (Blondel et al., 2008).

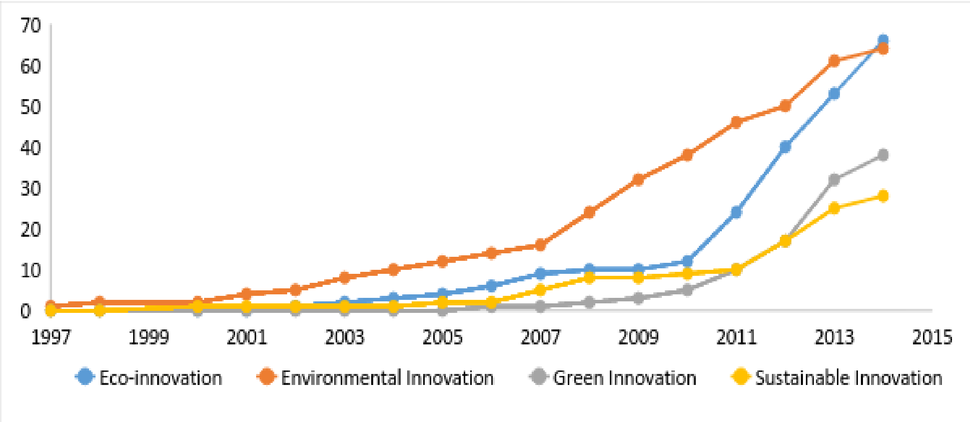
3.4 Data Analysis

3.4.1 Unfolding meanings and the evolution of the four sustainable terms

In the first part of our analysis, we investigate the evolution of use of the four terms (as keywords) over time and make a detailed analysis of the bibliometric characteristics associated with each one of them using the *tf-idf* as parameter. Since keywords are among the central elements of scientific papers –used to indicate their main topics – such an analysis is likely to provide insights into the changes on the use of these terms by the scientific community and their assumed meaning.

Figure 3.1 plots the cumulative counts of the four terms over time. *Eco-innovation* and *environmental innovation* are the most used terms. *Environmental innovation* is the oldest term and its cumulative growth trend presents two clear breakpoints: 2000 and 2007. It seems to be the most established term among the four and it presented a stable growth after 2007. Despite having followed the growth of the other two "less popular" terms until 2009, the use of *eco-innovation* dramatically increased after 2010 – becoming the most used since that year. The other two terms lag behind in popularity; *green innovation* was the most popular in 2013, which might suggest that it could catch up in the coming years. The use of *sustainable innovation* also increased after 2010, but it remains the least used among the selected terms.

Figure 3.1 Cumulative number of the four sustainable terms used as keywords over time



Source: own elaboration.

On a more detailed level, Table 3.1 shows the 10 most important keywords correlated--appearing as keywords with one of the four terms in the same paper--to each of the four sustainable terms, ranked according to their *tf.idf* value. By associating these sustainable terms with complementary keywords, we are able to draw some preliminary differences between their use by the scientific community. For instance, scholars working with eco-design use mostly the term *eco-innovation*, while *environmental innovation* is used by scholars dealing with regulatory and policy effects--worth mentioning is the presence of keyword "ecological modernism" as a reference to the "Ecological Modernization" school of policy research--and Porter-type competitive advantages derived from such innovations.

Sustainable innovation, on the other side, is a term used by scholars working with the more sociologic-driven approaches; these include actor network theory, user-driven innovations, and multilevel perspective. Finally, *green innovation* is related with management and competition issues, since its main correlated keywords are all related with such topics. There are similarities between the terms *eco-innovation* and *environmental innovation*, as both are correlated with keywords associated with quantitative modeling such as "triz", "indic", and "innovation survey", and between *sustainable innovation* and *green innovation*, given that both present high co-occurrence with keywords related to management issues.

Table 3.1 The 10-most important correlated keywords for each sustainable term. The keywords are ranked according to *tf.idf* value.

Environmental innovation		**Sustainable innovation**		**Eco-innovation**		**Green innovation**	
Keyword	*TF-IDF*	*Keyword*	*TF-IDF*	*Keyword*	*TF-IDF*	*Keyword*	*TF-IDF*
porter hypothesi	0,16	ant	0,12	ecodesign	0,20	competitive advantag	0,14
environmental regul	0,14	user-driven innov	0,11	triz	0,15	Environmental manag	0,12
ecological modernis	0,11	partnership build	0,11	sustainab	0,14	corporate environmental manag	0,12
Sustainab	0,10	sustainable business model	0,11	indic	0,11	green supply chain manag	0,11
innovation survey	0,10	multilevel perspect	0,10	environme ntal polici	0,08	sustainable develop	0,09

In the next step, we calculated the association between the sustainable terms and journals. Among the 196 papers, we found 92 scientific journals that contained at least one article with one of the four terms as a keyword. Table 3.2 shows the three most popular journals for each sustainable term. *Journal of Cleaner Production* (JCP) ranks as the most important for all the sustainable terms, and it is the only one to be present--among the first three--in each of them, reinforcing its claimed transdisciplinary nature. Eco-innovation is a term appearing in a relatively higher number of journals (42), which may indicate that its increased popularity after 2010 was the result of its use by different communities. As for the keywords shown in Table 3.1, the journals associated with *sustainable innovation* and *green innovation* reinforce the hypothesis that these terms are mainly related with business and management issues when compared with the other two terms.

Table 3.2 Most important journals. Percentage was calculated as the number of occurrences of a journal on the number of articles in the sustainable term group.

Environmental innovation (31 journals)	**Sustainable innovation (17 journals)**	**Eco-innovation (42 journals)**	**Green innovation (22 journals)**
Journal of cleaner production (22%)	Journal of cleaner production (32%)	Journal of cleaner production (15%)	Journal of cleaner production (21%)
Ecological economics (13%)	Technological forecasting and social change (11%)	DYNA (5%)	Business strategy and the environment (11%)
Research policy (9%)	Business strategy and the environment (7%)	Environmental engineering and management journal (5%)	Journal of business ethics (11%)

We found 406 unique authors in our database. Table 3.3 shows the three most present authors of the four sustainable terms.

Table 3.3 Most present authors. Numbers of publications for each author.

Environmental innovation (119 authors)	**Sustainable innovation (69 authors)**	**Eco-innovation (140 authors)**	**Green innovation (92 authors)**
Rennings, K (6)	Partidario, PJ (2); Smith, A; Quist, J; Boons, F; Tukker, A; Evans, S; Lambert, J	Peiro-Signes, A (6)	Chen, YS (6)
Mazzanti, M (4)		Chen, JL (3); Oltra, V; Ziegler, A; Rammer, C	Chang, CH (4)
Oltra, V (3)			Qi, GY (2); Tseng, ML: Zeng, SX

50 authors have more than one publication using at least one of the four sustainable terms as keywords. 36 of them always use the same keyword for all the publications, while 14 have used two different ones (no one has used three of four different keywords). Table 3.4 shows the number of authors by the use of the different sustainable terms as keywords.

Table 3.4 Number of authors for keywords. Numbers of authors using the different sustainable terms as keywords. Percentage shows the quota of authors - for each keyword - using only a keyword

	Eco	Env	Green	Sus	tot
Eco	**16**	10	2	2	30
Env	10	**8**	0	0	18
Green	2	0	**5**	0	7
Sus	2	0	0	**7**	9
Unique	53%	44%	71%	78%	-

Table 3.4 shows that about half of the authors that use *eco-innovation* or *environmental innovation* as keywords, they also use other sustainable terms as keywords. We found that the combination *eco-innovation* and *environmental innovation* is by far the most relevant, being used by 10 out of 14 authors. Thus, we found that *eco-innovation* is used by all the 14 authors using two sustainable terms as keywords, and that there are no combinations between two of the other three sustainable terms.

Table 3.5 shows the distribution of the sustainable terms according to main authors' affiliation country. Overall, Germany is the country with most scholars, particularly addressing *environmental innovation*, which is not surprising given the tradition by German scholars to study the topics related with environmental policy and regulation; this includes the so-called Berlin School of environmental policy research that is linked to the term ecological modernization[18] (Table 3.1).

Table 3.5 Most important countries. Percentages were calculated as the number of occurrences of a country on the total number of papers using the sustainable term.

Environmental innovation (19 countries)	**Sustainable innovation (14 countries)**	**Eco-innovation (20 countries)**	**Green innovation (12 countries)**
Germany (22%)	England (28%)	Spain (15%)	Taiwan (36%)
France (14%)	Netherlands (21%)	Netherlands (12%)	Australia (10%)
Italy (14%)	USA (7%)	Germany (11%)	USA (10%)

Sustainable innovation is used by scholars coming from English-speaking countries as well as The Netherlands, corroborating the results from Table 3.1, since the latter hosts many well-known academics working with the multilevel

[18] See Mez & Weidner (1997).

perspective and within technological transitions tradition. Again, this analysis shows some similarities between environmental innovation and eco-innovation, e.g. being more Europe-centered. In comparison, *green innovation* is a term used more often outside Europe, although the number of countries in which scholars refer to this term is overall low.

Finally, Table 3.6 lists the five most important references for the papers containing one or more sustainable terms as keywords, ranked by their *td.idf* value. References and citations are traditionally referred by the literature as indicators of interconnection between authors (Bornmann et al., 2008; Moed, 2005; Narin, 1976). Thus, looking at the central references in the four groups might indicate the association of the different sustainable terms with particular strands of literature.

In the case of *environmental innovation*, the most connected reference is the seminal paper by Porter & van der Linde (1995). This corroborates the results of Table 3.1, as it is the origin of the so-called Porter hypothesis. The other references are related to determinants of product and process environmental innovations. *Sustainable innovation* presents references that can mainly be associated with transition theories and systemic thinking, therefore also confirming the results of the co-word based analysis. Also here, *eco-innovation* shows similarities to *environmental innovation*, especially through shared referencing of works by Klaus Rennings and colleagues. In both cases, references point to determinants of eco-/environmental activities, especially in terms of structural and policy characteristics, and are therefore associated with ecological economics literature. Lastly, the term *green innovation* has, among its main references, papers linked to resource-based view, firm's competences, and competitive advantages. Also this is in line with the results shown in Table 3.1.

Table 3.6 Central references for each of the four sustainable terms. The references are ranked according to their *tf.idf*.

Sustainable term	TF.IDF	Reference
Environmental innovation	0,11	Porter, M. E., Van Der Linde, C., (1995). Toward a New Conception of the Environment-Competitiveness Relationship. The Journal of Economic Perspectives, 9(4), 97–118.
	0,10	Rennings, K., Ziegler, A., Ankele, K., & Hoffmann, E. (2006). The influence of different characteristics of the EU environmental management and auditing scheme on technical environmental innovations and economic performance. Ecological Economics, 57(1), 45–59.
	0,10	Jaffe, A. B., Newell, R. G., & Stavins, R. N. (2002). Environmental Policy and Technological Change. Environmental and Resource Economics, 22(1/2), 41–70.
	0,09	Brunnermeier, S. B., & Cohen, M. A. (2003). Determinants of environmental innovation in US manufacturing industries. Journal of Environmental Economics and Management, 45(2), 278–293.
	0,09	Cleff, T., & Rennings, K. (1999). Determinants of environmental product and process innovation. European Environment, 9(5), 191-201.
Sustainable innovation	0,08	Elzen, B., & Wieczorek, A. (2005). Transitions towards sustainability through system innovation. Technological Forecasting and Social Change, 72(6), 651–661.
	0,08	Shove, E. (2003). Converging Conventions of Comfort, Cleanliness and Convenience. Journal of Consumer Policy, 26(4), 395–418.
	0,07	Coenen, L., & Díaz López, F. J. (2010). Comparing systems approaches to innovation and technological change for sustainable and competitive economies: an explorative study into conceptual commonalities, differences and complementarities. Journal of Cleaner Production, 18(12), 1149–1160.
	0,07	Shove, E., & Walker, G. (2007). CAUTION! Transitions ahead: politics, practice, and sustainable transition management. Environment and Planning A, 39(4), 763–770.
	0,07	Hekkert, M. P., Suurs, R. A. A., Negro, S. O., Kuhlmann, S., & Smits, R. E. H. M. (2007). Functions of innovation systems: A new approach for analysing technological change. Technological Forecasting and Social Change, 74(4), 413–432.
Eco-innovation	0,11	Rennings, K. (2000). Redefining innovation - eco-innovation research and the contribution from ecological economics. Ecological Economics, 32(2), 319–332.
	0,07	Beise, M., & Rennings, K. (2005). Lead markets and regulation: a framework for analyzing the international diffusion of environmental innovations. Ecological Economics, 52(1), 5–17.

	0,07	Reid, A. & Miedzinski,M. (2008): SYSTEMATIC Innovation Panel on eco-innovation. Final report for sectoral innovation watch.
	0,07	Hellström, T. (2007). Dimensions of environmentally sustainable innovation: the structure of eco-innovation concepts. Sustainable Development, 15(3), 148–159.
	0,07	Carrillo-hermosilla, J., del Río, P., Könnölä, T., & del Rio Gonzalez, P. (2010). Diversity of eco-innovations Reflections from selected case studies. Journal of Cleaner Production, 18(18), 1073–1083.
Green innovation	0,15	Chen, Y.-S., Lai, S.-B., & Wen, C.-T. (2006). The Influence of Green Innovation Performance on Corporate Advantage in Taiwan. Journal of Business Ethics, 67(4), 331–339.
	0,11	Hart, S. L. (1995). A Natural-Resource-Based View of the Firm. The Academy of Management Review, 20(4), 986-1014.
	0,10	Henriques, I., & Sadorsky, P. (1999). The Relationship Between Environmental Commitment and Managerial Perceptions of Stakeholder Importance. Academy of Management Journal, 42(1), 87–99.
	0,10	Chen, Y.-S. (2008). The Driver of Green Innovation and Green Image – Green Core Competence. Journal of Business Ethics, 81(3), 531–543.
	0,10	Shrivastava, P. (1995). Environmental technologies and competitive advantage. Strategic Management Journal, 16(S1), 183–200.

3.4.2 Sustainable terms at community-level: the cluster analysis results

The second part of the data analysis focuses on cluster identification in the citation network and analysis of detected communities (See Section 3.3). Starting from the 400 items with keywords and references, we obtained 10 major clusters--containing 367 items--with more than two papers. The network was constructed using the bibliographic coupling between each pair of papers in our corpus as explained in the methodological section. The network was then clustered into communities of articles that show strong similarities in terms of shared citation patterns. Clusters with a high number of papers with one or more of the four sustainable terms are assumed to have a thematic association with the respective research field. The results are presented in the Table 3.7.

Table 3.7 Communities related to each of the sustainable terms. The numbers highlighted indicate that the cluster has a high number of papers using that term as keyword.

Cluster	Eco-innov	Environ mental innov	Green innov	Sustainable innov	None of the terms among the keywords	Total terms	% Sustainable terms
A	8	8	**27**	3	33	79	58%
B	7	**31**	2	-	33	73	55%
C	5	8	3	**16**	33	65	49%
D	**16**	-	1	1	19	37	49%
E	4	1	1	2	17	25	32%
F	**11**	-	-	-	13	24	46%
G	**5**	**8**	1	1	8	23	65%
H	**6**	**6**	-	-	8	20	60%
I	-	2	-	-	11	13	15%
J	1	-	1	**2**	4	8	50%

At first, *eco-innovation* is dominant in cluster D and F, *environmental innovation* in cluster B, *green innovation* in cluster A, and *sustainable innovation* in cluster C. Moreover, clusters G and H combine *eco-innovation* and *environmental innovation*, indicating that, for some papers sharing similar characteristics, these two terms are being used by the same communities. We have excluded clusters E and I from the discussion because of the low presence of papers with at least one of the four sustainable terms as keywords (respectively 32% and 15%) and cluster J because of its limited size.

For the eight selected clusters, Appendix 3.1 presents the most important keywords and references, and the following discussion will be based on these results. The *eco-innovation* term has been used in papers addressing issues related with the design of more environmental friendly technologies/products and the evolutionary dimension of environmental friendly innovation. We noticed that the scientific community, which focuses on eco-design, has widely used the term--as shown through both keywords and references from Cluster D--in which eco-design and sustainability are connected to the efficiency dimension of sustainability. The technical perspective of eco-innovation is also confirmed by the technical focus of two out of the three most relevant journals for that term--DYNA and Environmental Engineering and Management Journal; both journals focus on in the area of engineering, technology, and sustainability.

The regulation dimension related to the term is represented by the keywords and references from Cluster F and it is confirmed by the relative importance of authors such as M. Beise, K. Rennings, and R. Nelson. Cluster F includes also many works which theorize the evolutionary approach to innovation and how this approach may contribute to the diffusion of environmental technologies.

The term *environmental innovation* seems to be a mid to strong European placed term which focuses on the Porter´s hypothesis about the impact of environmental policies on competition of different sectors and industries and the determinants of innovation at the industry level, as shown in Cluster B. Clusters G and H demonstrate that, for some scientific communities, *eco-innovation* and *environmental innovation* have been used interchangeably. Cluster G relates the environmental dimension to the evolutionary economics theory, as represented by the central references to some of the most prominent scholars in this approach, including Richard Nelson and Franco Malerba. Cluster H focuses on the ecological modernization and industrial ecology/symbiosis.

The *green innovation* term represents the clearly delineated non-European, management-focused approach for innovation and sustainability, as seen through the strong affiliation with Cluster A. Its focus on the corporate dimension of sustainability is confirmed by the importance of the journals as well as main keywords used; almost all keywords related with some aspect of management and competitive conditions of firms. Lastly, the *sustainable innovation* term has a strong connection with the technological innovation system perspective and the transition approach. The works of René Kemp, Marko Hekkert, Anna Bergek, and Frank Geels are central within Cluster C.

3.5 Discussion

Both the analyses of keywords and communities generated compatible results, which allow us to draw some consistent remarks about the meanings and the use of the four sustainable terms by scientific communities. These remarks are summarized below.

- E*co-innovation* and *environmental innovation* have been used interchangeably by some communities (Clusters G and H), especially those related with evolutionary economics, ecological modernization and industrial ecology/symbiosis. The interchangeability of these terms is also confirmed by the important presence of several authors using these two keywords (table 3.4). The case of Rennings is a remarkable example of the interchangeability of these two terms among some scholars. While he mainly uses *environmental innovation* as keyword, his works are central references for the *eco-innovation* cluster F. However, the popularization of these terms occurred at different points in time, as eco-innovation became widely used only after 2010.
- Scholars dealing with eco-design strongly prefer to use the term *eco-innovation*, as indicated by the exclusivity of the community based within Cluster D. *Environmental innovation* is more strongly associated with regulatory aspects as well as scholars addressing the effects and determinants of such innovative activities (Cluster B). Both terms seem to be used mostly by European scholars.
- S*ustainable innovation* is a system-oriented term, especially related with scholars associated with the transition school (primarily emanating from The Netherlands and The UK) and complex systems. As these approaches carry a stronger sociological component, our analysis confirms the conclusions of Schiederig et al. (2012) regarding the difference between this term and the others.
- *Green innovation* is strongly related to management and competition objectives, as shown by the term's strong association with Cluster A. It is also a term used mostly by scholars outside Europe.

- All the different communities share Journal of Cleaning Production (JCP) as the most central journal. Although the analyses show different meanings and communities, we identified such journals as the platform through which knowledge between different scientific communities is shared.

Finally, we can answer to our main research question: *Do the four sustainable terms carry different meanings?* We found some similarities--especially among eco-innovation and environmental innovation and in the use of JCP. However, such four terms carry different meanings and identify different scientific communities from different traditions, well representing the complexity and the differences in the debate about innovation for sustainable development. Based on these conclusions, we suggest avoiding considering such terms as synonymous, without first considering the context in which they are used.

3.6 Conclusion

We reviewed the peer-reviewed literature about the relationship between innovation and sustainability, looking at the different meanings of four sustainable terms: *eco-innovation, environmental innovation, green innovation,* and *sustainable innovation*. Based on our findings, we can conclude that these sustainable terms focus on different topics and are affiliated with different communities. However, we found that there are some similarities between the terms and the communities, especially in regard to the terms *eco-innovation* and *environmental innovation*. All publications also share a common publication--the JCP--which seems to act as a "hub" for these different communities.

The Kuhnian perspective is confirmed as a valid key to analyze the evolution of knowledge within the scientific community. Innovation for sustainability can be framed as a complex/contested notion in which different scientific sub-communities highlight different visions and interests. The birth of different terminologies can be explained by the richness of debate among scholars. New and old terms are continuously shaped, abandoned, and re-used to highlight continuity and discontinuity with other meanings and with previous branches of research.

The scientific popularity of the different terms may be expected to influence the development of policies for sustainable development. While some terms focus on eco-efficiency, eco-design and other specific eco-performances of any innovation, others may lead to wider societal policies which target the demand side included – for example - users' values and ideologies. For this reason, we find the study of the evolution of terminology and meanings among the scientific community a relevant dimension to understand the overall societal debate about sustainability and the role of innovation.

