Is The Future Of Automotive Green(ish)?
A Longitudinal Patent Analysis On The Impact Of Regulation, Technology And Demand On Different Shades Of Green Innovations In The Automotive Sector Across OECD Countries.

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Dissertation written under the supervision of René Bohnsack and Arash Rezazadeh

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Resumo

Esta tese investiga os principais determinantes da eco-inovação na indústria automóvel, centrando-se especificamente na questão de saber se, e em que medida, o sector está a transitar do paradigma tecnológico do Motor de Combustão Interna (ICE) existente para um paradigma baseado nas tecnologias dos Veículos Eléctricos (EV). A inovação é medida utilizando dados de patentes como substituto, sendo as inovações destruidoras de paradigmas classificadas como "green" e as inovações que aumentam o paradigma como "greenish", com base nas classes de patentes. A análise centra-se em três factores principais da eco-inovação: a regulamentação (regulation push/pull), a tecnologia (technology push) e a procura (demand pull). O estudo emprega uma abordagem quantitativa abrangente baseada num conjunto de dados de painel a nível nacional de 34 países da OCDE de 2005 a 2021, desenvolvido especificamente para a investigação, compilando dados de várias fontes, incluindo a OCDE, a AIE e a OICA. As conclusões revelam que os factores da regulamentação, especialmente os mecanismos não mercantis, e os factores de atração da procura, impulsionam significativamente as inovações destruidoras de paradigmas. Em contrapartida, os factores de pressão tecnológica parecem promover inovações que melhoram as tecnologias ICE existentes. O estudo destaca a necessidade de quadros políticos integrados, claros e fiáveis, incentivos ao consumidor e ao mercado, e apoio complementar à I&D para estimular a mudança para o paradigma tecnológico baseado na tecnologia dos EV.

Abstract

This thesis investigates the key determinants of eco-innovation within the automotive industry, specifically focusing on whether and to what extent the sector is transitioning from the existing Internal Combustion Engine (ICE) technology paradigm to a paradigm based on Electric Vehicle (EV) technologies. Innovation is measured using patent data as a proxy, with paradigm-destroying innovations classified as "green" and paradigm-enhancing innovations as "greenish," based on patent classes. The analysis focuses on three major drivers of eco-innovation: regulation push/pull, technology push, and demand pull. The study employs a comprehensive quantitative approach based on a country-level panel dataset of 34 OECD countries from 2005 to 2021, developed specifically for the research, compiling data from several sources, including OECD, IEA, and OICA. Findings reveal that regulation push/pull factors, especially non-market mechanisms, and demand pull factors, significantly drive paradigm-destroying innovations. In contrast, technology push factors appear to foster innovations that enhance existing ICE technologies. The study highlights the need for integrated, clear and reliable policy frameworks, consumer and market incentives, and complementary R&D support to stimulate the shift toward the technological paradigm based on EV technology.

Keywords: eco-innovation, drivers, automotive, patents, policy stringency, regulation push/pull, technology push, demand pull, OECD countries, path dependency, technological paradigm, Internal Combustion Engine, Electric Vehicles.

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1. Introduction

"Enough of killing ourselves with carbon"

These powerful words, spoken by United Nations Secretary-General António Guterres on November 1, 2021, at COP26, stressed the urgency of transitioning away from fossil-fuel-dependent economies, and the catastrophic consequences of failing to do so for both the planet and the human race.

The transport sector is one of the most significant contributors to global greenhouse gas (GHG) emissions, with passenger cars accounting for roughly 10% of CO_2 worldwide emissions (Statista, 2024). Transport largely relies on the internal combustion engine (ICE) technological system, with 95% of the world's transport energy coming from fossil fuels (United Nations, 2021). In addition to GHG emissions, the ICE system contributes to the production of local pollutants, such as particulate matter (PM), hydrocarbons (HC), nitrogen oxides (NO_x), sulphur dioxide (SO_2), carbon monoxide (CO), and ground-level ozone (O_3), significantly affecting urban air quality (Krzyzanowski and Cohen, 2008). In light of this evidence, the innovation activity in the automotive sector plays a crucial role in the green transition and sustainable growth.

Therefore, in recent years, the transition from the ICE system to electric mobility has emerged as a critical and necessary solution for a sustainable future, as emphasized not only by academics (Colombo *et al.*, 2024) but also by some of the most influential figures in the global arena. For example, Elon Musk remarked that "all transport will go fully electric, with the exception of spacecraft" at the National Governors Association Summer Meeting in 2017 (Ward, 2017). Similarly, US President Joe Biden, in 2021, affirmed that "The future of the auto industry is electric. There's no turning back" during a visit to the Ford Rouge Electric Vehicle Center (The New York Times, 2021). Bill Gates, in his article "How do we move around in a zero-carbon world?" shared a similar sentiment: "Switching to electric vehicles and alternative fuels is the most effective way we can move toward zero emissions" (Gates, 2020). In 2015, at Monaco's first Formula E race, Prince Albert II asserted that "Electric Cars are the future" (The New York Times, 2015). Mary Barra, CEO Of General Motors, recently reaffirmed this vision, stating, "We believe in an all-electric future" at the Tamer Institute's 2024 Climate Business and Investment Conference (Sperling, 2024).

However, as former Chancellor of Germany Angela Merkel stated at the World Economic Forum in 2020, "The biggest and most difficult area of transformation is, as things currently stand, mobility. The transition to CO2-free mobility is a huge challenge." (Bundesregierung, 2020).

Given this, the present paper seeks to explore the drivers that can have an impact on the transition to electric mobility. It aims to provide insights and support to policymakers, governments, academics and anyone else researching ways to transform the above aspirational statements into actionable strategies, ensuring the vision of a sustainable, low-emission future becomes a reality before it is too late.

This study aims to explore the key determinants of eco-innovations in the automotive industry and assess whether, in the future, the sector could transition from the reliance on Internal Combustion Engine (ICE) technology to a paradigm centred on Electric Vehicles (EV) technologies, as reflected in this thesis's title *"Is The Future Of Automotive Green(ish)?"* and research question: "What is the impact of regulation push/pull, technology push and demand pull on paradigm-enhancing, (*greenish*), eco-innovations and paradigm-destroying, (*green*), innovations in the automotive sector"?

Therefore, this analysis seeks to disentangle the impact of a set of well-established drivers (regulation, technology and demand) on the emergence of radically new, EV-related technologies and incremental, ICE-related technologies. The goal is to determine whether these factors are steering the sector towards a fundamental technological paradigm shift or fostering incremental improvements within the existing ICE framework.

The study intends to make a significant contribution to the existing literature by performing a comprehensive country-level analysis over an extended time period that investigates the influence of all three sets of determinants upon the development of both radical, paradigm-destroying technologies and incremental, paradigm-enhancing ones. The empirical analysis relies on an original database constructed specifically for this research. This database primarily draws on data from the Organisation for Economic Cooperation and Development (OECD), with additional data coming from the International Organization of Motor Vehicle Manufacturers (OICA) and the International Energy Agency (IEA). To measure environmental innovations, patent data will be used as a proxy, categorizing patent classes to differentiate between ICE-related and EV-related technologies

The structure of this study is organized as follows: Section 2 outlines the literature related to the treated topics, beginning with an overview of eco-innovations and the automotive sector. It then reviews the literature on eco-innovation determinants, followed by a detailed examination of the main drivers within the automotive industry. Subsequently, it analyses relevant concepts such as technological trajectories and path dependency and concludes by presenting the research hypotheses and literature gaps this thesis addresses. Section 3 describes the empirical models and the data, Section 4 presents the findings, Section 5 discusses them, and section 6 concludes.

2. Literature Review

2.1 Eco-innovations and the automotive sector

The central theme of this paper is eco-innovation, chosen for its relevance in the present days and the growing scholarly interest in recent years (Díaz *et al.*, 2015). This thesis adopts the Rennings (2000) and Oltra *et al.* (2008) definitions of eco-innovation, which describe it as new or modified processes, practices, systems and products which benefit the environment and contribute to environmental sustainability. Additionally, to provide a broader understanding of eco-innovation, this definition is complemented by the OECD definition of eco-innovation as "the creation of new, or significantly improved, products (goods and services), processes, marketing methods, organizational structures and institutional arrangements which - with or without intent - lead to environmental improvements compared to relevant alternatives" (OECD, 2008, p. 19).