The boundaries of our analysis offer opportunities that can be targeted by further research. First, we focused on the four sustainable terms used by Schiederig et al. (2012), but during our data analysis, we spotted other terms that may have specific meanings (and communities), such as *eco-efficient innovation*, *low-carbon innovation*, *innovation for sustainability*, *socio-ecological innovation*, and *externality reducing innovation*, among many others. These terms may provide additional knowledge about the evolution of the academic literature and of scientific communities.

Second, since we narrowed the analysis to the scientific peer-reviewed literature; we are not able to explain the societal roots of these terms beyond the scientific communities. The Kuhnian perspective emphasizes the connection between scientists and overall societal dynamics. Yet, our methodology requires standardized keywords and references which cannot be guaranteed if we considered *grey literature* (e.g. industrial magazines, news, and reports from private and public organizations. However, recent developments in natural language processing, such as entity extraction techniques, might allow us to draw on broader collections of literature. Also more efficient normalization of references is gradually allowing for utilization by other larger academic publication databases (e.g. Scopus and Google Scholar).

Given these limitations and opportunities, future research can focus on understanding other remaining questions such as whether these terms and concepts originate within or outside the scientific community or such as the coevolution of these terms between the scientific community and other societal communities.

Appendix 3.1 – Cluster analysis' results

Cluster A ("Green Innovation")		
#	**Keywords**	**References**
1	green innov	Hart, S. L. (1995). A natural-resource-based view of the firm. *Academy of management review*, *20*(4), 986-1014.
2	environmental manag	Chen, Y. S., Lai, S. B., & Wen, C. T. (2006). The influence of green innovation performance on corporate advantage in Taiwan. *Journal of business ethics*,*67*(4), 331-339.
3	sustainable develop	Porter, M. E. (1995). The competitive advantage of the inner city. *Harvard Business Review*, *73*(3), 55-71.
4	innov	Shrivastava, P. (1995). Environmental technologies and competitive advantage. *Strategic management journal*, *16*(S1), 183-200.
5	competitive advantag	Barney, J. (1991). Firm resources and sustained competitive advantage.*Journal of management*, *17*(1), 99-120.
6	eco innov	Klassen, R. D., & McLaughlin, C. P. (1996). The impact of environmental management on firm performance. *Management science*, *42*(8), 1199-1214.
7	sme	Russo, M. V., & Fouts, P. A. (1997). A resource-based perspective on corporate environmental performance and profitability. *Academy of management Journal*, *40*(3), 534-559.
8	green supply chain manag	Chen, Y. S. (2008). The driver of green innovation and green image–green core competence. *Journal of Business Ethics*, *81*(3), 531-543.
9	new product develop	Fornell, C., & Larcker, D. F. (1981). Structural equation models with unobservable variables and measurement error: Algebra and statistics. *Journal of marketing research*, 382-388.
10	environmental polici	Henriques, I., & Sadorsky, P. (1999). The relationship between environmental commitment and managerial perceptions of stakeholder importance. *Academy of management Journal*, *42*(1), 87-99.

Cluster B ("Environmental innovation")		
#	**Keywords**	**References**
1	environmental innov	Lanjouw, J. O.; Mody, A.; (1996). Innovation and the international diffusion of environmentally responsive technology, *Research Policy*, Volume 25, Issue 4, June 1996, 549-571.
2	porter hypothesi	Brunnermeier, S.; Cohen, M. A. (2003). Determinants of environmental innovation in US manufacturing industries, *Journal of Environmental Economics and Management*, Volume 45, Issue 2, 278-293.
3	environmental regul	Jaffe, A. B., & Palmer, K. (1997). Environmental regulation and innovation: a panel data study. *Review of economics and statistics*, 79(4), 610-619.

4	innov	Jaffe, A. B., Newell, R. G., & Stavins, R. N. (2002). Environmental policy and technological change. *Environmental and resource economics*, 22(1-2), 41-70.
5	environmental polici	Popp, D. (2006). International innovation and diffusion of air pollution control technologies: the effects of NOX and SO2 regulation in the US, Japan, and Germany, *Journal of Environmental Economics and Management*, Volume 51, Issue 1, 46-71.
6	discrete choice model	Porter, M. E., & Van der Linde, C. (1995). Toward a new conception of the environment-competitiveness relationship. *The journal of economic perspectives*, 97-118.
7	climate chang	Milliman, S. R., & Prince, R. (1989). Firm incentives to promote technological change in pollution control. *Journal of Environmental economics and Management*, 17(3), 247-265.
8	patent	Johnstone, N., Haščič, I., & Popp, D. (2010). Renewable energy policies and technological innovation: evidence based on patent counts. *Environmental and Resource Economics*, 45(1), 133-155.
9	compet	Horbach, J. (2008). Determinants of environmental innovation—new evidence from German panel data sources. *Research policy*, 37(1), 163-173.
10	environmental management system	Popp, D. (2002). Induced innovation and energy prices. *American Economic Review*, 92, 160–180.

Cluster C ("Sustainable innovation")

#	Keywords	References
1	sustainable innov	Hekkert, M. P., Suurs, R. A., Negro, S. O., Kuhlmann, S., & Smits, R. E. H. M. (2007). Functions of innovation systems: A new approach for analysing technological change. *Technological forecasting and social change*, 74(4), 413-432.
2	innovation system	Kemp, R., Schot, J., & Hoogma, R. (1998). Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. *Technology Analysis & Strategic Management*, 10(2), 175-198.
3	biofuel	Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., & Rickne, A. (2008). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research policy*, 37(3), 407-429.
4	technological innovation system	Rip, A., & Kemp, R. (1998). *Technological change* (pp. 327-399). Battelle Press.
5	strategic niche manag	Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research policy*, 31(8), 1257-1274.
6	coast	Unruh, G. C. (2000). Understanding carbon lock-in. *Energy policy*, 28(12), 817-830.

7	co-evolut	Malerba, F. (2002). Sectoral systems of innovation and production. *Research policy*, 31(2), 247-264.
8	sustainab	Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research policy*, *36*(3), 399-417.
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3	recycl	Janssen, M. A., & Jager, W. (2002). Stimulating diffusion of green products.*Journal of Evolutionary Economics*, *12*(3), 283-306.
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CHAPTER 4

ECO-INNOVATION DYNAMICS AND GREEN ECONOMIC CHANGE: THE ROLE OF SECTORAL-SPECIFIC PATTERNS

by

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ABSTRACT

This paper investigates the features of Green Economic Change processes at the meso-level, the greening of industries. We argue that there is a major research gap in analysing the industrial dynamics of the greening of industries. We posit that, as for "traditional" innovations, it is possible to identify sectoral eco-innovation patterns and that these represent key but neglected factors in the dynamics of green economic change. The paper represents conceptual work and identifies eight specific characteristics of eco-innovation. These form the basis for identifying four core hypothesis which we suggest explain sectoral heterogeneity and identify likely sectoral eco-innovation leaders.

4.1 Introduction

In this paper we aim to discuss the Green Economic Change processes at the meso-level: the greening of industries. We argue that there is a major research gap in analysing the industrial dynamics of the greening of industries. Implicitly it is assumed in most research on sustainability issues and eco-innovation that the greening of industries depends on individual firms' incentives. We suggest that more structural explanations may apply. We posit that, as for "general" innovations it is possible to identify sectoral eco-innovation patterns (Pavitt, 1984), and these represent key but neglected factors in the dynamics of green economic change. Multiple questions arise connected to this complex novel agenda and we offer a first contribution to future research.

The last few years have seen the rise of the 'green economy' as an established albeit still emerging business concept and policy goal (UNEP/ILO/ITUC, 2008; UNEP, 2011; OECD, 2011a). At the firm level, undertaken eco-innovation and complying to environmental regulation has been generally considered an extra economic burden that firms would only apply when forced to by policy measures. A core argument of ecological economics theory and much sustainability research has been that these features represent an inherent characteristic of the capitalistic economy and cannot be changed (Costanza et al., 2006; Daly, 1974, 1993, 1995, 2005).

However, recent developments - particularly the last 5-7 years - towards the greening of the economy has proven these theories wrong and show the need for more dynamic evolutionary economic explanations of this phenomenon. This paper contributes to this, seeking to inquire into the industrial dynamics of the green economy. Our point of departure is that the recent rise of the green economy is more than a novel policy concept but rather reflects ongoing green economic change. We know, however, very little on the scope and nature of the green economy. The industrial dynamics of green economic change are little understood due to the lack of data and theoretical and empirical research in this area.

We argue, that we may characterize the green economic change as a techno-economic paradigm (TEP), but that there are indications that the green TEP will be quite distinct in character and is likely not to follow established patterns of economic long waves and industry cycles (Andersen, 2012). Our starting assumption is that the green TEP is of such a pervasive and systemic nature that it will affect all companies and industries and cause structural change of the global economic system (Andersen, 2012). But as emphasized by evolutionary theory firms and industries are heterogeneous, and they are therefore likely to be affected differently. Our focus, then, is on the adoption and diffusion patterns of green strategies and business practices by companies. In inquiring into the industrial dynamics of the greening of industry the starting question we ask here is how a population of interdependent companies is affected by the greening of the economy? Presuming that both vertical and horizontal industrial dynamics are important for the green economic change (Andersen 1999), in this paper we choose to unfold the neglected horizontal axis and ask further:

A) To which degree do firms go green sector wise?

B) Do a few carrier industries lead the green economic process or is it a more homogeneous process?

C) To what degree do different industries follow the same green development curves?

Overall, we aim to discuss the rate and nature (degree of homogeneity) of the sectoral green economic change. Sub questions are if we can identify sectoral clustering and leaders/carrier industries and discuss which industries will be the winners and losers in the green economic change process.

From an evolutionary economic perspective we may, then, trace how the economy is greening not just company by company, but industry by industry as green business models and green markets evolve, consolidate and diffuse. We expect that the green economic change process as other innovations, will follow a sigmoid (S-shaped, logistic) curve reflecting three phases: 1) The slow adoption by few players in the initial stages of the green economy characterized by high uncertainty and high entry and transaction costs (flat curve), 2) The takeoff phase of green markets as the rate of adoption increases (steeper curve), and 3) the consolidation and saturation phases as the green market(s) matures, producing first slower growth followed by another flattening of the curve. While we presume all industries will be going through these stages, we expect the development paths to differ.

An interesting question is if the green economic processes may deviate in character from 'general innovation' and give rise to novel innovation patterns? Is the friction to eco-innovation so high that the green economic change will not go very far or only affect some industries importantly?

While recognizing that these complex and radical economic change processes involve the co-evolution of many factors none the least the rise of new institutions, our focus here is on discussing possible sectoral patterns in the green economic change only and on providing a framework that may allow empirical testing on a wide scale. The core structural explanatory factors refer, as we shall return to, to the industrial characteristics of the sector as well as its 'environmental sensitivity' (Malaman, 1996).

We argue that the issues raised in this paper may inform us importantly on possible specific conditions for eco-innovation in different industries and explain why it is easier for some industries to go green than for others. The discussion, however, also has wider implications on the dynamics, stages and scope of the green economy, of which we currently know surprisingly little. Looking within industries and investigating the degree to which entire industries are greening may be seen as an important indicator of the maturity of green economic change; on the other hand, looking across industries and inquire into if many or all industries are greening may be seen as an even more important measure of green economy maturity. The paper is contributing more fundamentally to industrial dynamics research of green economic change and to building evolutionary eco-innovation theory.

The paper is structured as follows: in Section 4.2, we shortly provide some theoretical arguments which situate green economic change processes in a techno-economic paradigm setting. We discuss the specificities of eco-innovation and identify seven specific characteristics of eco-innovation. In Section 4.3, we review the main literature on sector-specific innovation patterns and discuss how they could be related with eco-innovation activities. These form an important basis for the last section, where we list a set of key hypotheses on sectoral patterns of eco-innovation. Finally, we bring our conclusions.

4.2 Eco-innovation, TEP and the Green Economy

Essential in evolutionary thinking is the transitory nature of innovation driven competition where entrepreneurial activity by pioneering firms and industries is followed by swarms of imitators leading towards a cyclical economic development (Schumpeter, 1939). These thoughts have been further developed into models of economy-wide techno-economic paradigm changes (TEP), where a major techno-organizational breakthrough leads to long waves in the economy (Freeman, 1991; Perez, 1983, 2010).

The greening of the economy, it is here suggested, should be seen as such an economy-wide techno-economic paradigm change. This has been pointed to be several researchers but not analysed in depth so far, neither conceptually nor empirically (e.g. Kemp and Soete, 1992; Andersen, 1999; Freeman, 1996; Bowen & Fankhauser, 2011; Deif, 2011; Kilbourne, 1998; Jänicke, 2012; Kostakis, 2013; Carlota Perez, 2013), with Mathews (2013) being the most thorough so far. We argue that green economic evolution follows similar dynamics as other cases of TEP but that there are specific characteristics of eco-innovative activities, which make it likely that the green TEP may unfold somewhat differently from the others.

A TEP is characterized by the penetration of novel premises for economic activity which means that each TEP will be distinct and lay the foundations for the next TEP (Perez, 2001; 2009). While some environmental research tend implicitly to presume that eco-innovation and environmental sustainability is the first radical systemic change of the economy this is far from the case. Evolutionary economic research has so far identified four to five successive TEPs (Perez, 1983, 2009; Freeman, 1991; Archibugi, 2001; Freeman and Louca, 2001), with the green TEP as well as biotech and/or nanotechnology as upcoming possible TEPs (Freeman, 1994; 1996; Andersen, 1999; 2012; Perez, 2010; 2013). This discussion emphasizes the cumulative nature of innovation, the longevity of changing direction in technology and the 'creative destruction' and learning it entails in many respects but also of the new opportunities new TEPS represent if recognized timely.

Some argue that behind the TEP discussion lies the notion that each TEP era facilitates the evolution or dominance of a new or distinct type of innovating firms (Archibugi, 2001). Here Pavitt's seminal taxonomy on sectoral patterns of innovation contributes to our understanding of the link between meso and macroeconomic development (Pavitt, 1984). However, the notion of a sector is not so clear cut. The standard definition of an industry is an aggregation of firms with a shared output which operate on similar markets. Typically, an industry is defined according to its principal product, e.g. the automotive industry or the tourism industry. Though many additional categorizations of industries exist, Pavitt's sectoral taxonomy may in fact contribute more to explaining patterns in innovating firms related to changes in the competitive conditions rather than patterns in sectoral behavior (Archibugi, 2001). We tentatively propose that each TEP represents marked changes in the competitive conditions leading to the dominance of distinct types of companies, and that the green economy, or the green TEP, is characterized by a new type of 'value based' competition. In the green economy firms' ability to profile themselves on their environmental performance and to identify the new green business opportunities is becoming a central competitive factor.

Figure 4.1 seeks to illustrate the parallel long term evolution of companies' innovative activities with economic activity. We propose that it is not relevant to identify the core 'carrier industries' of the green TEP given the pervasive nature of this TEP. Rather we argue that it is more relevant to discuss detailed sectoral patterns in eco-innovative activities in the economy in order to understand how the conditions for eco-innovation may vary across industries and over time as more and more firms are caught up by the green economic process. The TEP concept is important none the least as it puts the green economic change into an important historical context and allows us to discuss how the green economy and the related clean tech revolution may possibly effect the industrial organization and favor some type of companies and industries while creatively destroy others. It allows us also to raise the question to what degree the green TEP will rejuvenate the economy and hence represent discontinuity or whether the economic impacts will only be minor.

Figure 4.1 TEP & innovative patterns of industries.

Period	Successive Techno-economic Paradigms	Industrial organization	Typical industries & Innovations	Rise of Pavitt's category of firms
1770-1830	Early mechanization	Growing importance of small manufacturing firms	Textiles, Potteries, Machinery	Supplier dominated
1840-1880	Steam power and railway	Separation between producers of capital and consumption goods	Mechanical engineering, steel and coal	Specialized producers
1890-1930	Opportunities associated to scientific discoveries	Emergence of large firms	Chemicals, Electrical machinery, Engineering	Science based
1940-1980	Fordist and Taylorist revolutions	Oligopolistic competition for mass consumption	Automobiles, Synthetic products, Consumer durables	Scale intensive
1990-200?	Information and communication Economy	Networks of firms, strong user-producer interactions	Microelectronics, Telecoms, Software	Information intensive
2006-	Green Economy, circular revolution	Narrative competition based on social media, circular organization of production and consumption	ICT, nano and biotech, smart systemic solutions	Value based

Source: own elaboration.

At a very basic level, eco-innovations are ‘green’ innovations, that is, any innovations which remedy environmental problems. However, in practice it is quite difficult to capture and delimit what this entails which presents a number of analytical challenges (Andersen, 2006; Arundel, 2009; EIO, 2012; Eurostat, 2009; Kemp & Pearson, 2007). We need a more economic definition in order to understand how green competitiveness is undergoing change over time. Eco-innovation we here define as *innovations that aim to or which create green value on the market* see also (Andersen, 2008, 2012. This definition differs importantly from other definitions of eco-innovation or ’sustainable innovation’ as it is often refered to, by emphasizing economic rather than technical aspects. The definition captures two key issues of green economic change: A) when firms consciously pursue eco-innovation strategies and B) when the market recognizes a green product or rewards a companies’ green profile. Also, it is a dynamic definition, recognizing that greening is a moving target (Kemp and Soete, 1993; Kemp, 2010; Kemp and Andersen, 2004; Andersen, 2006), in contrast to more absolute definitions.

It goes beyond this paper to go into further discussion of eco-innovation definitions and taxonomies. Rather we focus instead of bringing a list of core characteristics of eco-innovation which provide important inputs for the theoretical discussion afterwards. We propose that eco-innovations are characterized by[19]:

C1. Being extraordinarily systemic (value chain/life cycle assessment, recycling, SCP).

C2. Having unusually high information costs (credence characteristics, relativity, complexity).

C3. Having a strong normative element (inherently good to be green).

C4. Being more open than ’general’ innovations.

[19] See also Andersen (2008) for a previous version.

C5. The environmental potential is in part technology dependent.

C6. The technical infrastructure and physical planning is important.

C7. Policies such as regulations and fiscal incentives are extraordinarily important.

C8. The carrying capacity/resilience of the local biosystem matters.

Before discussing these in more detail, let us comment briefly on the implications of this for our discussion on the dynamics of sectoral eco-innovation and its relation to the rate and direction of green economic change, including to which degree we might expect greening to be a homogenous trend versus a more heterogeneous one. The effect of these characteristics is that there are induced and related innovations vertically as well as horizontally which lead to expansionary processes, as more and more firms are pulled into the green economic process (Andersen, 1999, 2012). There are thus strong multiplier effects to green economic change. But another central effect of the characteristics, on the other hand, is very high dynamic transaction costs to greening, particular in the early phases (Andersen, 1999).

We may conclude from this that two reciprocal but related processes are at work. The first is related to the latter argument, stating that there is much friction to eco-innovation, supported by the lock-in into none green practices, strategies, capabilities and mind-sets that have persevered for 50 years (since the start of environmental regulation in the 1940-50s), which is well documented in much empirical eco-innovation research (Kemp & Soete, 1990; Kemp, 1994; 2009). This should lead to a long gestation period and a slow heterogeneous move up the green S-curve where the green laggard industries function as bottlenecks to green economic change (Andersen, 1999).

The former argument, on the other hand, should entail a relatively fast homogenous move up the green S-curve, as companies, supported by widespread policies, relatively fast pull each other into the green economic process. Realizing that both arguments hold some relevance, further theoretical and empirical argumentation is needed.

4.3 Industrial characteristics and eco-innovation

The selection environment in which firms are subject when innovating is a complex structure of specific technological, socio-economic and institutional configurations and tend to be characterized by relatively invariant and path-dependent *routines.* These arise as a response to persistent uncertainty, risk, learning patterns, and technological characteristics that are inherent to innovative activities (Arthur, 1989; Dosi, 1982; Dosi & Nelson, 1994; Nelson & Winter, 1977, 1982).

Many scholars have argued how some elements of selective environments – e.g. innovation sources, demand and technology characteristics and institutions - are constrained by sectoral boundaries, indicating that firms could be subject to some convergence along sectoral patterns of innovation (Nelson & Winter, 1982; Pavitt, 1984; Winter, 1984; Breschi & Malerba, 1996; Klevorick et al., 1995; Malerba & Orsenigo, 1993, 1997; Malerba, 2002). Following this argumentation it is likely to presume that some level of sectoral convergence related to green economic change processes could be observed.

The interplay between the established, complex sectoral structures and the eco-innovation core characteristics presented above we see as the key factors that could generate sectoral patterns of eco-innovation. As a simplification of a vast number of variables, we divide the industry characteristics into three dimensions, namely technological, competitive/market, and institutional characteristics and discuss these while clarifying the eight characteristics further below.