For the purpose of this study, these definitions were preferred over the Oslo Manual definition of eco-innovation (OECD and Eurostat, 2005), which includes the implementation of a new technology developed by a different firm or institution (Arundel and Kemp, 2009), and the EU-funded "Measuring Eco-Innovation" project's definition (Kemp and Pearson, 2007), which adds a subjective view (Horbach *et al.,* 2012), stating that the innovation must be new only to the firm. There are many other similar definitions which were developed in the last decades; most of them are reported in the paper of Díaz *et al.*(2015, p. 5).

The automotive sector has been selected for analysis for several key reasons.

Firstly, as mentioned in the Introduction, it is highly relevant today as one of the industries that greatly contributes to greenhouse gas emissions. According to the International Energy Agency (IEA) 2021 Report (Bouckaertet al., 2021), to achieve the net zero by 2050, as called for in the Paris Agreement, it is necessary to completely cut sales of new internal combustion engine passenger cars by 2035 and phasing out all unabated coal and oil power plants by 2040.

According to Nunes and Bennet (2008, p.1), "The automotive industry is one of the industries that have visibly suffered a strong demand for higher environmental performance. This industry has enjoyed years as the main source of employment and economic growth and still has a strong political influence; nevertheless, today, it is being pointed out as one of the major contributors to air pollution in urban centres".

Secondly, it is a sector which has seen significant environmental innovations in the past years (Bhatia and Jakhar, 2021; Maldonado-Guzmán *et al.*, 2021). From the 1970s, oil shocks and growing environmental awareness (Meadows *et al.*, 1972) have spurred efforts into the “greening” of the engine, aiming to reduce energy consumption and emissions (Faria and Andersen, 2017). However, it is worth noting the presence of an ongoing debate about the negative environmental impact also electric cars may have. For example, the Arthur D. Little (ADL) report (2016) argues that while EV cars reduce their local contribution to greenhouse gas emissions, they have their own set of environmental challenges related to human health, primarily due to the use of large battery packs.

Finally, the automotive industry is often analyzed for its potential regarding product design and eco-innovation (Segarra-Oña *et al.*, 2011; Sierzchula *et al.,*2012; Díaz *et al.*, 2015), and it is an exemplary case for examining competing technological trajectories (Mazzei *et al.*, 2023) and lock-in effects (Christensen, 2011), concepts that will be thoroughly discussed later in this thesis.

2.2 Drivers of eco-innovation

There is a large body of literature discussing the drivers of eco-innovation, and what stands out in most studies is that public policies, supply-push and demand pull are the critical factors for shaping the rates of creation and diffusion of these environmental-related innovations (Horbach, 2008; Del Río, 2009; Nemet, 2009; Kuhlmann *et al.*, 2010; Horbach *et al.*, 2012; Triguero *et al.*, 2013).

A large body of literature agrees that regulation is a critical source and driver of eco-innovation (Rennings, 2000; Nemet, 2009; Doran and Ryan, 2012; Horbach *et al.*, 2012; Johnstone *et al.*, 2012; Costantini and Crespi, 2013; Bohnsack *et al.*, 2015; Aghion *et al.*, 2016; Calel and Dechezleprêtre, 2016) and helps its diffusion (Wagner and Llerena, 2011). Regarding expected regulations, i.e. those in the stage of evaluation or adoption by policymakers, Triguero *et al.* (2013) found that they have a positive effect on the development of green innovation, too.

This is because regulations are strategic tools for policymakers to allocate the appropriate amount of resources toward the generation of technological and scientific knowledge, addressing substantial market failures in this area (Nelson, 1959; Arrow, 1962). This is especially relevant for environmentally-related innovations due to the well-known double externality problem: the development and diffusion of eco-innovations generate significant positive externalities that are inevitably captured by third parties. As a result, firms may underinvest in R&D since they do not fully internalize the social returns of their inventive efforts, leading to sub-optimal allocation of R&D resources (Rennings, 2000; Jaffe *et al.*, 2005; Rennings *et al.*, 2006; Oltra *et al.*, 2008; Horbach *et al.*, 2012).

For instance, Veugelers (2012, p.1170) underscores that "the private clean innovation machine, left on its own, is not up to this challenge (reducing greenhouse emissions). It needs government intervention to address the combination of environmental and knowledge externalities and overcome path dependencies".

However, regulation can also be a source of institutional lock-in, as claimed by Foxon (2002). Additionally, environmental regulations vary significantly between countries, leading firms to develop green technologies that respond to a heterogeneous set of incentives and regulatory requirements (Tatoglu *et al.*, 2014; Kawai *et al.*, 2018; Marin and Zanfei, 2018), thus possibly creating opportunities for firms to exploit competitive advantages across different markets.

Regulations can be market-based or non-market-based, and regarding their impact, the literature is discording, with some studies arguing that the former are more capable of fostering eco-innovations (Jaffe *et al.,* 2000; Popp, 2003; Costantini *et al.*, 2015), and others considering the potential of the latter to be more effective (Carraro, 2000; Rennings, 2000). Many studies highlighted, in fact, the difficulties in ranking these two types of instruments with regard to their efficacy in spurring eco-innovation (Fischer *et al.*, 2003; Requate, 2005; Kemp and Pontoglio, 2011; Veugelers, 2012).

Furthermore, the literature has provided substantial evidence of the importance of both technology push and demand pull instruments in the development of eco-innovation (Rennings, 2000; Newell, 2010; Horbach *et al.*, 2012).

On the technology push side, it has been found that the quality and level of technological capabilities acquired through R&D are critical for the development and diffusion of eco-innovation both at a micro and at a macro level (Löschel, 2002; Popp *et al.*, 2009, 2011a, 2011b; Johnstone *et al.*, 2012). Blum-Kusterer and Hussain (2001) claim that new technology is a crucial driver for eco-change and sustainability improvements, which aligns with Horbach (2008), who found in a longitudinal study that enhancing "knowledge capital" through R&D triggers environmental innovations. Similarly, Segarra-Oña *et al.* (2011) argue that formal innovative activity (patents) and total expenditure on technology acquisition influence firms' eco-innovative orientation.

However, the relationship between the supply push of R&D and eco-innovation is complex and sometimes inconclusive, showing conflicting results in the literature. Cuerva *et al.* (2014) highlight that technological capabilities foster conventional innovation but not green innovation in a low-tech sector. Also, Cainelli *et al*. (2011), in a study on industrial firms in Emilia Romagna, show that general R&D is less related to innovation adoption with respect to other factors such as foreign ownership or networking.

When considering the technology push, firms' strategies also play an important role and should be considered (Ghisetti and Rennings, 2013; Cecere *et al.*, 2014). Firms, in fact, play a fundamental role in the sustainable growth process by engaging in green innovations development (De Marchi, 2012; Kesidou and Demirel, 2012; Dangelico, 2016) and including low-carbon energy solutions into their businesses (Pinkse and Van den Buuse, 2012; Albino *et al.*, 2014; Bodas-Freitas and Corrocher, 2019). However, firms often rely on their existing technologies and competencies, so they are more likely to pursue incremental environmental innovations rather than explore new paradigms (March 1991; Levinthal and March 1993).

These inconclusive results about technology push may be clarified by the findings of Petruzzelli *et al.* (2011). These authors found that the technologies underpinning eco-innovations tend to be more complex and novel compared to other innovations. This higher level of novelty appears to be detrimental to the value of eco-innovation, at least in the short-medium term. They also find that developing such innovations often necessitates greater collaboration with external actors, which is essential for creating the most valuable innovations. In fact, it has been discovered by many studies that activities involving collaboration are important for the development and adoption of eco-innovation, such as networking with other firms and institutions (Cainelli *et* al., 2011; Klewitz & Hansen, 2013), knowledge sharing (Wong, 2013) and collaboration with research institutes and universities (Triguero *et al.*, 2013).