4.3.1. Technological characteristics

The effort required to make the transition towards “green strategies” will differ across sectors as some industries’ production is more polluting, or otherwise environmentally damaging, than others, being this is a key feature of the 'environmental sensitivity' of a sector (Malaman, 1996). Naturally, these technological features are not given but are subject to institutional change, as policy makers shift environmental goals and policy instruments over time and space. While the technology base also influences on the (possibly green) product features, we will discuss this further in section 4.3.2 on market characteristics. The production process has been at the core of environmental regulation and the heavy pollution industries have been those industries subject to earliest and strictest regulation (Cole, 2000), while less polluting and service industries have not been subjected to the same degree of policy pressure (Carrión-Flores and Innes, 2010).

Nevertheless, some industries technologies happen as a starting point to have a better fit to environmental goals than others. Others are fortunate to have suppliers or customers with strong green capabilities, which facilitates their greening, e.g. it is a lot more demanding for producers of pesticides, PVC and petrol to eco-innovate than producers of wood based houses, polyester or paper. Even though the paper industry has been very polluting (and still is in many parts of the world), the bio-based product can easily come to appear green, also facilitated by the historic tradition for making recycled paper. Small window producers may benefit from the strong green capabilities of their big glass producers in making energy efficient windows etc.

Finally, the literature also points out the specificities of non-manufacturing sectors, following similar ideas applied to non-environmental innovations (Castellacci, 2008; Evangelista, 2000). According to Cainelli & Mazzanti (2013), service industries are subject to less strict environmental regulations and economic instruments because of their relative low impact on the environment, and these differences could impact the eco-innovation performance. They found that "(…) the drivers of EI [environmental innovation] differ across service industries, with an important role played by cooperation, training, environmental management systems and public funding" (p. 1602).

Some researchers argue that there is a link between being innovative and being green. E.g. Carrión-Flores & Innes (2010) analysed 127 manufacturing industries and concluded that eco-innovation intensity is statistically greater in research intensive sectors. Others argue that eco-innovations in general tend to rely more on external sources of knowledge and information compared to other innovations (Belin et al., 2009; Horbach et al., 2012; Rennings & Rammer, 2011), and others, which may explain the former, that firms that realize eco-innovations are more likely to cooperate with other actors (Andersen, 1999; Cainelli et al. 2010).

Because environmental issues have been historically regarded as marginal concerns along existing techno-economic paradigms, it is expected that, in order to achieve their environmental goals, some sectors would have to radically change their technologies and consequently their core technological capabilities. In these sectors, eco-innovations tend to be more complex and rely on different knowledge sources (Horbach et al., 2012). These features may though be cross sectoral more than sectoral even though we know some sectors are more research intensive or innovative than others (Pavitt, 1984).

These findings give support to eco-innovation characteristics C1, C2, C4, and C5. However, we argue that this is not true for all sectors: it depends on the "fit" between existing technological characteristics and capabilities and environmental goals, both subject to sectoral specificities. Moreover, such fit tends to be unstable over time, since both industrial characteristics and environmental sensitivity are in constant change. In this sense, we agree that opportunities and pressures related with eco-innovations are specific to each technological regime (Belis-Bergouignan et al., 2004; Berkhout, 2005; Hansen et al., 2002).

4.3.2 Firms, Competition and market characteristics

The competitive conditions also have an impact on eco-innovations' dynamics. Rothenberg & Zyglidopoulos, (2007) discuss two dimensions of competitive conditions affecting eco-innovative activity. First, sectors characterized by highly competitive conditions and low munificence - the capacity of sustaining resources (i.e. demand, natural and financial resources) for one or more firms to survive and growth - tend to develop a short-term mentality and avoid experimentation along technologies for which firms do not possess capabilities, as the amount of resources available must be invested in critical areas of operation (Zyglidopoulos, 1999). In this sense, firms operating in such environments are expected to avoid investing in eco-innovations that do not offer competitive advantages on the short-term. On the other hand, high munificence conditions open space for long-term technological planning, including investments in eco-innovations (Carter & Dresner, 2001). Secondly, highly dynamic markets (which bring uncertainty about future competitive and technological conditions) induce firms to consider alternative technologic pathways (Buchko, 1994), making them more open to invest on eco-innovation development (Aragon-Correa & Sharma, 2003; Koberg et al., 2003).

Several studies point out the positive effects of firm size on eco-innovation opportunities through, for instance, their access to higher amounts of financial and human resources, their existing innovation capabilities and competences, as well as their brand and access to networks (Rehfeld et al., 2007; Greening & Gray, 1994; Brunnermeier & Cohen, 2003). Others emphasize that sectors less concentrated and/or with smaller firms tend to be more flexible and open to new technologies, and oligopolistic structures are more able to influence policymakers to adopt loose environmental regulations (Carrión-Flores and Innes, 2010).

The capital intensity also has a relationship with eco-innovation activities depending on the sector characteristics. In mature industries, the intensive use of durable and capital intensive assets lead to inertia and resistance to change towards greener technologies, since firms have few economic incentives to invest in new assets, being the rate of innovation dependent on their normal depreciation (Markard, 2011). In expanding sectors and in those where capital assets are older and/or inefficient, however, it is likely that capital intensity holds a positive – albeit temporary – effect on the greening of the industry, since the investment in new production and support infrastructures can be used to diffuse eco-innovations (Carrión-Flores & Innes, 2010; del Río *et al.,* 2011; see also Chapter 6).

Fankhauser et al., (2013) suggest that the competitive advantages that some sectors and/or countries have today may be not sufficient in the future, as many of them "(…) lag behind in terms of green conversion" (p. 902). However, the existing market shares and capabilities can play an important role to firms green competitiveness. For instance, they found that some sectors (i.e. engines and turbines, and motor vehicles) present a positive relationship between eco-innovation and existing, country-specific competitive advantages – so far, highlighting the role of the existing sectoral structure to foster eco-innovation activity. In these sectors, they expect no major changes on competitive structure as result of "green conversion". In other sectors, such as energy production, storage and distribution, however, relatively weak players from South Korea, the UK and US – which however have strong eco-innovation capabilities – could be able to be leaders in the future.

4.3.3. Institutional characteristics

The role of institutions - especially regulations and wider policy instruments – on eco-innovation activities is probably the most well studied dimensions of the eco-innovation literature. The Porter hypothesis (Porter & van der Linde, 1995) refers on how "…properly designed environmental standards can trigger innovation that may partially or more than fully offset the costs of complying with them" (p. 98). Other factors discussed in the literature include the effects of anticipation of future regulation and regulatory stringency on the generation of eco-innovation opportunities (Ambec et al., 2013; Jaffe & Palmer, 1997; Nameroff et al., 2004).

However, little is said about the role of sector-specific institutions on eco-innovation activity. As Dolata (2009) states, however, institutionalized mechanisms can exert important effects on technological change: "while some sectoral systems and its established actors may, at an early stage, ignore and underestimate even serious technological challenges, others may possess institutionalized mechanisms that even facilitate path-deviant transformations." (pp. 1067). But the degree to which different industries are subject to sector specific policies has not really been analysed. As already said, much empirical research shows that the heavy polluting industries are subject to targeted environmental regulations.

Also, the role of internationalization and export-intensity on eco-innovation is related to the institutional context. This theme still remains controversial. Some scholars highlight that less export-intensive industries are likely to be more eco-innovative, since regulations tend to be stronger in nationally protected and regulated sectors such as energy production and distribution (del Río et al., 2011). Others emphasize that internationally competitive corporations may have to deal with distinct environmental regulations depending of the country or regions, and therefore are more prone to adopt environmental management and sustainable design practices throughout the whole organization (Brunnermeier and Cohen, 2003).

Furthermore, new organizational configurations can emerge from the investment in eco-innovations: according to Horbach et al. (2012), eco-innovative activities are related with new forms of labour organization and supply chain management. Also in this case, sectoral patterns can generate different results: Marin & Mazzanti (2013) argue that the relationship between environmental efficiency and labour productivity - one of the main sources of both economic and environmental gains that characterizes the concept of eco-innovation adopted here - differs across manufacturing sectors, "(…) underlining different eco-innovation opportunities of different branches, different reactions to [policy] events and different structural changes in production and energy processes" (p. 40).

Finally, the literature also points out the specificities of non-manufacturing sectors, following similar ideas applied to non-environmental innovations (Castellacci, 2008; Evangelista, 2000). According to Cainelli & Mazzanti (2013), service industries are subject to less strict environmental regulations and economic instruments because of their relative low impact on the environment, and these differences could impact the eco-innovation performance. They found that "(…) the drivers of EI [environmental innovation] differ across service industries, with an important role played by cooperation, training, environmental management systems and public funding" (p. 1602).

4.4 Hypothesis on sectoral eco-innovation

In this section we provide an integrated view of the interplay between industry characteristics and sectoral environmental sensitivity in formulating core hypothesis on sectoral eco-innovation. We refer to the above eco-innovation characteristics by their numbers, e.g. C1, C4.

Earlier it has been argued that the greening process is an unusually uneven economic process (Andersen, 1999). In an early quite pioneering empirical quantitative study on eco-innovation in Italy, Malaman argued that different sectors are characterized by differences in their 'environmental sensitivity' (Malaman, 1996) which he saw as related to the degree of environmental impact from their production process, fitting to C5. The more polluting industries are seen as the more environmental sensitive as they are subject to more environmental regulation (see C7). While this argument is well supported by other research (Arora & Cason, 1996; Fukasaku, 2005; Hitchens et al., 1998; Lopez & Montalvo, 2012), we would like to expand the notion of sectoral environmental sensitivity to include more parameters.

Our argumentation reflect in part a more nuanced perspective on eco-innovation but also the present more mature stage of the green economy compared to the case in the mid-1990s when Malaman's paper was written and the greening of the economy was in a very early stage of development. While regulation is a core driver particularly of early phases of eco-innovation (see C7) reputation, or green branding of the company or specific products, is an important driver of market driven eco-innovation (see C3).

Related to this we suggest to include positive green business opportunities among the environmental sensitivity argumentation and focus not only on process eco-innovations but also product eco-innovations. Some industries technology base, capabilities and products happens to be more environmentally benign than others (also related to C6 and C8). This may, though, not be in any absolute sense but is also subject to change as the green agenda and the institutions supporting and defining it changes over time, an important issue when interpreting C5. E.g. in the

1990s recycled board based packaging became a green product relative to PVC packaging. In the 2000s the production of wood houses is considered a green product which it was not ten years ago as the current ‘circular economy’ agenda emphasizes bio-based products, resource efficiency and recovery (Andersen, 2012).

In suggesting hypothesis for explaining sectoral patterns of eco-innovation we are, as stated, looking for possible structural explanations rather than emphasizing the agency of individual companies, which matters too of course in realizing green business opportunities. We suggest the following core hypotheses (there are a number of other less important not included here) the argumentation being based primarily on a theoretical understanding of eco-innovation and green distal dynamics:

The most environmentally sensitive industries, which are likely to be the pioneering and or most green industries are (three of them with a subcategory):

1) The most polluting (technological characteristics)
    a. Industries with a green reputation problem

2) Industries with many large companies (resources, brand)
    a. Industries with long term strategies (capital intensive)

3) Industries whose products are ‘evidently’ green
    a. Industries where early green market standards are in place

4) Industries close to the consumer/with life style products (reputation)

Ad 1. We argue that the most polluting industries are among today’s green leaders. This is largely a technological characteristic as some industries are inherently more polluting than others. Indeed changing the technology base into something environmentally benign is a core challenge for all industries in the green economy but easier to achieve for some industries than others. The long exposure to environmental regulation has caused long term learning and capability building, often including the introduction of environmental management systems, certified LCA, environmental accounting etc., which the industries less subjected to regulation have not experienced. Some industries have additionally experienced severe green reputation problems which either may lead to defensive or (sometimes later) proactive green strategies, the latter representing a more mature stage of green economic change. Examples are the oil production industry investing in renewable energy technologies lately, comprehensive eco-innovation in the chemical industry, the paper industry becoming a leader in circular eco-innovation, and the automotive industry innovating to shift the automobile reputation.

Ad. 2. Industries with many large companies are among the green leaders. The big companies are core green eco-innovators and market makers because they have the sufficient extra resources to undertake the demanding work, compare the high information and transaction costs related to C1 and C2. Also they have the largest reputation need, compare C 3. The big companies have to invest heavily in green standards and certifications to verify their green credibility which are key processes in the green economic change. Additionally, the biggest companies tend to dominate the most capital intensive industries which typically have long term strategies, such as pharmaceuticals, which are well aligned with the inherent long term thinking behind green strategizing. Examples are the pharmaceutical biotech and glass industry.

Ad. 3. Industries whose products are 'evidently' green or where early green market standards are in place are among the green pioneers and leaders. This argumentation is related to the still considerable problem of market penetration for green products. Green markets are often still poorly functioning (Andersen, 1999, 2012). The industries whose products appear evidently green or which are recognized as green icons, e.g. the bicycle, recycled paper, windmills, have "easy" conditions for product eco-innovation and green marketing. Some industries are lucky (though some also invest themselves in making these) that green information standards are well developed, e.g. in personal care products and energy efficient devices which are among the most eco-labelled products. However, green market information standards are lacking in many other product areas such as in construction, compare C2, and C3. Good conditions for green marketing is important to avoid being accused of ‘green washing’, particular in an industry for which there have been scandals such green washing.

Ad. 4 Industries close to the consumer or with life style products typically have more attention to product eco-innovations such as personal care products food, hotels and electronic equipment, compare C3.

These four core hypotheses emphasize four core different aspects we argue are key to sectoral eco-innovation dynamics. Ad 1., the most polluting refer to the greening of the production process which is where the whole green regulation agenda started and is still centred. Ad 2, the large company argument, refer to the organizational changes related to green economic change where the rise of big companies have been key to the emergence of environmental management and later eco-strategizing and green supply chain management practices. Ad.3, the evidently green products, brings attention to product eco-innovations and their dynamic and context specific features. Finally ad.4, the close to the consumer argument highlights the position in the value chain and the character of products as being significant.

We intend to test these hypotheses empirically. As already touched upon there are both vertical and horizontal eco-innovation dynamics at work, the stronger the horizontal dynamics are relative to the vertical dynamics the more we will see sectoral eco-innovation patterns. Also, the more mature the green economy, the less pronounced the sectoral patterns will be.

4.5 Conclusions

Aligning with evolutionary economic theory which argues that some elements of selection environments are constrained to some degree by sectoral boundaries, this paper has posited that, as for "general" innovations it is possible to identify sectoral eco-innovation patterns, and that these represent key but neglected factors in the dynamics of green economic change. We offer a conceptual clarification and a first set of core hypotheses.

The paper identifies eight specific characteristics of eco-innovation which form the basis for identifying four core hypotheses which we suggest may explain sectoral heterogeneity and identify likely sectoral eco-innovation leaders. The most environmentally sensitive industries, which are likely to be the pioneering or most green industries, are (main groups only mentioned here):

1. The most polluting (technological characteristics).
2. Industries with many large companies (resources, brand).
3. Industries whose products are 'evidently' green.
4. Industries close to the consumer/with life style products (reputation).

It is not the suggested hypotheses that are most interesting in this paper, certainly other hypothesis could be suggested, but the research questions and argumentation lying behind them, none the least the eight specificities of eco-innovation. We propose to look at structural explanations rather than agency in explaining eco-innovation and suggest that unfolding the meso level can provide important understandings of green industrial dynamics so far little researched. Much more attention has been placed so far on the vertical greening dynamics than the horizontal. We do not question that vertical eco-innovation dynamics are important but we argue that the horizontal dynamics also play a role and that these have been severely neglected,

Many of our arguments run contrary to existing well-recognized conclusions in eco-innovation and wider sustainability research. E.g. that highly polluting industries are the green leaders rather than villains, that large companies rather than small or new are heading eco-strategizing and green capability building, and that there to some degree are structural explanations to green market penetration and not only good green business models.

We have sought to frame the eco-innovation and green economy concept in a different way treating the company as eco-innovator rather than as polluter, and emphasizing the importance of the changing firm-market (green) learning process over time. We link up the micro, meso, and macro foundations for understanding the evolution of green technical and organizational change and the interrelations with the context that shape the rate and direction of innovation. We propose, in short, to present some important determinants of green economic change. These arguments, and the empirical research that will hopefully follow up on this, are important for a better and more nuanced discussion of green industrial dynamics but also for understanding the stage and scope of the green economy.

CHAPTER 5

SECTORAL DYNAMICS AND TECHNOLOGICAL CONVERGENCE: AN EVOLUTIONARY ANALYSIS OF ECO-INNOVATION IN THE AUTOMOTIVE SECTOR

by

Lourenço Galvão Diniz Faria and Maj Munch Andersen

ABSTRACT

With few notable exceptions, the origins, dynamics and extent of sectoral "greening" over time remain little understood in empirical terms and even less as part of an evolutionary process of technological change. By analyzing all patents granted to a selected sample of major automotive firms, the paper undertakes an analysis of the breadth and strength of the greening in the automotive sector from 1965 to 2012, focusing on changes in three specific aspects: 1) the concentration of green patenting; 2) the convergence/divergence of firms strategies; and 3) the participation of alternative technologies on the total patenting activity of the sector. 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 some findings in the literature, we do not observe a substantial decrease in investments following the end of the so called technological 'hypes', nor the concentration on one specific technology at a time, but the development of all green technologies simultaneously. We see these findings as evidence that the industry is greening.

5.1 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, 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), and hardly any focus has been given so far to broad sectoral patterns of eco-innovation (Andersen & Faria, 2015; Oltra & Saint Jean, 2009a).

Using one case, the automotive industry, this paper aims to investigate empirically the dynamics and scope of eco-innovation activity in a broad, sectoral level. More specifically this entails inquiring into the degree which we observe the convergence/divergence of firms' technological strategies towards selected green technologies.

Our methodology consists of the application of two specialization indexes to test the hypotheses related with the sectoral convergence to all patents from a selected group of major automakers at the Derwent World Patent Index database from 1965 to 2012, allowing us to analyze from the initial phase of eco-innovation emergence to recent years, and recognized the patents related with green technologies using the recently developed IPC Green Inventory and the OECD's list of Environmentally-sound technologies (EST).

The automotive industry is chosen as a case due to several reasons. Firstly, automobiles and the automotive industry are essential for the functioning of modern societies, but the sector imposes enormous costs in terms of environment harm and intensive use of nonrenewable resources; not only from the production process (as for chemicals, paper, steel, cement and others) but also from the product utilization (MacKenzie and Walsh, 1990). Driving a car has been a symbol of unsustainable consumption for decades and the automotive industry has been considered a 'dirty' industry (Lowe, 1990; Nieuwenhuis & Wells, 2003; Parry et al., 2007; Cole, 2000; Jänicke et al., 1997).

Moreover, the green product technologies can be easily recognized since predominately they are related to major changes in the main components of the motor: the powertrain. It is therefore an example of an industry with distinguishable product eco-innovations, which enables an interesting 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 other findings in the literature, we do not observe a substantial decrease in investments following the end of the so called technological 'hypes', nor the concentration on one specific technology at a time, but the development of all green technologies simultaneously.

Apart from contributing to these empirical 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 (Arundel & Kemp, 2009; Fukasaku, 2005; Horbach et al., 2005).

5.2 Evolutionary eco-innovation dynamics and the role of green technologies in the evolution of automotive sectoral change

The automotive sector has been traditionally pointed out as one of the clearest examples of a technologically mature industry (Abernathy & Clark, 1985; Aggeri et al., 2009; Cooper, 2011; 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 and Wells, 2007b).

In recent years, however, many important transformations on technological regimes and institutions in the automotive sector are taking place, some with potential to challenge the current dominant design, including the incorporation of microelectronics and information and communication technologies[20] (Leen and Heffernan, 2002; Seidel et al., 2005), the growing pressures to generate energy efficient products, as governments and users are increasingly aware[21] of the negative externalities in terms of environment harm and intensive use of non-renewable resources associated with automobiles. Moreover, the dependence on imported fuel, the instability of oil prices, and increasing exploration costs for new oil fields put additional pressure for automakers to develop energy efficient automobiles as quickly as possible (Nieuwenhuis and Wells, 2003; Parry et al., 2007).

The existing literature has focused mainly on discussing and proposing solutions for the so called socio-technical issues that are source of much of the inertia that characterizes this transformation, including the effects of standards (Brown et al., 2010), financial incentives (Sierzchula et al., 2014), economic viability (Kihm and Trommer, 2014), consumer attitudes and perceptions (Egbue & Long, 2012), among others. It often presents a pessimistic or reactive view about the role of firms in creating and taking advantage of green rents, focusing to a high degree on policy effects and the role of government as the main agent of change (see also Penna & Geels, 2015; Djik & Yarime, 2010; Steinhilber et al., 2013; Sierzchula et al., 2012).

Some of their relevant findings indicate that there were interspersed periods of excitement and disappointment ("hypes") towards automakers' investments in

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[20] 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).

[21] 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/.