As far as the demand pull is considered, it has been found that market demand and the level of prices are critical incentives to eco-innovations for firms (Newell *et al.*, 1999, 2006; Popp, 2002; Beise and Rennings, 2005; Johnstone *et al.*, 2010). At the same time several studies argue that customer perception and the value consumers put to green products or services is a driver in the firm's decision to engage in eco-innovation (Rehfeld et *al.*, 2007; Kammerer, 2009; Dangelico and Pujari, 2010; Grunwald, 2011; Wagner and Llerena, 2011; Doran and Ryan, 2012; Horbach *et al.*, 2012).

However, the inventive effort driven by demand pull is not always directed toward a specific solution, such as electric vehicles, but rather toward broader consumer goals, such as pollution reduction, and this happens particularly when users lack the competencies and abilities to fully assess the problem (Fontana and Guerzoni, 2008; Guerzoni, 2010).

Finally, the literature identified other important drivers of eco-innovations. Two relevant ones are financial constraints and the presence of pressure groups or stakeholders. Johnson and Lybecker (2012) consider financial availability a key driver of eco-innovations. Eco-innovators from the private sector experience great difficulty in attracting venture capital funds for development (Halila and Rundquist, 2011), thus a common policy recommendation to incentivize eco-innovation is to reduce financial constraints characterizing SMEs (Cuerva *et al.*, 2014). Additionally, also pressure groups or stakeholders have been identified as factors influencing eco-innovation practices for firms. For instance, Guoyou *et al.* (2013) discovered that foreign customers may drive companies to adopt a strategy of product/process eco-innovation, whereas foreign investors affect the adoption of green process innovation.

2.3 Regulation push/pull, technology push and demand pull in the automotive sector

Several studies have empirically investigated the influence of regulatory push/pull factors, technology advancements, and market demand in promoting eco-innovation within the automotive industry. Some of the most relevant findings will be presented below with the aim of providing the reader with a comprehensive foundation for the subsequent analysis and discussions in this paper, guiding the exploration of how these factors interact and influence the development of environmentally-related technologies in the automotive sector.

Zailani *et al.* (2015) conducted a survey study on several firms in the Malaysian automotive supply chain industry and found that regulations, market demand and firm internal initiatives positively impact green innovation initiatives, which in turn are observed to have a positive effect on firm's sustainable performance (i.e. economic, social and environmental). Similarly, Maldonado-Guzmán *et al.* (2024) examined the role of environmental regulations in eco-innovation development and sustainable performance within the Mexican automotive industry. They concluded that stringent regulations, combined with effective enforcement, significantly drive eco-innovation, enhancing sustainable performance. These studies underscore that through a robust regulatory framework, eco-innovations can be fostered, and this will not only reduce environmental impact but also improve the sustainable performance of the firms developing and/or adopting them. A patent-based analysis of European Information and Communication Technology (ICT) firms by Corrocher and Ozman (2020) corroborates these findings, demonstrating that the development of green technologies is positively associated with firm performance.

Mondéjar-Jiménez*et al.* (2015) segmented the Spanish automotive industry based on firms' environmental orientation and claimed that tailored vertical policies are key for promoting eco-innovation. Their study highlights that regulatory frameworks need to be specific and targeted to drive environmental innovation within the sector effectively.

Kuik (2007) conducted a study about the impact of eco-innovations of three car fuel efficiency programs: the European Automobile Manufacturers' Association (ACEA) Agreement, the Corporate Average Fuel Economy (CAFE) of the US Congress and the Top Runner Program in Japan. This study evidenced that these environmental policies induce incremental innovation rather than radical and breakthrough discoveries, with the European and Japanese industries being more stimulated than the US program by environmental regulations.

Haščič *et al.* (2008) discovered that gasoline prices and regulatory standards positively influence environmental technologies in the automotive industry. They noted that domestic policies impact foreign innovations more than domestic ones due to the anticipatory behaviour of domestic firms regarding upcoming regulations. This interesting phenomenon was also studied by Shao *et al*. (2021), who discovered a positive neighbourhood spillover, called the "ripple effect", in a study on the impact of environmental regulations on green innovations in different regions of China. Additionally, Dechezleprêtre *et al.* (2012) also studied the effects of policies on foreign countries' green innovation outcomes in the automotive sector. With a study on 49 countries over a period of fifteen years, they examined how regulatory distance impacts the transfer of environmentally sound technologies (EST) in automotive, discovering that the number of new ESTs increases when the regulatory differences between two countries decrease. Moreover, this study indicates that a greater regulatory distance between the source country and the export market of the recipient country has a negative and statistically significant effect on environmentally sound technologies.