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. 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 a hydrogen or fuel cell hype – and shifted again towards hybrid and battery electric technologies by the end of the decade (Bakker et al., 2012; Bakker, 2010a; Penna & Geels, 2015; van den Hoed, 2005).

From this point of view, there is technologies would 'compete' with each other and the outcome is presumably the dominance of one technology over the others through successive transitions based on the level of technologic complexity (Bakker, 2010b; Chanaron & Teske, 2007; Hoed & Vergragt, 2006; Pilkington, 2004). As an example, some authors believe in multiple transitions from ICE to EV led by hybrid vehicles as intermediate solution, and then followed by full battery electric vehicles (Brown et al., 2010; Steenhof & McInnis, 2008).

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, 2009b; Wells & Nieuwenhuis, 2012; Sierzchula et al., 2012), acknowledging the importance of gradual improvements that can take decades and are above the "hypes" (Rosenberg, 1976; Patel & Pavitt, 1997).

By focusing on the general effects of regulation, policymaking, and hype cycles, scholars miss the role of emerging sector-, region- and firm-specific elements that can shape the overall eco-innovative dynamics - including the effects of regulations - over time. Our analysis aims to contribute to this important – albeit neglected – dimensions of the green economic change, looking at the formation of sector-specific patterns of eco-innovation over the past decades.

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, 1997; Klevorick et al., 1995; Malerba & Orsenigo, 1993, 1997; Malerba, 2002; Nelson & Winter, 1982; Pavitt, 1984; Winter, 1984, Dosi, 1988).

The strength and range of sectoral patterns of innovation is relative, as other dimensions also affect innovative activities (Peneder, 2010). 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, reflected in innovation strategies (Barney, 1991; Clausen, 2013; Cohen & Levinthal, 1990; Dosi et al., 1997; Fagerberg, 2003; Leiponen & Drejer, 2007; Peneder, 2010; Teece & Pisano, 1994; Teece, 1980).

The evolutionary literature also points how country-specific and region-specific characteristics could play an important role in defining firms' innovative strategy (Asheim and Gertler, 2006; Cooke et al., 1997; Freeman, 1988; Lundvall, 1992; Patel and Pavitt, 1997). Likewise, 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 and Pavitt, 1997), and firms may develop technological competences by using local resources and spillovers (Patel and Vega, 1999).

We trace the emergence and diffusion of eco-innovative activities within the automotive sector over time to understand how overall greening movement is reflected in firms' technological strategies. Our objective is to test the existence of a converging movement of automakers' strategies over time as indicative of emerging sectoral patterns of eco-innovation, similar to the sectoral innovation patterns pointed by the literature. 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 and Pavitt, 1997). For that, we test two hypotheses:

H1a: The sector presents a comprehensive reduction of concentration of green patenting activity over time.

H1b: The sector presents an increase or maintenance in levels of concentration of green patenting activity in the sector over time.

To strengthen the analysis, we also test if the potential convergence is based on a common portfolio of green technologies. In the opposite case, we would observe heterogeneous groups with different eco-innovation strategies.

H2a: The convergence of automakers' green technological strategies is characterized by a common portfolio of green technologies.

H2b: Automakers' green technological strategies are not similar, indicating that heterogeneous groups of firms pursue different strategies.

The hypotheses H1a and H2a can be interpreted as indications of increasing collectively perceived technological opportunities and decreasing risks associated with eco-innovations, and therefore a sectoral convergence and emerging sectoral patterns of (eco)innovation based on multi-technology development (Malerba & Orsenigo, 1997; Pavitt, 1998), while the hypotheses H1b and H2b would indicate that eco-innovation strategies have other determinants, such as firm-specific or geography-specific elements (Clausen, 2013; Leiponen and Drejer, 2007; Patel and Pavitt, 1997; Peneder, 2010).

Lastly, we also check a third, complementary set of hypotheses related with the breath of the greening of the automotive sector. They are related to the importance of alternative technological trajectories (i.e. fuel cells, electric motors) to the overall green patenting activity in the sector over time. Accordingly,

H3a: Alternative trajectories (in relation to the dominant design) are becoming increasingly responsible for the growing of green patenting activity within the sector.

H3b: Alternative trajectories (in relation to the dominant design) have a small effect on the growing of green patenting activity within the sector.

5.3 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 (Blind et al., 2009; Chang, 2012; Haupt et al., 2007; 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 (Archibugi & Planta, 1996; Basberg, 1987; Breschi et al., 2003; Comanor & Scherer, 1969).

We selected a group of major automakers to represent the sectoral activity in the sector, therefore combining several firm-level analyses to construct a picture of the eco-innovation activity at the sector (Ernst, 2001). In fact, this method excludes some relevant actors such as new automakers, suppliers, universities and research centers. However, we believe 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 (Malerba & Orsenigo, 1997; Pavitt, 1984).

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. To avoid low-quality patents, we selected only granted patents filled on European Patent Office (EPO), US Patent Office (USPTO), and World Intellectual Property Organization (WIPO).

Instead of using keywords to define each technologic group of patents as usual (Frenken et al., 2004; Oltra and Saint Jean, 2009b), we adopted selected International Patent Classification (IPC) codes related with identified "green patents" in different technological fields, since many green technologies may not present keywords such as "hybrid vehic*" or "fuel cell" in their patents' titles and abstracts. To identify the codes related with each technology, we used the recently developed IPC Green Inventory and the OECD's list of Environmentally-sound technologies (EST) (See Appendix 5.1).

We selected three main (green) technological areas to analyze in this paper: Internal Combustion Engines' (ICE) green technologies (Post combustion and Integrated emissions controls, reflecting predominately the incremental innovations towards more energy efficient and cleaner power trains); Hybrid and Electric propulsion systems; and Fuel cells' electric propulsion systems. We also included a group of so called *complex patents*: since every patent can be attributed with more than one IPC code, some patents have codes associated with two or more groups of technologies (e.g. fuel cells and electric/hybrid, or fuel cells and ICE green). The presence of complex patents indicates the "cross-fertilization" between two or more technologies.

The sample of firms was chosen based on two requirements: 1) the automaker must be listed on OICA's World Motor Vehicle Production ranking 2012[22]; and 2) the number of patents filled on the selected patent offices must be of at least 500[23] up

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

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

to 2013. Based on these criteria, We selected 17 car manufacturers based on sales performance and patenting activity 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. The chosen car manufacturers are all multinational companies with considerable R&D expenditures, even though the degree of patenting activity varies somewhat (See Table 5.1).

Table 5.1 Descriptive data (1965-2012)

	Total Patents	ICE green	Electric/ Hybrid	Fuel cells	Complex patents
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
VW	6026	773	230	54	119
TOTAL	*144931*	*20879*	*9138*	*5669*	*4609*

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 (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 patent portfolio 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, 2010), 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.

We also adopted a normalized Relative Technologic Specialization Index derived from Relative Specialization index (Balassa, 1963; Brusoni & Geuna, 2005; Debackere & Luwel, 2005; Nesta & Patel, 2005; Pavitt, 1998; Soete, 1987), in order to measure the evolution of firms' trajectories on the specified green technological areas. 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 and Patel, 2005):

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

In order to linearize and attenuate the effects of the largest patentees in our sample (such as Toyota, Honda, and General Motors, see Table 5.1) on the average portfolio, we transformed each P_{ij} using natural logarithms, thus $P_{ij} = \ln(1 + P_{ij})$.

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 and Patel, 2005).

5.4 Data analysis

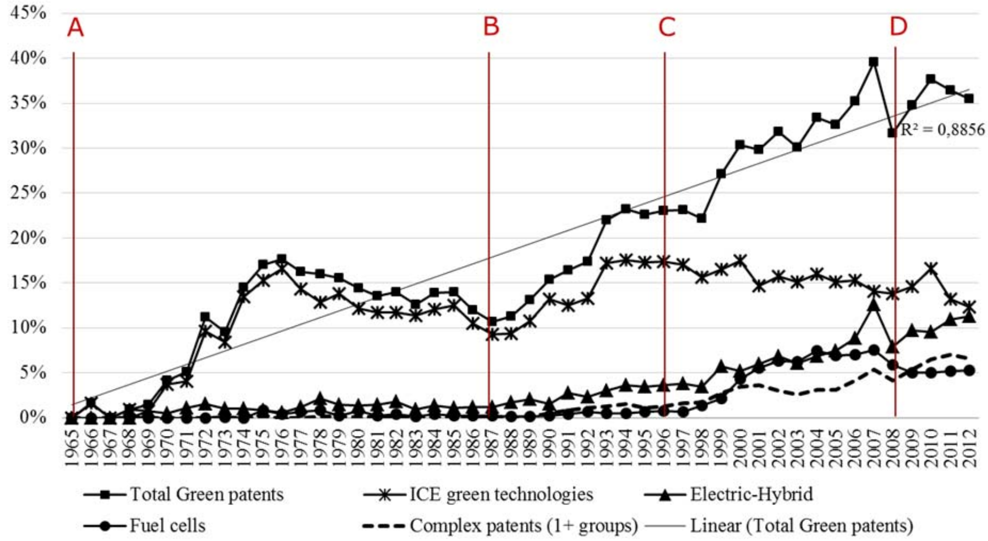
5.4.1 Evolution of green patenting in the automotive sector

The evolution of green patenting as a share of total patenting in our sample (Figure 5.1) 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. 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).

Figure 5.1 Green patents' production as % of total patenting activity in the sample



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 and 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).

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)[24]. 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 Vehicles (ZEV I) Program[25] 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 5.1), since most automakers remained reluctant to invest heavily in such risky alternative technologies[26].

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*

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

[25] 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

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

green patenting in this phase was caused solely by the growth of patenting in alternative technologies, such as electric/hybrid and fuel cells (Figure 5.1).

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.

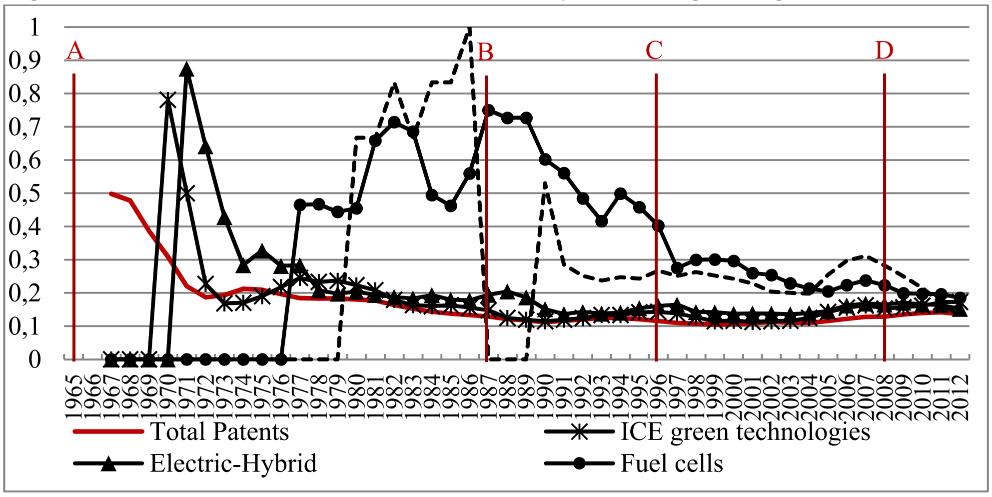
Finally, the last phase (2008-2012) consists of the immediate effects of the crisis (e.g. profit reduction, cost cutting), the reduction of financing to hydrogen-based fuel cell program in U.S., and the introduction of advanced hybrid and electric vehicles, such as Nissan Leaf, Tesla Roadster and Model 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.

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).

5.4.2 Technological convergence/divergence towards of eco-innovation activity

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 5.2). We used 3-year moving averages to avoid the effects of seasonal fluctuations in patenting activity.

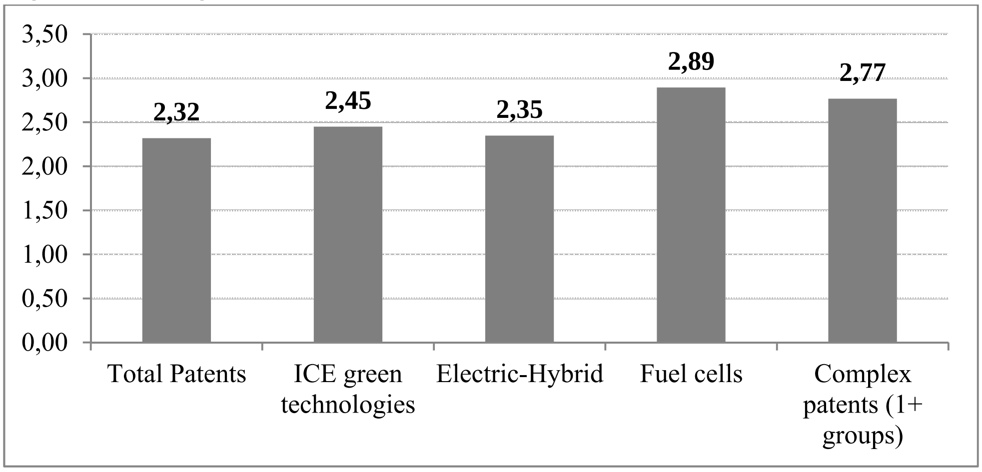
Figure 5.2. Herfindal-Hirschman index (HHI), 3-year moving average (1965-2012)



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.

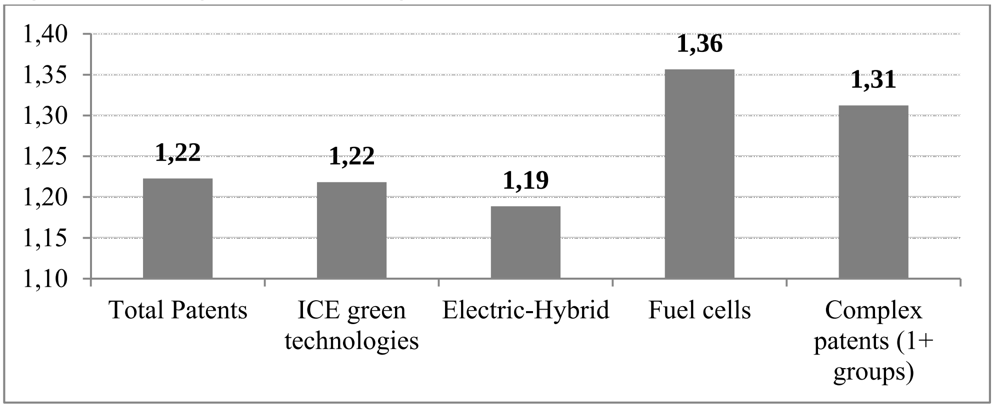
The fuel cells and complex patents, on the other side, have been quite concentrated in one or few automakers until the beginning of the 1990s. One explanation for such behavior can be that these technologies are more complex, demanding more resources and capabilities and offering greater risks than the others (Singh, 1997). The Figure 5.3 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 5.3 Average number of inventors per patent (1965-2012)



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 5.4), 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 5.4 Average number of assignees per patent (1965-2012)

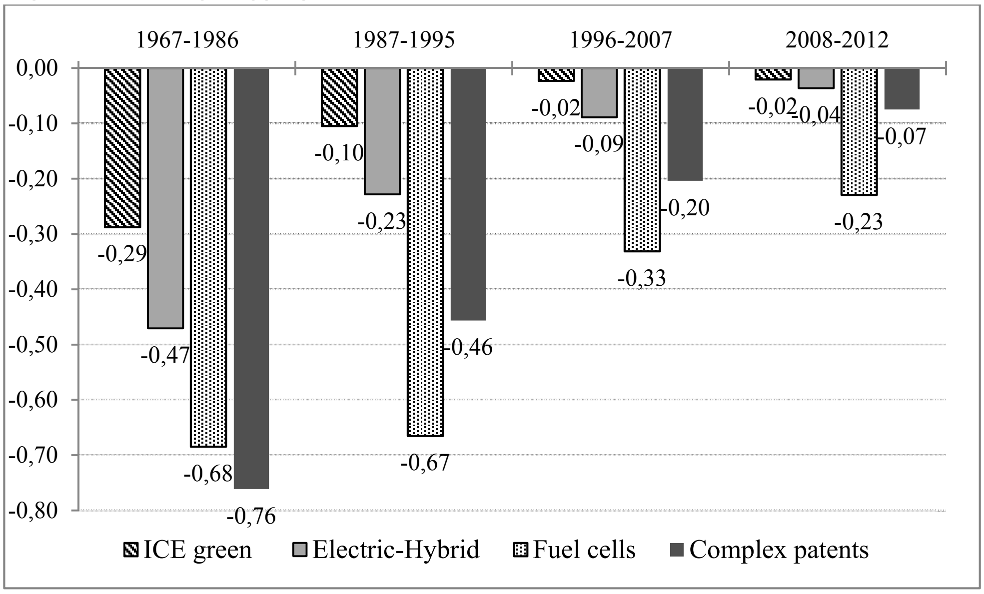


Regarding the Relative Technological Specialization Index, after calculating the four technology-specific indexes for each firm and for each year, we aggregated them using the average of all firms' indexes for each technology:

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

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 5.5.

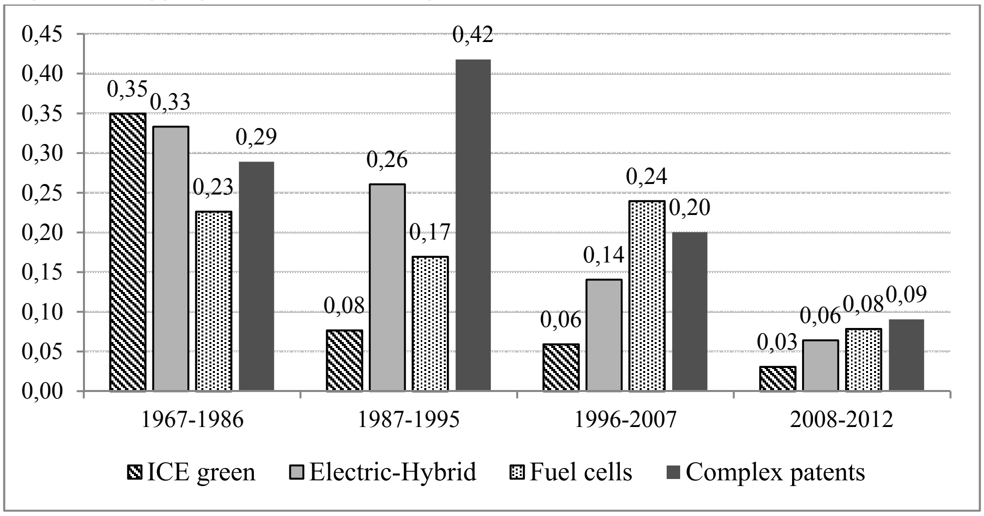
Figure 5.5 Average Aggregated RTSI



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 $\overline{RTSI_i}$ for each technology and time period (Figure 5.6). Except for the first period, when most firms were not developing alternative technologies (therefore the RTSI was always -1, with less variation), 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 5.6 Aggregated RTSI – Average standard deviation



In a sectoral perspective, standard deviations had been also 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 (Sierzchula et al., 2012).

5.4 Final considerations

The paper has provided some of the first rigorous, detailed longitudinal evidence of sectoral eco-innovation patterns and proven that the automotive industry is in fact greening to a very high degree. As far as we know, this is the first time the extent and dynamics of greening within an entire industry has been thoroughly investigated.

We propose that the automotive sector case presented could be seen as a strong indication of a rapidly maturing green economy. Our data demonstrates 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 (Wells and Nieuwenhuis, 2012). Based on these findings, we accept the hypothesis H3 that alternative trajectories (in relation to the dominant design) are increasingly responsible for the growing of innovative activity within the sector.

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, 2010a), 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.

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 on 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 even after the 2008 crisis. Our findings suggest that the hypothesis H1a is valid, that over time, we would observe a reduction of concentration of green patenting activity, thus rejecting the hypothesis H1b.

The strong convergence in green ICE, Hybrid/Electric and Complex portfolios supports the hypothesis H2a of a convergent movement of automakers' green technological strategies towards a common strategy, which is also supported in the literature (Frenken et al., 2004; Oltra and Saint Jean, 2009b; Sierzchula et al., 2012). 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. We see in other words, not only competition but also merging between the technologies, since these patents are related with components that can be used for two or more of these technologies.

The development of fuel cells, however, continues to be relatively more concentrated than the other technologies in our sample. It corroborates the argument 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, though this hypothesis requires further research.

Finally, we argue that the methodology, albeit being used in other research topics, has proven to be rigorous to analyze the greening of sectors in a global perspective, hence the paper also contributes to methodological development in the eco-innovation field, where few longitudinal in-depth studies have yet been made, to a high degree due to the poor quality of eco-innovation data and problems in defining green technologies and products (Fukasaku, 2005).

Several inquiries remain in order to take this analysis towards the aggregate level of sectoral eco-innovation patterns and wider understandings of green economic change. Investigations such as the induced effect of the automotive industry on other industries and vice versa on eco-innovation; on identifying the degree to which the automotive sector has been an early or late entrant into the green economy; the degree of green market maturity relative to other industries and, finally, to which degree the automotive industry may be characterized as a carrier industry for the greening of the economy. We thus acknowledge that comparative studies with other industries would bring important insights to the overall positioning of our findings.

Appendix 5.1 – List of IPC (International Patent Codes) for each technology

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/*			

CHAPTER 6

SECTORAL PATTERNS VERSUS FIRM-LEVEL HETEROGENEITY - THE DYNAMICS OF ECO-INNOVATION STRATEGIES IN THE AUTOMOTIVE SECTOR

By

Lourenço Galvão Diniz Faria and Maj Munch Andersen

ABSTRACT

This paper sheds light on some important but underestimated elements of the green industrial dynamics: the evolution of firms' eco-innovation activities, the gradual formation of sectoral-specific patterns in firms' strategies, and the role of firm-specific characteristics in explaining divergent strategic behaviors. We conduct a two-step empirical analysis in the automotive sector using patent data from 1965 to 2012. Our findings suggest a process of co-evolution of firms' strategies and indicate that sectoral-specific patterns of eco-innovation are present in this sector. For Fuel cells technologies, however, we observe the formation of two opposite patterns, and our econometric analysis indicates that the positioning of the firms between these two groups was significantly affected by the firms' profit margins, the size of patent portfolio, and the financial crisis.

6.1 Introduction

The remarkable rise of the green economy and the role of eco-innovations as mechanisms to reach higher levels of both economic and environmental development have been object of little attention by evolutionary innovation scholars, especially assuming that the recent rise of the Green Economy is more than a novel policy concept but rather reflects ongoing green economic change (Andersen, 2008a). The focus of the (few) studies in this field has been mainly on the role of policy and regulation mechanisms in influencing eco-innovation (Hojnik and Ruzzier, 2015; Kemp and Oltra, 2011).

The understanding of policy mechanisms is essential for those who characterize the greening process as a struggle between niche-specific eco-innovations and established, unsustainable technologies, immersed in socio-technical systems that are characterized by institutional inertia (Markard, 2011; Schot and Geels, 2008, 2007). This scientific stream which dominates environmental sustainability research, however, underestimates the role of firms' agency, and therefore the role of corporate strategies and its relation with eco-innovation dynamics. While there are a rising number of case studies on firms' eco-innovation activities and evolution, there are few which situate them in a historical context as part of a wider economic evolution. Even fever who investigate how different dimensions affect firms within a sector regarding their technological strategies towards eco-innovation, see though (Berrone et al., 2013; del Río et al., 2016; Hojnik & Ruzzier, 2015; Mazzanti & Zoboli, 2006).

Our paper takes an evolutionary economic perspective (Dosi, 1988; Nelson & Winter, 1982; Perez, 2009) to investigate the degree and dynamics of sectoral greening, adding more fundamentally to the still limited literature on the industrial dynamics of the greening of industry (Andersen and Faria, 2015). We aim to analyze the rate and direction of the greening of a sector, highlighting the firm-level dynamics of eco-innovation in the automotive sector over the last decades through a patent-based analysis.

As for general eco-innovation research, there are also in the automotive sector few studies that deal with the changes in technological strategies of individual firms. While some highlight the increase in technological variety due to the greening of the sector (e.g. Frenken et al., 2004; Oltra & Saint Jean, 2009b), others defend that some firms are developing specific green technologies (Pohl and Yarime, 2012; Sierzchula et al., 2012). Many cite successive shifts in firms' strategies between fuel cells, battery electric and hybrid electric technologies during the past 20 years (Konrad et al., 2012; van den Hoed, 2007). Overall, the evidence on the dynamics and pattern of eco-innovation in the sector and the factors affecting firms' decision to develop one or another green technology remain fragmented and inconclusive.

In mature markets, firms with better dotation of internal resources or specific combinations of external conditions (i.e. regulations, competition) may have different perceptions about risks and opportunities of developing new technologies compared to firms that face inadequate conditions (Abernathy & Clark, 1985; Barney, 1991; Cyert & March, 1963; Lundvall, 1992; Pavitt, 1990). On the other hand, this dynamics is influenced by technology specific elements (Malerba & Orsenigo, 1996). Since the greening of the sector is characterized by the existence of competing technologies at different development stages and with distinct degrees of differentiation from the dominant design, the decision to invest in one or more of these technologies might be more or less influenced by firms' internal and external characteristics (Wesseling et al., 2015).

In a previous paper on eco-innovation in the automotive industry which focused more on the meso level (Faria and Andersen, 2015, Chapter 5). We pointed out a strong reduction in the concentration of green patenting activity within the automotive sector for some core technologies, namely Advanced Internal Combustion Engines (ICE), Hybrid/Electric Engines, and Complex patents[27] in the past decades. However, a fourth group, Fuel cells, remained relatively more concentrated in few firms. In this paper we seek to expand on these findings, with a particular emphasis on investigating if the aggregate reduction in patenting

[27] This group is formed by patents that represent the combination between two or more groups and denote a cross fertilization between the different green technologies.

concentration is reflected in the firm-level data, and why the fuel cell case differ from the others.

Our findings suggest a process of co-evolution of firms' strategies and indicate that s*ectoral-specific patterns of eco-innovation* are present in this sector (Franco Malerba, 2002; Mazzanti & Zoboli, 2006; Oltra & Saint Jean, 2009a, Andersen & Faria, 2015; Faria & Andersen, 2015). For Fuel cells technologies, however, we observe the formation of two opposite patterns, and our econometric analysis indicates that the positioning of the firms between these two groups was significantly affected by the firms' profit margins, the size of patent portfolio, and the financial crisis.

The paper is organized as follows: In section 2, we conduct a critical literature review on the determinants of changes in firms' technological strategies for innovation and eco-innovation, and discuss the greening of the automotive sector in perspective. Section 3 presents the data preparation and methodological steps for the descriptive and econometric procedures. The results of both analyses is presented and discussed in Section 4. The final remarks are presented thereafter.

6.2 Literature review

6.2.1 Determinants of changes in firms' technological strategies

According to the evolutionary perspective of technological change, the dynamics of technological change is characterized by mechanisms of variety creation and selection immersed in a complex structure of technological, economic, and institutional elements (Dosi & Nelson, 1994; Lundvall, 1992; Malerba, 2002; Nelson & Winter, 1982), assuming that technological change (and potentially market change) is a systemic process marked by successive *technologic life cycles* in which the rate of innovation and the diversity of products and processes is constantly altered by changes in that complex structure (Abernathy and Clark, 1985).

As Faber & Frenken (2009) puts, the strength of such evolutionary perspective "(…) lies in its strong microeconomic foundations. It builds on behavioral theory of the firm and provides a more realistic description of the technological black box" (p. 467), and differences in firm behavior and characteristics have a crucial role in explaining innovation dynamics (Nelson, 1991). The study of such dynamics must include an understanding of which factors influence changes in firms' technological strategies, as these factors reflect the creation and selection mechanisms.

A technological strategy can be understood as the continuous alignments between firms' *internal capabilities/competencies and external conditions* in unique arrangements in order to generate and sustain competitive advantages (Christensen *et al.*, 1987, Porter, 1996). Organizations operating in lean environments tend to develop a short-term mentality and avoid technological experimentation (Aldrich, 1979; Rothenberg and Zyglidopoulos, 2003), directing innovative search to the neighborhood of the established technologies in order to exploit existing firm-specific assets and competences and avoid potential risks, often generating core-rigidities[28] (Dosi, 1988; Leonard-Barton, 1998; Patel & Pavitt, 1997; Prahalad & Hamel, 1990), unless they perceive sufficient opportunities to overcome such inertial forces and change their strategies towards new trajectories (Perez, 2009).

In lean and mature markets, firms with better dotation of internal resources[29] and/or healthier financial records - and therefore greater flexibility - may perceive smaller risks of developing new technologies compared to struggling firms that face scarce or inadequate internal resources to bet and bigger obstacles to obtain external funding for their R&D activities (Barney, 1991; Cainelli et al., 2006; Cohen & Levinthal, 1990; Cyert & March, 1963; Patel & Pavitt, 1997; Pavitt, 1990; Schumpeter, 1942). Moreover, external elements - including the characteristics of regulatory, competitive and scientific/technological environments, can generate

[28] Numerous studies point out that this inertia may promote the entrance of new firms that perceive smaller risks due to their absence of organizational and technological inertial forces (Abernathy and Utterback, 1978; Anderson and Tushman, 1990; Henderson and Clark, 1990).
[29] By *internal resources* we mean all resources firms possess to undertake their innovative activities including, for example, their capabilities, R&D structure, organizational routines, tacit knowledge, alliances and networks (Barney, 1991).

both incentives or obstacles to change (Abernathy & Clark, 1985; Di Stefano et al., 2012; Lundvall, 1992; Perez, 2009; Porter & Linde, 1995). General economic conditions, reputation scandals and crises may also exert important influences in firms' willingness to change technological strategies (Archibugi et al., 2013; Paunov, 2012; van den Hoed, 2007).

Since firms in the same sector or region often share internal characteristics and are subject to similar external conditions (i.e. regulations, competition), collective perceptions about technologies' risks and opportunities might arise, originating sector- (Breschi & Malerba, 1996; Klevorick et al., 1995; Malerba & Orsenigo, 1993, 1997; Malerba, 2002; Nelson & Winter, 1982; Pavitt, 1984; Winter, 1984) or geographic-specific patterns of innovation (Asheim & Gertler, 2006; Cooke et al., 1997; Freeman, 1988; Lundvall, 1992; Patel & Pavitt, 1997). On the other hand, distinct patterns may arise in the same sector or country due to firm heterogeneity, i.e. differences in internal resources or bounded rationality (Dosi, 1997; Leiponen & Drejer, 2007; Peneder, 2010).

Observable changes in technological strategies can be considered indicators of perceived opportunities from new technologies. By observing the existence (or not) of patterns of change in firms technological strategies, one is able to understand which dimensions stand out as main drivers of innovation (Patel and Pavitt, 1997). Cainelli et al. (2015) argues that firms' internal and external characteristics play a crucial role to understand eco-innovation's development due to its higher complexity (in terms of novelty, uncertainty and variety) when compared with established technologies.

Among the eco-innovation literature, however, scholars have been mainly focusing on the role of institutional mechanisms such as environmental policy instruments in influencing firms' green technological strategies, given the specific challenges and barriers that the market forces face in the greening process such as the "double externality problem" (Bernauer et al., 2006; Brunnermeier & Cohen, 2003; Frondel et al., 2007; Green et al., 1994; Horbach et al., 2013; Horbach et al., 2012; Jaffe & Palmer, 1997; Johnstone et al., 2009; Johnstone, 2008; Kesidou & Demirel, 2012; Porter & Linde, 1995; Rennings, 2000; van den Hoed, 2007).

Despite the substantial contribution to the understanding of aggregated, general eco-innovation determinants, this literature barely touches on how firms under similar institutional stimuli form their green technological portfolios. As Berrone & Fosfuri (2013, p. 892) arguments, “little is known as to why some firms engage in more environmental innovation than others and, perhaps more important, under what conditions firms pursue this type of innovation”. There’s a lack of understanding on how different dimensions affect a same group of firms to change their technological strategies towards clean technologies and become specialized. Our objective in this paper is to shed some light on this topic by investigating one case, namely the dynamics of eco-innovation in the automotive sector over the last decades.

6.2.2 The greening of the automotive sector

The automotive sector is a mature, capital intensive industry where strong competitive forces are present, pushing firms to focus on their core competences and inhibiting the emergence of new competitors, as well as alternative business models and technological trajectories (Abernathy & Clark, 1985; Breschi & Malerba, 1996; Prahalad & Hamel, 1990). Accordingly, the technological regime of the sector is characterized by the introduction of incremental innovations based on a *dominant-design* composed by some fundamental features such as internal combustion engines (ICE), all-steel car bodies, multi-purpose character, and fully integrated productive processes (Orsato and Wells, 2007b).

Automakers have competed on a range of parameters, the most important being price, autonomy, power, noise, velocity, comfort, design, reliance, and more lately safety which have formed the basis of their competitive behavior. Some firms use their superior competences in certain parameters as sources of competitive advantages, i.e. Volvo in safety, VW in price, Citroën in design etc. (Clark and Fujimoto, 1991; Urde, 2003).

Not until the 1960s and 1970s did green parameters begin to play a role as the negative environmental impact of automobiles arose as an important issue in the early environmental agenda (Høyer, 2008; Meadows et al., 1972). Noticeably at that time, it influenced the creation of the first tailpipe emission standards – such as the U.S. Clean Air Act and the European regulation ECE 15/01 – followed by other national and regional environmental regulations targeted towards automobiles and related activities (Faiz et al., 1996).

As those early regulations have proved insufficient to solve the environmental issues pointed, a second wave of regulations, incentives and research collaboration projects has started from the beginning of the 1990s onwards, including the California's Zero Emission Vehicle (ZEV) program, the first comprehensive regulation aiming not only to reduce emissions to lower levels but also enforcing investments in zero emission vehicles.

The literature holds that, in an aggregated level, the increase in automotive eco-innovation has been conducted mostly in response to potential or effective stricter national and regional regulations and other policy instruments (Bergek and Berggren, 2014). In fact, the ZEV regulation is regularly pointed as the main determinant of the increase on R&D investments in alternative technologies (Budde et al., 2012; Dijk and Yarime, 2010; Frenken et al., 2004; Penna and Geels, 2014; Schlie and Yip, 2000; Sierzchula et al., 2012; van den Hoed, 2007).

While even regional regulations can influence their global strategies (Bohnsack et al., 2015), potentially leading to a convergence movement towards green technologies throughout the whole sector (Kolk and Levy, 2004), the existence of competing green technologies at different development stages and with distinct degrees of differentiation from the dominant design implies that such convergence might be restricted to some of them (Hojnik & Ruzzier, 2015; Malerba & Orsenigo, 1996).

Faria & Andersen (2015) [Chapter 5] offer some evidence of this convergence by observing a substantial reduction of the sectors' patenting activity concentration for green Internal Combustion Engines (ICE), Hybrid/Electric Engines, and Complex patents[30]. For the group of patents related with Fuel cells, however, such reduction of concentration happened later and was significantly less intense than for the other groups, an indication that the investment in such technology is still concentrated in the hands of few firms. The present paper aims to expand these findings by analyzing the eco-innovation dynamics of this sector on a firm-level, combining with other sources of data, in order to answer the following questions:

- How incumbent automakers have been reacting strategically when faced with a complex and highly uncertain scenario, and to which degree and at what rate have their strategies been greening?
- How is their eco-innovation behavior mainly affected by external (i.e. geographic, sectoral) vis-à-vis firm-specific patterns? What is the degree of heterogeneity in the development of eco-innovation strategies (Brunnermeier and Cohen, 2003; Utterback, 1971)?
- Why and how firms have been positioning themselves about the leadership in Fuel cell technologies? Which elements can explain their decision to invest or not in such technologies?

6.3 Methodology

While the market diffusion of green technologies is still very incipient, it is possible to observe the characteristics of the greening process by using indicators that reflect the direction of technological change. Patent-based life cycles start earlier than sales-based life cycles but they are both interconnected, i.e. the product that will be sold in the future is the result of cumulative innovative processes performed in the past (Haupt et al., 2007; Patel & Pavitt, 1997; Pilkington, 2004).

The rate of growth in patenting in a certain technologic field can be used as proxy of its importance and maturity degree (Blind et al., 2009; Chang, 2012; Haupt et al., 2007; Nesta & Patel, 2005), and patent applications are considered a robust indicator of firms' technological competences as it signs that the firm has sufficient

[30] This groups is formed by patents that represent the combination between two or more groups and denote a cross fertilization between the different green technologies.

competences to produce knowledge pieces in the technological frontier for a given technological field (Breschi et al., 2003; Chang, 2012). Despite its main limitations as an innovation indicator (Pakes, 1986; Pavitt, 1985), patent grants can be used as a proxy for the level of eco-innovation activity and also to analyze changes in the technological trajectory in a given sector, particular in medium-high tech industries such as the automotive industry (Oltra et al., 2010).

Patent-based data was collected from the Derwent World Patent Index (Thomson Reuters), from 1965 to 2012, for 18 car manufacturers chosen to represent the sector, based on OICA's World Motor Vehicle Production ranking 2012 (See Appendix 6.1). The chosen manufacturers are all big multinational companies representing 90% of global sales of passenger vehicles (2012) and with considerable R&D expenditures, even though the degree of patenting activity varies considerably. To avoid low-quality patents, we selected only granted patents filled in the European Patent Office (EPO), US Patent Office (USPTO), and World Intellectual Property Organization (WIPO), and grouped them by technology.

In opposition with most studies using patents to analyze eco-innovative activities in the automotive sector (Rizzi et al., 2014; Sierzchula et al., 2012; Wesseling et al., 2014), we identified the IPC codes related with each technology (Pilkington & Dyerson, 2006) using the recently developed IPC Green Inventory[31] and the OECD's list of Environmentally-sound technologies (EST), therefore including patents that may be ignored by keyword-based searches. We identified patents related with Internal Combustion Engines' (ICE) green technologies; Hybrid and Electric propulsion systems, Fuel cells, and a group of Complex patents[32].

[31] These lists use specialists in different fields to classify IPC codes according to their main technological group. Source: http://www.wipo.int/classifications/ipc/en/est/.

[32] Since every patent can be attributed with more than one IPC code, some patents have codes associated with two or more groups of technologies (e.g. fuel cells and electric/hybrid, or fuel cells and ICE green patents). The presence of complex patents indicates the "cross-fertilization" between two or more groups, and therefore an increase in complexity of these technologies.

To capture the level of specialization of the firms in a given green technology, a Relative Technologic Specialization Index (RTSI) is calculated, derived from Relative Specialization index (Balassa, 1963; Brusoni and Geuna, 2005; Chang, 2012; Debackere and Luwel, 2005; Nesta and Patel, 2005; Soete, 1987) which is commonly used as an indicator of international commerce relative specialization, in order to measure the evolution of individual firms' relative specialization on the specified technological areas. The formula for the RTSI for a given year is

$$\mathrm{RTSI_{ij}} = \frac{\left(\mathrm{P_{ij}}/\sum_{\mathrm{i}} \mathrm{P_{ij}}\right)}{\left(\sum_{\mathrm{j}} \mathrm{P_{ij}}/\sum_{\mathrm{i}} \sum_{\mathrm{j}} \mathrm{P_{ij}}\right)}$$

where $\mathrm{P_{ij}}$ represents the number of patents from technology i on the patent portfolio of firm j. The RTSI 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.

In order to attenuate the effects of the largest patentees in our sample, we adopted an average of all firms' share:

$$RTSI_{ij} = \frac{\left(P_{ij}/\sum_i P_{ij}\right)}{\frac{1}{n}\sum_j\left(P_{ij}/\sum_i P_{ij}\right)}$$

Using the patent data and the RTSI, the analysis is conducted through two steps, summarized in the next subsections.

6.3.1 Descriptive analysis of the firm-level dynamics of eco-innovation

In the first part of the analysis, the RTSI values for each firm and technology are used to conduct a descriptive analysis of the automakers' strategies on a firm-level through a series of graphs in which we plot the average and standard deviation of the RTSI values in five different time phases divided according to major milestones in the greening of the automotive sector:

- Phase AB, from 1965 to 1986, covers the era of implementation of the earliest environmental regulations and experimentation with green technologies in the sector;
- Phase BC, from 1987 to 1996, covers the rise of the sustainable development discussion, the implementation of stricter regulations such as the Carb ZEV, and the formation of partnerships between 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.;
- Phase CD, from 1997 to 2007, covers the first mass market innovations, i.e. the hybrid Toyota Prius, and the tightening of the emissions regulations targeted to ICE vehicles worldwide, as well as the rise of hydrogen-based investments and incentives;
- Phase DE, from 2008 to 2012, covers the effects of the crisis and the introduction of new hybrid and electric vehicles such as Nissan Leaf, Tesla Roadster and Model S.

The RTSI values are normalized in order to simplify and compare symmetrically the results (Nesta and Patel, 2005):

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

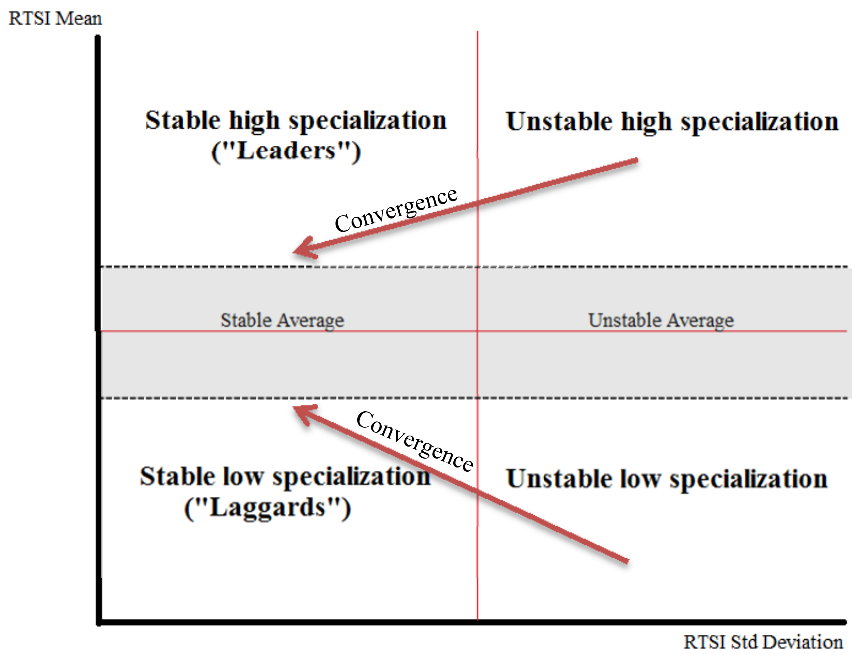
The index is able to reveal how firms develop and change their technology portfolios - and consequently their strategies - over time. Accordingly, if [-1 < RTSIn < 0], the firm *j* has a smaller share of patents on technology *i* than the sector average and the closer to -1, the less specialized is the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

When analyzed over time, the index 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 might indicate that the firm is in a process of *technological catching up*. If the index is consistently over 0 (and especially over 0.3), it indicates that such firm has a persistent relative specialization on the technology analyzed (Nesta and Patel, 2005).

The data is presented in a series of graphs, each one divided in four quadrants according to the average portfolio of the firms in the sample (RTSI = 0) in the y-axis and average standard deviation in the x-axis, as demonstrated in the Figure 6.1. Accordingly, firms in the top left quadrant maintain high and stable specialization ("leaders"), while firms in the bottom left have consistently very little or no specialization over the period ("laggards"). Finally, the top and bottom right quadrants represent firms that have unstable high and low specialization profiles, respectively, and could be considered "experimenters" (although that might not be necessarily true for firms in the top right quadrant).

Figure 6.1 Dynamic comparison between firms' RTSI



The two dashed lines in the y-axis represent the superior and inferior limits of the average portfolio (Nesta and Patel, 2005), and the firms inside the grey area present an stable/unstable RTSI that is similar to the average portfolio of firms in the sample. The *sectoral convergence* is observed if most firms are moving towards the stable average (left grey area) over time.

6.3.2 Econometric analysis on the determinants of technological strategies on Fuel cells

Following the subsection 6.2.1, we propose that firms' decision to become specialized (or not) in fuel cell technologies, or to develop a technological strategy that contemplates such technologies, is a function of its internal and external characteristics. We aim to isolate the effect of some of the main characteristics that may affect such decisions, namely: a) the effect of internal assets that might affect firms' propensity to develop fuel cell technologies; b) the country-specific determinants; and c) the effects of external shocks.

A panel is constructed using the patent data and RTSI previously calculated for the years 2003 to 2012 (10 years) for 16 automakers[33], combined with additional firm-level data (R&D expenditures, sales, profit margins) collected from the Orbis database (Bureau van Dijk), in order to statistically test which characteristics of firms are positively or negatively related with relative technological specialization in the Fuel cells patenting.

We estimate a Random effects linear model using the following reduced form equation, adapted from Brunnermeier & Cohen (2003):

$$\begin{aligned}(\mathrm{RTSI\_FC}_{i,t}) = {} & \alpha_i + \gamma_t + \beta_1(\mathrm{PROFMG}_{i,t}) + \beta_2(\mathrm{RNDINT}_{i,t}) \\ & + \beta_3(\mathrm{LOGPAT}_{i,t}) + \beta_4(\mathrm{LOGSALE}_{i,t}) + \beta_5(\mathrm{REG\_NA}_i) \\ & + \beta_6(\mathrm{REG\_ASIA}_i) + \beta_7(\mathrm{FINCRISIS}_{i,t}) + \varepsilon_{it}\end{aligned}$$

[33] Isuzu and Porsche were excluded due to lack of firm-level data for the period analyzed.

where *RTSI_FC* stands for the Revealed Technological Specialization Index for Fuel cells (dependent variable), representing firms' technological specialization. As independent variables we use profit margins (*PROFMG*), R&D intensity[34] (*RNDINT*), total patenting (*LOGPAT*), and sales (*LOGSALE*) to represent the effects of firms' financial health, internal resources and size; two binary variables for geographical-specific effects (*REG_NA* for North American and *REG_ASIA* for Asian firms, Europe is omitted in the model); and one binary variable representing the 2008 crisis to capture the effect of such external shock (*FINCRISIS* = 1 if year ≥ 2009, 0 otherwise). α_i, γ_t and ε_{it} captures, respectively, unobservable firm heterogeneity, time effects, and other unobservable effects (residual error).

Additionally, we use the firms' RTSI on ICE (*RTSI_ICE*), electric/hybrid engines (*RTSI_EV*) and complex patents (*RTSI_COMP*), and their average number of inventors (*AVGINV*) and assignees (*AVGASSIG*) per patent as control variables. Table 6.1 summarizes the basis statistics.

Table 6.1. Summary statistics

Variable	*Panel*	*Mean*	*Std. Dev.*	*Min*	*Max*	*Obs*	
RTSI_FC	Overall	1,121	1,180	0	4,867	N =	160
	Between		1,066	0	3,100	n =	16
	Within		0,567	-0,817	2,889	T =	10
PROFMG	Overall	0,032	0,055	-0,217	0,137	N =	160
	Between		0,031	-0,023	0,069	n =	16
	Within		0,046	-0,163	0,123	T =	10
RNDINT	Overall	0,035	0,013	0,007	0,065	N =	160
	Between		0,012	0,010	0,055	n =	16
	Within		0,006	0,014	0,061	T =	10
LOGPAT	Overall	8,309	1,033	6,433	10,195	N =	160
	Between		1,033	6,867	9,807	n =	16

[34] Following other analysis in the field, we do not impose a lag structure for R&D intensity and profit margins (Brunnermeier & Cohen, 2003; Hall et al., 1986).

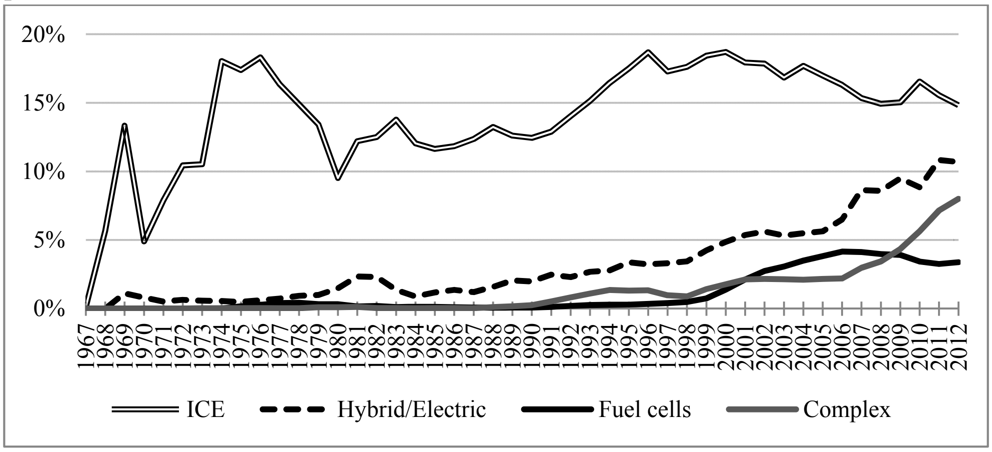
	Within		0,246	7,347	9,016	T =	10
LOGSALE	Overall	11,092	0,759	9,348	12,446	N =	160
	Between		0,756	9,624	11,974	n =	16
	Within		0,191	10,470	11,608	T =	10
REG_NA	Overall	0,125	0,332	0	1	N =	160
	Between		0,342	0	1	n =	16
	Within		0	0,125	0,125	T =	10
REG_AS	Overall	0,500	0,502	0	1	N =	160
	Between		0,516	0	1	n =	16
	Within		0	0,500	0,500	T =	10
FINCRISIS	Overall	0,400	0,491	0	1	N =	160
	Between		0	0,400	0,400	n =	16
	Within		0,491	0	1	T =	10
AVGINV	Overall	0,908	0,378	0,249	2,150	N =	160
	Between		0,336	0,388	1,605	n =	16
	Within		0,192	0,277	1,452	T =	10
AVGASSIG	Overall	1,047	0,486	0,084	2,297	N =	160
	Between		0,293	0,498	1,752	n =	16
	Within		0,394	0,077	2,155	T =	10
RTSI_ICE	Overall	1,069	0,779	0	4,253	N =	160
	Between		0,592	0,218	2,378	n =	16
	Within		0,526	-0,355	3,467	T =	10
RTSI_EV	Overall	3,441	0,968	1,790	6,240	N =	160
	Between		0,696	2,131	5,049	n =	16
	Within		0,694	1,486	5,793	T =	10
RTSI_COMP	Overall	1,354	0,269	1,020	2,540	N =	160
	Between		0,150	1,070	1,632	n =	16
	Within		0,226	0,884	2,524	T =	10

6.4 Data analysis and discussion

6.4.1. Descriptive analysis of the firm-level dynamics of eco-innovation

The Figure 6.2 shows the average share of green technologies in automakers' patent portfolios, or the point where the RTSI = 0 for each year in the sample (Section 6.3). Any strong convergence observed in the firms' individual RTSIs mean that firms are converging *to these trajectories*.

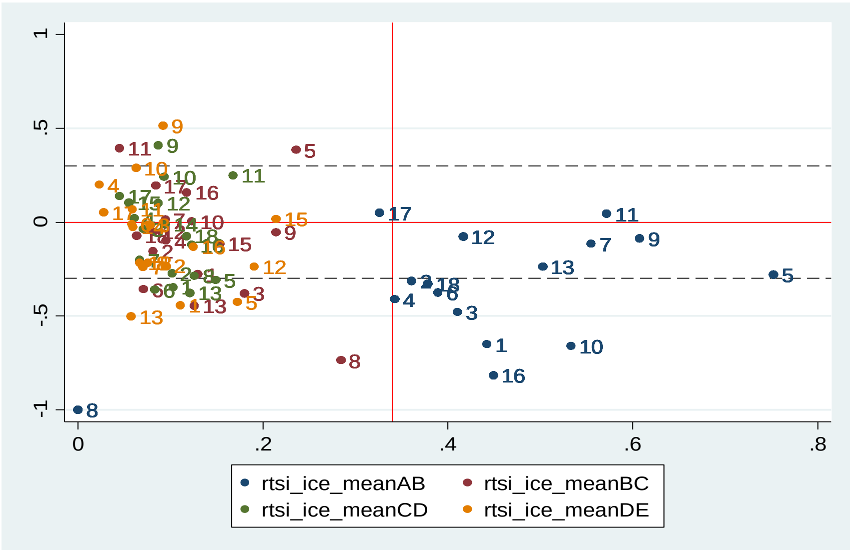
Figure 6.2 Average share of selected green technologies in automakers' patent portfolios



Based on this graph alone, we can conclude that after the 1990s, the share of firms' patent portfolios devoted to ICE technologies has been declining while the share related with alternative technologies has been increasing considerably. Moreover, in line with the core evolutionary thinking (Nelson & Winter, 1982), it demonstrates the cumulative, path dependent nature of green technological development in a sectoral level, marked by smooth increases in the patent shares. At least in this perspective, the role of hype cycles and radical changes in expectations is less intense than many argue (Bakker, 2010a; Sierzchula et al., 2012; van den Hoed, 2007).

The Figure 6.3 shows the dynamics of automakers' technological strategies for green ICE. Each dot represents a firm's average RTSI during one of the five phases described in the subsection 6.3.2. Each firm has a correspondent number, listed in the Appendix 6.1. Although it is not possible to track every firm due to the amount of data in the graphs, the objective is to recognize the patterns and dynamics, for which the figures are useful. The blue dots represent the position of firms in the first phase (AB). In this phase, most firms are placed in the bottom right quadrant below the dotted line, indicating that they were briefly experimenting in these technologies but still not demonstrating long-term commitment.

Figure 6.3 The evolution of relative technological specialization in green ICE

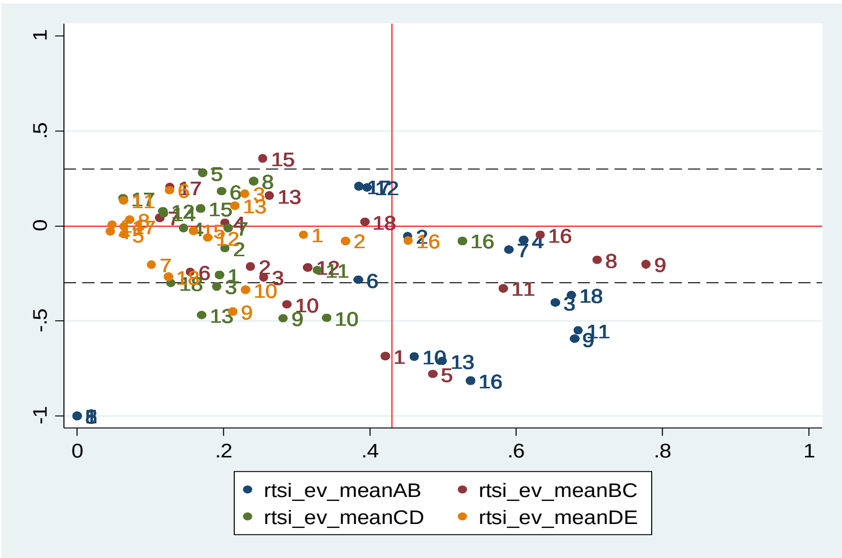


In the following phase, BC, we observe that most firms converge towards the average zone and move to the quadrants in the left, as the red dots show in the graph. These changes persisted for in the subsequent phases (green and orange dots) and indicate that consistent, *sectoral-wide patterns* were formed for this technology. These patterns reflect widely perceived opportunities and risks that were quickly perceived by most firms and influenced their technological strategies for the next periods (See Section 6.2). Comparing the convergence in Figure 6.3

with the trend in Figure 6.2, we conclude that the firms are converging towards a strategy of reducing the share of patenting activity devoted to this group of technologies.

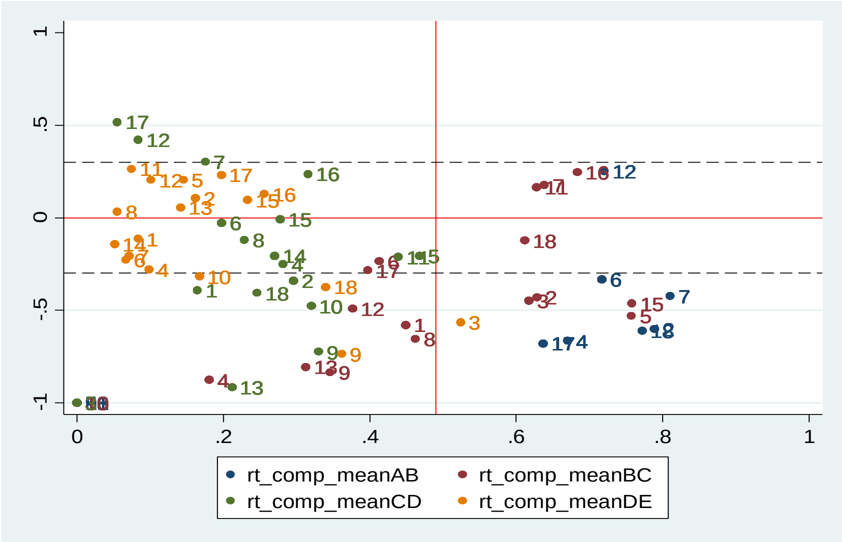
The same convergence movement is observed for the Electric and Hybrid technologies (Figure 6.4), although in this case it has been more gradual than for green ICE, perhaps reflecting the risks represented by their relative distance from the dominant design. Many firms were already positioned in the average stable zone in the first and second phases, but the sector-wide convergence only emerged in the period CD (1997-2007) onwards. The Figure 6.2 shows that this convergence is associated with an increase of the participation of these technologies in firms' patent shares.

Figure 6.4 The evolution of relative technological specialization in Hybrid and Electric engines



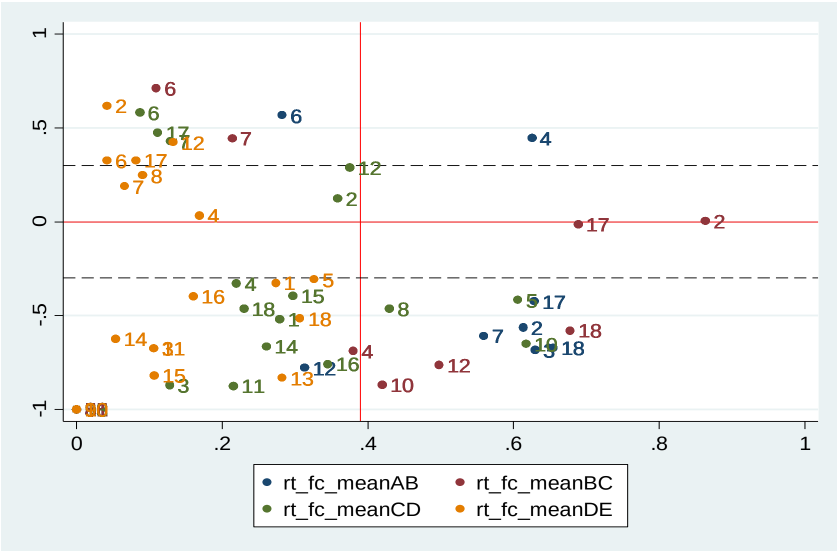
The development of Complex patents, which represent the cross-fertilization between one or more green technologies, has been subject to an even more recent process of convergence (Figure 6.5) that only took shape in the last period, DE, after 2008, although also here it was clearly a gradual process over all phases. Even more interesting is to compare with the results in Figure 6.2, which shows a significant increase in firms' share of this group of patents in the same period. Therefore, more than a simple average, the trend described in that figure reflects a pattern of strategic change among most firms in our sample.

Figure 6.5 The evolution of relative technological specialization in Complex patents



Finally, the evolution of fuel cells shows the weakest convergence of the four groups, corroborating the findings of Faria & Andersen (2015) [Chapter 5], which indicated that this technology has maintained relatively more concentrated than the others (Figure 6.6). In fact, few firms had any fuel cell specialization in the first two phases, while during the phase CD (1997-2007) most firms established a position in the left quadrants but in *divergent* directions, creating two groups: one of highly specialized firms in the top and another of low specialized firms in the bottom – only Ford situated in the "average zone" during the last phase.

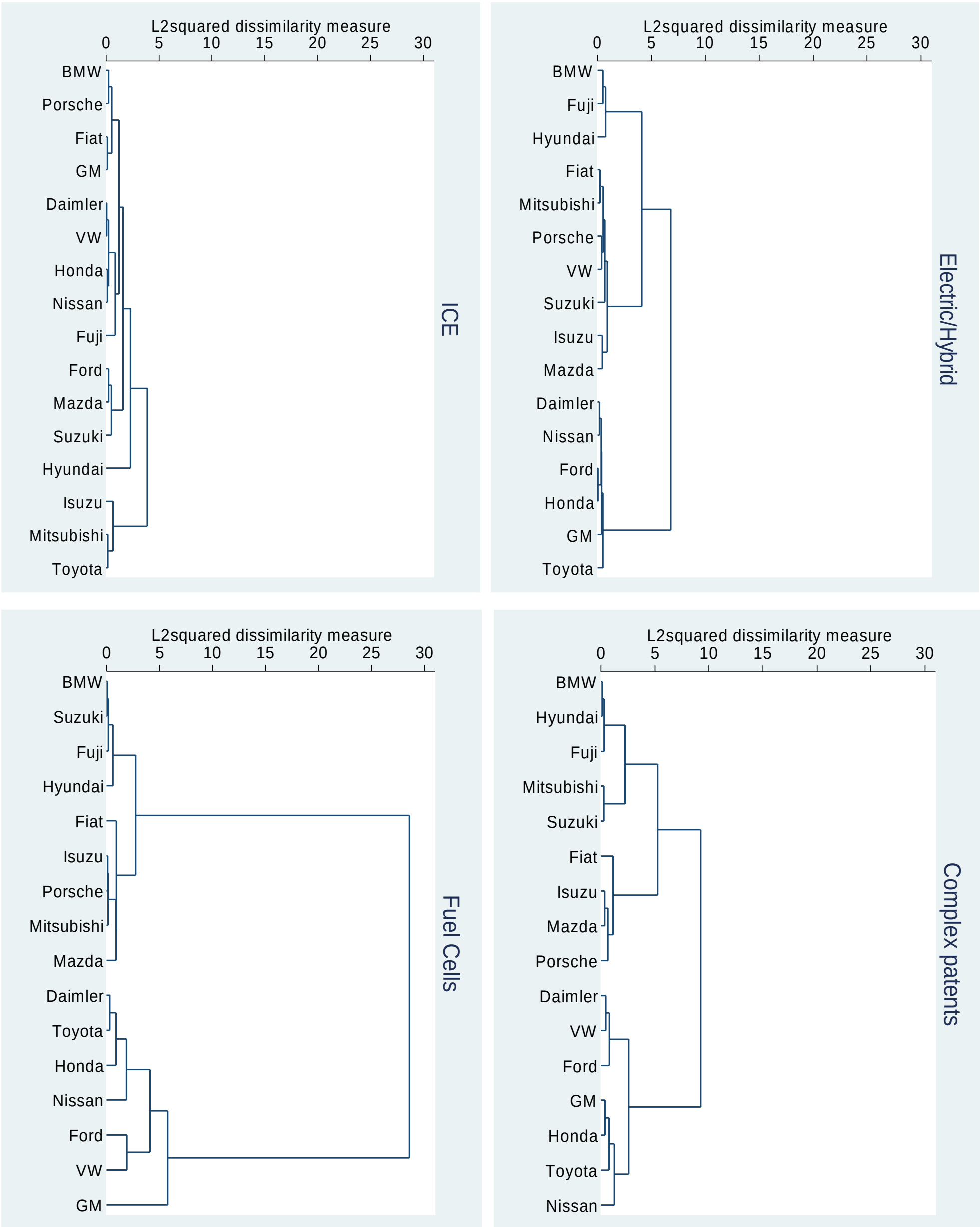
Figure 6.6 The evolution of relative technological specialization in Fuel cells



To put the dynamics of firms' technological strategy in perspective, we ran a Ward's cluster analysis over the whole period (1965-2012) to group firms according to patterns in their strategic behavior (Chang, 2012), as measured by their RTSI average and standard deviation in each of the phases[35]. The cluster analysis uses an agglomerative algorithm to group the firms according to similarities in their variance over time. It starts out with *n* clusters of size 1 and keeps agglomerating until all the observations are included into one cluster (Murtagh and Legendre, 2011; Ward Jr, 1963) as shown in Figure 6.7.

[35] Two firms, Renault and PSA, were excluded of this analysis due to lack of data in the two first phases.

Figure 6.7 Patterns of technological change – Cluster Analysis



The dissimilarity measure indicates the Euclidian distance among the firms' RTSI variation, and the higher its value before two clusters "merge" (indicated by the connecting lines), the higher is the dissimilarity among them. Likewise, we found a low dissimilarity when the last groups merge for the ICE technologies (L2-squared around 5), thus the differences between the two groups are minimal. The distance is slightly higher for Electric and Hybrid technologies and for Complex patents, where firms' strategies took more time to converge, but the highest – by far – is the one for Fuel Cells, reaching a L2-squared superior of 30 before the two last groups merge.

The results suggest that is possible to distinguish two major clusters for each technology, which are described in the Appendix 6.2. The validity of the cluster analysis is examined through an one-way MANOVA, as in Chang (2012). The p-values are all significant (at 5% confidence level), confirming that there are significant differences between the two groups for each technology. The marginal tests, however, show that the differences between the two major groups have been reducing for Electric/Hybrid and Complex technologies, as the two coefficients related with the last phase (EV_DE and COMP_DE) are not significant. The differences in the RTSI among these two clusters in each technologic group are summarized on Table 6.2 below. For each technology, Cluster 1 seems to represent the "laggards", while the Cluster 2 represents the "leaders".

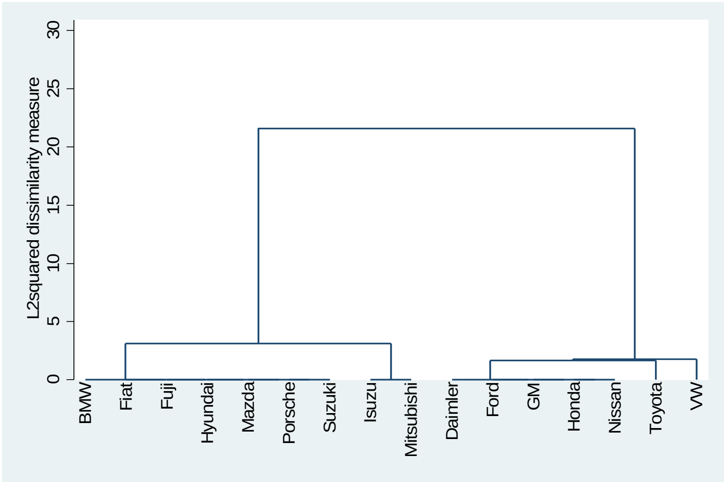
Table 6.2. Differences in average RTSI among the two clusters for each technologic group

	ICE					Electric/Hybrid				
Cluster	Total	AB	BC	CD	DE	Total	AB	BC	CD	DE
1	-0,28	-0,44	-0,16	-0,15	-0,17	-0,42	-0,71	-0,27	-0,21	-0,08
2	0,12	0,00	0,17	0,27	0,21	-0,02	-0,02	-0,08	0,04	-0,03
Distance	*0,40*	*0,45*	*0,33*	*0,42*	*0,38*	*0,40*	*0,69*	*0,20*	*0,25*	*0,04*

	Fuel cells					Complex patents				
Cluster	Total	AB	BC	CD	DE	Total	AB	BC	CD	DE
1	-0,85	-0,97	-1,00	-0,73	-0,55	-0,60	-1,00	-0,52	-0,41	-0,12
2	-0,07	-0,30	-0,15	0,15	0,20	-0,24	-0,44	-0,33	0,01	-0,08
Distance	*0,79*	*0,67*	*0,85*	*0,89*	*0,75*	*0,37*	*0,56*	*0,19*	*0,42*	*0,04*

For each technology, Cluster 1 seems to represent the “laggards”, while the Cluster 2 represents the “leaders”, although, as mentioned, the distance between the groups reduces in the last phase for some groups. By combining the position of each firm in the four technologies as a new cluster analysis (Figure 6.8 and Appendix 6.2), we are able to recognize two major groups that represent the overall leaders and laggards in the relative specialization in green technologies in our sample.

Figure 6.8 Relative leadership in all technology groups – Cluster analysis



The one-way MANOVA overall results also validate this second cluster analysis for all technologies but ICE (see Appendix 6.3). We interpret this as a sign that the firms that are the relative “leaders” in the alternative technologies are not necessarily the leaders in the green ICE specialization. Table 6.3 summarizes the differences in the RTSI between the two major groups of “leaders” and “laggards”. Also in this data we observe the gradual convergence between the two groups in the last phases at the point that there is virtually no difference between the technological specialization of the leaders and the laggards. Again, the only exception is Fuel cells, for which the distance of the two groups is remarkable even in the last phase.

Table 6.3 Differences in average RTSI among the two major clusters

		Average RTSI for each phase				
		Total	AB	BC	CD	DE
ICE	Cluster 1	-0,250	-0,463	-0,113	-0,063	-0,095
	Cluster 2	-0,147	-0,225	-0,074	-0,092	-0,098
	Distance	*|0,103|*	*|0,238|*	*|0,039|*	*|0,030|*	*|0,003|*
Electric/ Hybrid	Cluster 1	-0,434	-0,752	-0,314	-0,204	-0,057
	Cluster 2	-0,050	-0,070	-0,058	-0,007	-0,065
	Distance	*|0,384|*	*|0,682|*	*|0,255|*	*|0,196|*	*|0,008|*
Fuel Cells	Cluster 1	-0,853	-0,965	-1,000	-0,739	-0,551
	Cluster 2	-0,065	-0,290	-0,150	0,152	0,200
	Distance	*|0,789|*	*|0,674|*	*|0,850|*	*|0,891|*	*|0,752|*
Complex	Cluster 1	-0,604	-1,000	-0,523	-0,407	-0,116
	Cluster 2	-0,235	-0,438	-0,333	0,009	-0,078
	Distance	*|0,369|*	*|0,562|*	*|0,190|*	*|0,416|*	*|0,038|*

We conclude, from this first analytical effort, that most firms in the sector have experienced increased convergence in their technological strategies for green ICE, Electric/Hybrid, and “Complex” technologies. For the last two technologic groups, this meant an increase in the share of these technologies on firms’ patent portfolios (Figure 6.2), while for the former we observe the opposite. The analysis indicates that, at least for the patenting activity, we are observing the gradual formation of robust sectoral patterns of eco-innovation in this sector. As discussed, this might be a strong indicator that technological opportunities are being collectively perceived by most firms in the sample, overcoming the eventual risks that are associated with changes in technological strategies (see Section 6.2).

However, this conclusion is not valid for Fuel cells, as both the evolution of the RTSI and the Cluster analysis point to the existence of two very distinct groups among the sample. As discussed in Section 6.2, besides sector-specific elements, other determinants -- such as geographic or firm-level characteristics -- might be contributing to the formation of divergent technological strategies for this technology. In the next subsection, we further investigate the effect of some of these determinants on the fuel cell patenting.

6.4.2 Econometric analysis on the determinants of technological strategies on Fuel cells

This subsection present the results of the econometric analysis, in which we inquiry into firm-specific characteristics that might have had an influence on their decision to specialize in fuel cell technologies, as measured by their relative specialization indexes. Specifically, we aim to test the influence of firms' financial health (profit margins), innovation efforts (R&D intensity and size of patent portfolios), size (sales), headquarters' location, and the consequences of the financial crisis.

Although firm size and R&D expenditures are regarded as important drivers of innovation activities in the evolutionary literature (Cohen et al., 1987; Patel & Pavitt, 1997; Schumpeter, 1942; Shefer & Frenkel, 2005), empirical analyzes have generated inconclusive evidence of their role as eco-innovation drivers (Table 6.4). Other potential drivers - firms' financial health, headquarters' location, and exogenous shocks, have been little investigated (del Río et al., 2016), but the few analyzes conducted also show inconclusive evidence.

Table 6.4. Empirical evidence on the effects of the independent variables over eco-innovation activity

Variable	*Statistically significant*	*Not significant/mixed evidence*
Size	Kammerer, (2009); Kesidou & Demirel, (2012); Rehfeld et al., (2007); Triguero et al., (2013); Veugelers, (2012);	Cainelli et al., (2012); Cleff & Rennings, (1999); Frondel et al., (2007); Wagner, (2007);
R&D expenditures	Belin et al., (2011); Cainelli et al., (2015); Cuerva et al., (2014); del Río et al., (2015); Ghisetti et al., (2014); Horbach, (2014); Ziegler, (2015);	De Marchi, (2012); Horbach et al., (2012); Horbach, (2008);
Geographic location	Cainelli et al., (2015);	Horbach, (2008); Ziegler, (2015);
Financial health	Cuerva et al., (2014); Wesseling et al., (2015);	del Río et al., (2015); Horbach, (2008);
Exogenous shocks	n.d.	n.d.

Source: adapted from del Río et al. (2016).

In our analysis, we investigate how and if these factors affecting firms' technological (relative) leadership – rather than firms' investments in eco-innovation - in one specific green technology, namely fuel cells. The objective is to find correlations between firms' characteristics and the specialization in fuel cells that might explain the results generated in the previous analysis, were we found two divergent patterns of specialization over the last two phases. The results of the econometric analysis are summarized in the Table 6.5.

Table 6.5 Panel data, Random effects linear model – Main results

Dependent variable: RTSI_FC	(1)	(2)	(3)	(4)
PROFMG	3.227***	3.271***	2.563**	2.450**
	(1.15)	(1.16)	(1.01)	(1.05)
RNDINT	-9.034	-8.342	-2.203	-0.475
	(10.60)	(10.24)	(7.68)	(6.97)
LOGPAT	0.565*	0.602*	0.618**	0.623**
	(0.33)	(0.34)	(0.29)	(0.27)
LOGSALE	-0.421	-0.411	-0.239	-0.178
	(0.53)	(0.51)	(0.42)	(0.38)
REG_NA	0.570	0.477	0.251	0.125
	(0.99)	(0.95)	(0.87)	(0.83)
REG_AS	0.047	0.023	-0.011	-0.014
	(0.81)	(0.80)	(0.74)	(0.70)
FINCRISIS	-0.194	-0.191*	-0.205+	-0.231**
	(0.14)	(0.11)	(0.13)	(0.10)
AVGINV		0.019		0.075
		(0.13)		(0.12)
AVGASSIG		0.076		-0.047
		(0.29)		(0.31)
RTSI_ICE			-0.189	-0.312
			(0.25)	(0.23)
RTSI_EV			0.184	0.252*
			(0.14)	(0.15)
RTSI_COMP			0.252+	0.250+
			(0.17)	(0.17)
Constant	1.293	0.694	-1.606	-2.499
	(4.01)	(3.90)	(3.02)	(2.69)
N	160	160	160	160

Regression coefficients are in upper rows, standard errors in brackets. Robust variance estimates were used. Significance levels: + at $p<0.15$, * at $p<0.10$, ** at $p<0.05$, *** at $p<0.01$.

The coefficients in all regressions indicate a positive and very significant effect of firms' profit margins in the relative specialization in fuel cells technologies. The size of the patent portfolio is also significant and positively correlated with the dependent variable. Almost all regressions also point out that the 2008 crisis had a statistically significant and negative effect over the technological strategies in fuel cells. Thus the general economic situation and firms' financial health are indeed important determinants of the divergence between the firms in the sector regarding this technology.

However, the positive effect of profitability over green technology development might not be valid for all alternative technologies: Wesseling et al. (2015) found a negative association between the current profitability and firms' decision to invest in EV (electric vehicles) technologies. The variables representing firm size and R&D intensity presented no statistically significant effect on FC specialization, as many authors suggest (see Table 6.4). This might be explained by the intrinsic competitive, technological and productive conditions in this sector, namely its requirements of high capital intensity and intense product innovation dynamics (Zapata and Nieuwenhuis, 2010).

Finally, the dummy variables representing the geographic location are not significant, reinforcing the idea that large firms in automotive industry are in fact global and their technological strategies are becoming more independent of the specific conditions in their home countries. Among the control variables, the regressions found a positive but statistically weak correlation between the specialization in fuel cells and in two other groups of technologies, namely Hybrid/Electric and Complex patents. This correlation is grounded in the fact that these technologies share many components, and the development of Hybrid and Electric cars may have provided an important push to the development of fuel cell technologies (van den Hoed, 2007).

6.5 Conclusions

One of the biggest strengths of the evolutionary perspective is its strong microeconomic foundations. In this sense, similarities and differences in firm behavior and characteristics have a crucial role in explaining innovation dynamics (Faber & Frenken, 2009; Nelson, 1991). This article sheds light on some important but underestimated elements of the green industrial dynamics: the evolution of firms' eco-innovation strategies, the gradual formation of sectoral-specific patterns in firms' strategies, and the role of firm-specific characteristics in explaining divergent strategic behaviors.

While realizing that patents can only inform us partly on eco-innovation activities, the analysis so far has proven valid for investigating important green competitive restructuring of the automotive industry. Our findings indicate that the evolution of eco-innovation activity in the sector for the last 40 years was marked by a gradual convergence among firms' share of green patents in three of the technologic groups analyzed - green ICE, Electric/Hybrid and Complex patents - independently of firms' home country or other characteristics.

The results corroborates some hypothesis in the literature and challenges others: first, the fact that most automakers are developing diverse green technologies confirms that the greening of the sector is causing the technological variety in the sector to increase over time (Frenken et al., 2004; Oltra and Saint Jean, 2009b). Second and most important, the convergence among automakers' green technological strategies, despite significant regional differences in environmental policies and organizational profiles (Rugman and Collinson, 2004), suggest a process of co-evolution of firms' strategies and indicates the existence of s*ectoral-specific patterns of eco-innovation* in this sector (Franco Malerba, 2002; Mazzanti & Zoboli, 2006; Oltra & Saint Jean, 2009a, Andersen & Faria, 2015; Faria & Andersen, 2015). Moreover, the results show the cumulative nature of green technological development in a sectoral level and relativizes the influence of hype cycles (Bakker, 2010a; Sierzchula et al., 2012; van den Hoed, 2007).

The findings points that the convergence is *technology-specific*: we observed that the group of Fuel cells presented two divergent technological trajectories, generating contrasting groups. Previous studies highlighted the role of institutional stimuli (mainly the ZEV regulation and the role of leaders such as Daimler and General Motors) technological advantages (i.e. better learning curves when compared with the other alternative technologies), and firms' expectations affecting the decision to develop Fuel cell technologies in the automotive industry

(Budde et al., 2012; van den Hoed, 2007). We expanded these findings by examining other firm-specific characteristics that may affect this decision and lead to divergent trajectories.

The econometric analysis indicates that the general economic situation and firms' financial conditions are indeed important determinants of the divergence between the firms in the sector regarding fuel cells. The literature points that developing riskier technologies requires healthy economic track records from innovating firms (Cainelli et al., 2006; Cyert and March, 1963; Forsman, 2013). Likewise, the development of fuel cells is considered complex and riskier when compared with the other alternative technologies due to high uncertainty on the costs of hydrogen production, distribution and storage (Debe, 2012; Maxton and Wormald, 2004; Oltra and Saint Jean, 2009b; Pilkington, 2004; van Vliet et al., 2010; Veziroglu and Macario, 2011).

Because fuel cells technologies offer more risks for being perceived as more uncertain and complex, only automakers with healthier economic conditions would have enough incentives to develop it when balancing the opportunities and risks associated with this decision. As a policy advice, these findings recommend that, besides providing institutional stimuli such as regulations demand-pull, policymakers have to create conditions to maintain firms' incomes during the transition process associated with the greening of the economy, especially during severe economic crisis (Andersen, 2008b). It is possible that the negative effect of the financial and economic crisis over the greening of the economy can be stronger than previous though for radical technologies (Archibugi et al., 2013), perhaps even more than the institutional inertia.

Finally, we emphasize that the relationship between the green transition and financial health may be increasingly subject to feedback mechanisms as environmental performance becomes important to stakeholders (Rennings and Rammer, 2011): in two months after admitting that it had deliberately equipped 11 million of its diesel vehicles with a "defeat device" to "cheat" at U.S. emissions testing, Volkswagen saw its reputation for environmental friendliness melt, its rating at Moody's drop one notch, the company's market capitalization dropped

40% and it was charged in 6.7 billion Euros, not including future penalties or compensations (Blackwelder et al., 2016).

We acknowledge that these findings are subject to methodological and data limitations. The use of patents to measure innovative activity is far from perfect (Griliches, 1990; Pakes, 1986), and many innovations simply cannot be patented and many are not patented because it may be easier – and safer - to restrict competitors' access to technical information about new industrial processes instead of disclosing the information required for patenting them . Moreover, our sample does not include first-tier suppliers, big automakers from emerging countries – especially China and India, and new entrants such as Tesla Motors. We are also not able to capture recent events - including the Volkswagen scandal mentioned earlier and the overvaluation of Tesla Motors' stocks, on firms' technological strategies.

Our analysis contributes to a firm-level understanding of eco-innovation in general and in the automotive sector, increasing our understanding of the dynamics of sectoral eco-innovation patterns, their formation and strength, depending on technology- and firm-specific elements. Additionally, the paper offers methodological insights for the study of dynamics of eco-innovation at the firm and sector levels. Several inquiries remain in order to take this analysis towards the aggregate level of inter sectoral eco-innovation patterns and wider understandings of green economic change. Investigations such as the induced effect of the automotive industry on other industries and vice versa, and on identifying the degree to which the automotive sector has been an early or late entrant into the green economy, the degree of green market maturity relative to other industries and indeed to which degree the automotive industry may be characterized as a carrier industry for the greening of the economy. These issues require the expansion of the analysis conducted in this paper to other sectors, for what our methodology could serve as reference.

Appendix 6.1 List of Automakers

Automakers			
Number	*Name*	*Number*	*Name*
1	BMW	10	Mazda
2	Daimler	11	Mitsubishi
3	Fiat	12	Nissan
4	Ford	13	Porsche
5	Fuji	14	PSA
6	GM	15	Renault
7	Honda	16	Suzuki
8	Hyundai	17	Toyota
9	Isuzu	18	VW

Appendix 6.2. Groups of automakers according to the cluster analysis

	Technologic group				
Automaker	ICE	Electric/Hybrid	Fuel Cells	Complex	Overall
BMW	1	1	1	1	1
Daimler	1	2	2	2	2
Fiat	1	1	1	1	1
Ford	1	2	2	2	2
Fuji	1	1	1	1	1
GM	1	2	2	2	2
Honda	1	2	2	2	2
Hyundai	1	1	1	1	1
Isuzu	2	1	1	1	1
Mazda	1	1	1	1	1
Mitsubishi	2	1	1	1	1
Nissan	1	2	2	2	2
Porsche	1	1	1	1	1
Suzuki	1	1	1	1	1
Toyota	2	2	2	2	2
VW	1	1	2	2	2

Appendix 6.3. One-way MANOVA Statistics

		Overall test			Marginal test			
		statistic*	f-value	p-value		R-squared	f-value	p-value
ICE	W	0,397	4,180	0,027	ICE_AB	0,35	7,52	0,016
	P	0,603	4,180	0,027	ICE_BC	0,18	3,09	0,101
	L	1,518	4,180	0,027	ICE_CD	0,47	12,60	0,003
	R	1,518	4,180	0,027	ICE_DE	0,30	6,11	0,027
		statistic*	f-value	p-value		R-squared	f-value	p-value
Electric/ Hybrid	W	0,167	13,720	0,000	EV_AB	0,72	35,82	0,000
	P	0,833	13,720	0,000	EV_BC	0,11	1,72	0,211
	L	4,991	13,720	0,000	EV_CD	0,24	4,39	0,055
	R	4,991	13,720	0,000	EV_DE	0,02	0,24	0,632
		statistic*	f-value	p-value		R-squared	f-value	p-value
Fuel Cell	W	0,243	8,580	0,002	FC_AB	0,48	12,89	0,003
	P	0,757	8,580	0,002	FC_BC	0,57	18,82	0,001
	L	3,119	8,580	0,002	FC_CD	0,69	30,49	0,000
	R	3,119	8,580	0,002	FC_DE	0,52	14,98	0,002
		statistic*	f-value	p-value		R-squared	f-value	p-value
Complex	W	0,319	5,860	0,009	COMP_AB	0,66	26,64	0,000
	P	0,681	5,860	0,009	COMP_BC	0,06	0,90	0,358
	L	2,132	5,860	0,009	COMP_CD	0,24	4,50	0,052
	R	2,132	5,860	0,009	COMP_DE	0,00	0,06	0,811
		statistic*	f-value	p-value		R-squared	f-value	p-value
All Groups	W	0,157	14,800	0,000	ICE	0,06	0,83	0,377
	P	0,843	14,800	0,000	EV	0,74	39,74	0,000
	L	5,381	14,800	0,000	FC	0,74	40,60	0,000
	R	5,381	14,800	0,000	COMP	0,42	10,28	0,006

*W = Wilks' lambda L = Lawley-Hotelling trace P = Pillai's trace R = Roy's largest root

CHAPTER 7

CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

7.1 Introduction

In the preceding chapters, I discussed two fundamental gaps in the eco-innovation research. First, a better conceptualization of eco-innovation and its positioning within scientific communities. Second, the theoretical and empirical analysis of sectoral patterns of eco-innovation.

In general, our findings expand our understanding of these two gaps related with the same phenomenon, challenge some assumptions in the literature, and open ways for future research. In the first chapter, we posit the following research question to be answered along the thesis:

- Can we observe the rise of sector-specific patterns of eco-innovation in the automotive sector?

At the end of the thesis and enlightened by our findings, I am capable to offer a proper answer to this fundamental question, which also has implications for the general eco-innovation - and innovation – theories.

In this chapter, I summarize the relevant findings of the previous chapters, compare with the existing findings in the literature. I close the thesis by offering some advice for further research based on the discussion and findings presented.

7.2 Discussion of findings

7.2.1 Eco-innovation concept and meanings

Innovation analysis is a complex and multidimensional research topic. From products and processes to marketing and organizational methods, the concept gathers multiple phenomena under the same umbrella: the introduction of novelty in the socio-economic system (Baregheh et al., 2009).

As a subgroup, eco-innovation also shares much of the same complexity, with further elements added due to its additional environmental dimension, which per se is also multidimensional. In an effort to operationalize the concept, we believe, the widely accepted definitions of eco-innovation ignore this complexity and end up reducing the concept to simple technical features such as immediate eco-efficiency improvements, sometimes defined as measurable reductions in greenhouse gases or specific, harmful substances, elements that cannot be directly verified in all eco-innovations, notably those related with new organizational and behavioral practices.

I therefore emphasized two of the main issues ignored by those definitions, which I consider to be the most problematic ones. First, the necessity of economic gains has to be placed in perspective. Eco-innovations, as any other radical innovations, may initially generate lower individual benefits than existing technologies and therefore be restricted to market niches. The necessity of economic advantages to diffuse positive environmental effects is not a characteristic of all eco-innovations: some may be purely responses to stricter regulations or other forms of pressure from the society.

However, the generation of economic advantages and improved performance is a determinant to the long term diffusion of these technologies towards mainstream markets (Andersen, 2008). To establish when economic gains are necessary to spread the positive environmental effects of a new technology, may be convenient to conduct a dynamic analysis of what constitute an eco-innovation over different phases in time and space.

Second and most important, many of the main definitions consider that technologies designed to be environmentally-friendly but unable to provide immediate environmental advantages would not be considered as eco-innovation, ignoring some of the principles of the greening of the economy, including the systemic nature of green technological change (Andersen, 2004; Nill & Kemp, 2009; Oltra & Saint Jean, 2009a): the net reduction of environmental impacts may depend on the use of distinct related innovations and technologies, many of which are absolutely necessary albeit do not offer any immediate gain. Similarly to the economic gains, environmental gains may also require a certain period of experimentation and incremental innovation that can last for years or even decades.

Albeit being random and exogenous, unintended environmental gains are included in most definitions of eco-innovation. Besides being impossible to predict and therefore to influence via policymaking, unintended gains do not represent a true greening of the economy as a new techno-economic paradigm based in new heuristics, values, behavior and perceptions. Accordingly, eco-innovations are distinct from innovations because they can be used as tools to guide and understand the greening of the economy, not because they provide individual environmental gains *per se* (Andersen, 2008).

A final contribution to this Chapter for the literature is the historical analysis of the eco-innovation concept. Although the literature generally attributes the introduction of the concept to Klemmer et al. (1999), Fussler & James (1996) or (Klaus Rennings, 2000), I found that the concept in fact goes back to the 1970s, in two relatively unknown papers which were never credited in the main literature reviews (for example, in Carrillo-Hermosilla et al., 2010 and Schiederig et al., 2012): Pampel & van Es (1977) and Taylor & Miller (1978), which discussed the adoption of environmental innovations in agriculture from a sociological point of view.

In the Chapter 3, we touch in another important issue for eco-innovation research: the development of distinct meanings and scientific communities around terms that are often considered as synonymous in the literature (Dias Angelo et al., 2012; Karakaya et al., 2014; Schiederig et al., 2012). Differently from the cited reviews, our results indicate that these four terms can be, to some extent, identified with different scientific communities.

We found an association of term *sustainable innovation* with scientific communities dealing with complex system-oriented approaches, especially the transition school of UK and The Netherlands. *Green innovation* is associated with the business management, especially outside Europe. *Eco-innovation* is associated with an eco-design community, although it overlaps with *environmental innovation* especially for communities associated with evolutionary economics, which makes sense since some of the first applications of the concept in this context also used both terms interchangeably, e.g. Rennings (2000). We also found a correspondence between journals and communities, and – very interesting – the use of the Journal of Cleaner Production as common platform of the all the different communities associated with the terms.

7.2.2 Sectoral patterns of eco-innovation

In Chapters 4, 5 and 6, we discussed and analyzed sectoral eco-innovation patterns. The evolutionary economic theory argues that the selection environments are influenced by sectoral-specific elements. We extend this notion to eco-innovation patterns, arguing that it represents a key but neglected dimension in the dynamics of green economic change (del Río et al., 2016; Mazzanti and Zoboli, 2006; Oltra and Saint Jean, 2009a).

First, in Chapter 4, we offer a conceptual clarification and a first set of core hypotheses to guide the search for sectoral eco-innovation patterns. We suggest that the greening of the economy should be understood as a new techno-economic paradigm change (Freeman, 1996a) with specific characteristics which make it likely to be somewhat differently from the previous ones, e.g. firms' ability to profile themselves on their environmental performance and to identify the new green business opportunities is becoming a central competitive factor.

Three dimensions of industries that might generate distinct sectoral patterns of eco-innovation were discussed, namely technological, competitive/market and institutional characteristics of sectors. As environmental impacts are technologic specific and firms in the same sector share a limited group of technologies, we argue that each sector as a specific environmental sensitivity (Malaman, 1996) that influences both environmental regulation and innovation. Moreover, the existence of green-oriented firms in a value chain might push the rest of the tiers to go green as well. Finally, it is expected that, in those sectors demanding for systemic green technologies, firms may have to increase their innovation expenditures and change radically their capabilities.

Second, we argue that, in the absence of proper policy incentives, sectors characterized by highly competitive conditions and low munificence tend to develop a short-term mentality and avoid investing in eco-innovations that do not offer competitive advantages on the short-term. Expanding sectors and those which present capital assets that are depreciated or economically inefficient might find better incentives to conduct eco-innovation than those in which high capital intensity prevents firms to invest in new assets.

Finally, from an institutional point of view, we believe that sectors that are exposed to more regulations (global industries, export- or import-intensive) have more incentives to eco-innovation as they are exposed to a higher number of institutional environments, while in nationally protected and regulated sectors the eco-innovation dynamics tends to be local (Brunnermeier and Cohen, 2003). Moreover, many environmental regulations and standards are sector-specific.

We investigated the effects and intensity of such sectoral patterns of eco-innovation in Chapters 5 and 6, which compose the main empirical part of the thesis. Instead of comparing two or more sectors, we analyzed deeply the dynamics of one specific sector, although the ultimate goal is to serve as benchmark to compare with other sectors in future studies. We assume that the existence of convergence among firms' technological strategies over time is an indicative of emerging sectoral patterns of eco-innovation. The opposite situation is a divergence in their strategies signaling heterogeneity or random behavior, possibly due to other firm- or geographic-specific elements but also rules of thumb (Dosi, 1997; Leiponen & Drejer, 2007; Patel & Pavitt, 1997; Peneder, 2010).

In Chapter 5, our findings indicate that the main alternative technologies present in this sector have followed very different trajectories over the past decades but have become more homogeneous in the last years of the sample. First, the internal combustion and electric-hybrid technologies presented a quite stable path since the 1970s and were rapidly incorporated in most firms' technological portfolios. Being closer to the dominant design mean that the opportunities related with these technologies are easily perceived, thus overlapping the risks associated with the investment in these technologies.

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. The development of fuel cells is considered complex and riskier when compared with the other alternative technologies due to high uncertainty on the costs of hydrogen production, distribution and storage (Debe, 2012; Maxton and Wormald, 2004; Oltra and Saint Jean, 2009b; Pilkington, 2004; van Vliet et al., 2010; Veziroglu and Macario, 2011).

The Chapter 6 corroborates these results and raises additional issues. The reduction in the concentration observed in the preceding chapter is reflected in the firm-specific analysis: most firms converged towards an "average portfolio", especially after the 1990s and, for the group of "complex patents" in the mid-2000s.

The evidence in both chapters of a convergence in firms' technological strategies indicate that, despite significant regional differences in environmental policies and organizational profiles, firms perceived similar risks and opportunities and thus have taken similar decisions in relation to their investments in most of these alternative technologies -- as measured by the share of these groups of technologies in their patent portfolios.

We interpret this convergent movement as a sign of the gradual rise of sectoral-specific patterns of eco-innovation in this sector, highlighting, however, an overlap between sector-specific and technology-specific factors that becomes evident when we compared the group of Fuel cells with the other technologies: while the latter group demonstrated increased convergence over time, the former presented two divergent technological trajectories in the last years of the sample, generating two contrasting trajectories within the firms in the sector, one of leaders and one of laggards.

The literature points that developing riskier technologies requires healthy economic track records from innovating firms (Cainelli et al., 2006; Cyert and March, 1963; Forsman, 2013). For a more complex technology, as we believe to be the case of fuel cells, the risks are greater and the opportunities are reduced, conditions that are amplified by lean environments that pushes firms to short-term strategies and core competences. In this scenario, the literature says that only firms with greater financial performance and resources will have enough flexibility and perceive sufficient opportunities in such a long-term trajectory (Barney, 1991; Cainelli et al., 2006; Cohen & Levinthal, 1990; Cyert & March, 1963; Patel & Pavitt, 1997; Pavitt, 1990; Schumpeter, 1942). The econometric analysis indicates that, indeed, the firms' financial conditions are important determinants of the divergence between the firms in the sector regarding fuel cells, together with general economic shocks. These results are of special importance since the financial health of the firms have been little investigated in the eco-innovation literature (del Río et al., 2016).

Other factors, including geographic-specific and firm size were not significant in our analysis, although they might play important roles in other industries that are not as global as the automotive sector.

As a policy advice, these findings recommend that, besides providing institutional stimuli such as regulations demand-pull, policymakers have to create conditions to maintain firms' incomes during the transition process associated with the greening of the economy, especially during severe economic crisis (Andersen, 2008).

7.2.3 Implications to the understanding of eco-innovation in the automotive industry

The analysis conducted in Chapters 5 and 6 corroborates and challenges some findings in the literature concerning specifically the automotive sector. The increase in the greening of the sector as a process marked by the emergence of new technological trajectories and the convergence of firms' strategies is also supported in the literature (Frenken et al., 2004; Oltra and Saint Jean, 2009b; Sierzchula et al., 2012).

It is often argued that most automakers shifted their R&D activities from battery-electric to fuel cell technologies during the 2000s – leading to a hydrogen or fuel cell hype – and shifted again towards battery electric technologies by the end of the decade (Bakker et al., 2012; Bakker, 2010b; Penna & Geels, 2015; van den Hoed, 2005). However, the dynamics of the sector that is observed in our patent data indicates a much more incremental and co-evolutionary process between these technologies rather than a competitive pattern, with most manufacturers progressively adopting active positions in alternative technologies development (Oltra & Saint Jean, 2009b; Wells & Nieuwenhuis, 2012; Sierzchula et al., 2012). This behavior is consistent with the principle of path-dependent, cumulative and incremental but continuous change that is predicted in evolutionary theories (Nelson and Winter, 1982).

The importance of profitability for the investment in fuel cells that the econometric analysis conducted in Chapter 6 points out might be explained by the intrinsic competitive, technological and productive conditions in this sector, namely its requirements of high capital intensity and intense product innovation dynamics (Zapata and Nieuwenhuis, 2010), inhibiting firms that do not present high profitability in investing in such complex technology since they focus on short-term core activities.

The positive relationship contrasts with the findings of Wesseling et al. (2015) for electric vehicles, as he found a negative association between the current profitability and firms’ decision to invest in this technology, reinforcing the importance of technology-specific dynamics.

Finally, our findings show a decline in the relative participation of “green” internal combustion engines’ patents in the firms’ portfolios, which may signalize the beginning of a reversal in the balance between the incremental investments in the dominant design and alternative technologies that could eventually, in the future, lead to the exhaustion in the opportunities associated with the current paradigm, defying those who argue that the attempts of going green remain marginal to the sector (Wells and Nieuwenhuis, 2012).

7.3 Suggestions for future research

Some suggestions for future research are given in this section. With the discussions and findings present in this thesis, I expect to contribute to open new paths within eco-innovation research.

The critical analysis of the eco-innovation concept opens room for the discussion of more accurate definitions that capture the complexity of the environmental issues. The discussion suggests that, in order to reach the optimal point between overly subjective and objective eco-innovation definitions, a closer look on how the characteristics of the greening process change over time and also among countries and sectors is required. Without these considerations, the concept may be used as mechanism to lock in sectors in inefficient technological trajectories, as I exemplified with the automotive regulation case.

I suggest further that the identification of firms’ changes towards technologies that have great *potential* to reduce environmental impacts might be better indicators of real greening in the sectors where systemic changes are required, instead of relying on technical parameters that are difficult or impossible to measure. Despite the complexity of this challenge, already pointed in the literature (del Río et al., 2016), it is fundamental to understand the differences in what can be considered an eco-innovation, e.g. in different sectors, although in-depth analysis may contribute to assemble this puzzle.

For instance, to conduct the research in the automotive sector, instead of defining eco-innovation as usual, e.g. from the direct impacts of technologies, a number of "promising technologies" (electric/hybrid, fuel cells) were selected, some of which are still at very early stages of development and performance, but whose development indicate clearly a move of firms' strategies towards authentic green behavior. It may well be the case that similar methods cannot be generalized to all sectors of economic activity, but precisely because of this a more detailed analysis of what effectively constitutes the greening of distinct sectors is needed before any generalization.

The boundaries of our bibliometric analysis in Chapter 3 offer opportunities that can be targeted by further research in the formation of different scientific communities and meanings related with this field. An investigation of these terms beyond scientific papers, including industrial magazines, books, news, and reports from private and public organizations, and including other related terms such as *eco-efficient innovation*, *low-carbon innovation*, *innovation for sustainability*, *socio-ecological innovation*, and *externality reducing innovation* may further expand and complement our findings.

A number of authors already mentioned the lack of sectoral studies in eco-innovation as an important gap in the literature (del Río et al., 2016; Oltra and Saint Jean, 2009a; Oltra, 2008) and we are still in the early phases of this discussion. We do not fully understand how the sector-specific factors influence eco-innovation in different sectors.

Although we investigate only one case, the analysis conducted for the automotive sector in Chapters 5 and 6 may serve as a benchmark for comparison of the dynamics and characteristics of eco-innovation in different sectors. The methodology that we developed can be adapted to other sectors that present adequate characteristics, namely big representative firms, considerable patenting activity, and distinguishable green technologies.

The lists of green patents that were used in both chapters are not restricted to automotive technologies. Both the IPC Green Inventory and the OECD's list of Environmentally-sound technologies (EST) present IPC codes for technologies that may be linked to other sectors, including Oil and Gas, Cement, Fertilizers, Agriculture, Glass, Paper and Celluloses, Lightning, and others.

Due to restrictions in the data, we were not able to analyze some important issues in the automotive sector that might be also targeted in future research. We did not include suppliers, smaller automakers, and those from emerging countries like China and India. The inclusion of these actors can add new elements in the dynamic analysis of the eco-innovation in the sector.

Moreover, recent events such as the rise of Tesla Motors as leading company in electric vehicles and potential major competitor, as well as the recent "Dieselgate" scandal involving the Volkswagen group were not captured in this study but may also add important elements to the analysis in the future.

The substantial increase in the relative number of complex patents that we found indicates a process of cross fertilization between the different technologies, e.g. fuel cells and electric/hybrid, electric/hybrid and ICE and so on. Further research may target these complex patents to understand the process of hybridization among the selected technologies.

Finally, our econometric analysis found a significant effect of exogenous aspects such as the post-crisis period and firms' profit margins. Further research may focus on the effect of the financial and economic crisis over the greening of the economy and to other sectors, which can even be stronger than previous though for radical technologies (Archibugi et al., 2013), perhaps even more than the institutional inertia.

ABSTRACT

This thesis aims to contribute to the understanding of the transition between "dirty" and "green" technologies, as well as some structural characteristics of a green economy. We deal with the dynamics of the greening process in an evolutionary perspective and more specifically with the sector-specific patterns that arise in this process.

Combining quantitative and qualitative methods, the thesis investigates theoretical aspects of the eco-innovation concept and the emergence of sectoral patterns of eco-innovation using the automotive sector as case study. Five articles that are here represented in chapters investigate these two phenomena. The discussion starts with two papers that are centered in the critical discussion of eco-innovation concept and its development and narrows to the ultimate focus of discussing empirically and theoretically sectoral patterns of eco-innovation.

In the second part of the thesis, I investigate the existence and strength of sectoral patterns versus fundamental heterogeneity in eco-innovation activities using the automotive sector as a case study. The core assumption is that the observation of patterns in firms' green technological strategies reflect the formation of sectoral patterns of eco-innovation. We chose the automotive sector due to its environmental impact, importance for the economy and society, and for its intrinsic characteristics.

Our findings point out to a convergence in automotive firms' technological strategies, indicating that, despite significant regional differences in environmental policies and organizational profiles, firms perceived similar risks and opportunities and thus have taken similar decisions in relation to their investments in most of the alternative technologies in the sector (for example, electric and hybrid vehicles and, to a less extent, fuel cells), as measured by the share of these groups of technologies in their patent portfolios.

We interpret this convergent movement as a sign of the gradual rise of sectoral-specific patterns of eco-innovation in this sector, highlighting, however, an overlap between sector-specific and technology-specific factors that becomes evident when we compared one specific group of technologies, Fuel cells, with the other technologies: while the latter group demonstrated increased convergence over time, the former presented two divergent technological trajectories in the last years of the sample, generating two contrasting trajectories within the firms in the sector, one of leaders and one of laggards. Further research indicates that one of the factors related with this divergence is the firms' financial conditions. These results are of special importance since the financial health of the firms has been little investigated in the eco-innovation literature. Other factors, including geographic-specific and firm size were not significant in our analysis, although they might play important roles in other industries that are not as global as the automotive sector.

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