On the technology push side, research underscores the importance of R&D and technological capabilities in fostering eco-innovation. Potter and Graham (2019) explored the co-development of electric, hybrid, and fuel cell technologies within the Japanese automotive industry, emphasizing that supplier involvement and collaborative R&D strategies are crucial for technological advancements. Their study shows that sustained collaborative investment in R&D and strong supplier technological capabilities are vital for the co-development and diffusion of electric and hybrid technologies, while the same effect is not significant for fuel cell-related ones.

Wu *et al.* (2020) further supported this by demonstrating that technological capability and cooperative R&D strategies significantly enhance eco-innovation performance in China's new energy vehicle industry. Moreover, they found that state ownership strengthens this positive R&D input-output relation. These findings align with those of Scarpellini *et al.*(2012), who highlighted the role of private-public collaboration in driving R&D and eco-innovation in Spain, suggesting that these partnerships are essential to compensate for the lack of internalization of eco-innovation activities by companies.

Louis and Felice (2009), with a case study on the Volvo Company, discussed the dynamics of market pull, technology push, and legislation for eco-innovations. They emphasized that while technology push is crucial, the complexity and novelty associated with eco-innovations require substantial collaboration, strategic anticipation of market trends, and legislative alignment. Their findings indicate that innovative capabilities and technological advancements are essential, but coherent policies and market mechanisms must support them.

Fernando *et al.* (2021) examined the impact of eco-innovation on recycled product performance and competitiveness in the Malaysian automotive industry, finding that competition pushes consumer demand for sustainable products and significantly influences firms' innovation activities.

Peiró-Signes and Segarra-Oña (2018) studied the Spanish automotive industry and found that past decisions regarding environmental orientation significantly affect future eco-innovative behaviours of firms in the long term, reinforcing the importance of market demand in shaping firms' innovation strategies. Van den Hoed (2007), who conducted a study on the emergence of fuel cell technology in the automotive industry, further corroborated these insights, revealing that market demand for performance improvement may induce radical eco-innovations.

Fewer studies, including the two reported below, have analyzed the impact of a combination of these factors and their interplay on eco-innovations in the automotive industry; thus, this will be one of the gaps in the literature addressed by the present study.

Demirel and Kesidou (2019) underscore the importance of aligning regulatory, technological, and market demands to stimulate eco-innovation. They found that eco-R&D, instead of generic R&D, is crucial for firms to meet these demands, emphasizing that a supportive voluntary regulatory environment coupled with capabilities in sensing the green market demand can significantly enhance eco-innovative outcomes.

Similarly, the study by Costantini *et al.* (2015) on the biofuels sector demonstrates that an integrated approach, combining technological and market drivers, effectively promotes eco-innovation. In particular, they found that demand pull policies have a more significant impact on innovation dynamics regarding mature technologies, while for less mature technologies innovation, a dual role of demand pull and technology push is observed to foster eco-innovations.

2.4 Technological trajectories: lock-in, path dependence, and green transition in the automotive industry

The concept of carbon lock-in, introduced by Unruh (2000), illustrates how energy systems become entrenched in carbon-intensive infrastructures due to path dependencies. This phenomenon is particularly relevant in the automotive industry, where existing investments in internal combustion engine (ICE) technologies create significant inertia against the shift to greener alternatives.

The presence of a lock-in effect in the automotive industry that supported the ICEs production has been widely confirmed and observed by past literature (for example, see: Johan Schot *et al.*, 1994; Cowen and Hultén, 1996; Unruh, 2002; Orsato and Wells, 2007).

For over a century, in fact, the ICE has been the predominant technology in vehicles. Although the first engines, introduced by Otto, Daimler and Benz in the 1880s, have been greatly improved over the years, "they are in principle surprisingly similar to today's engines" (Dijk and Yarime, 2010, p. 1375). The study by Dijk and Yarime (2010) found that this is due to engines being significantly locked into a trajectory of internal combustion technology, which has produced inertia in the sector despite social pressures. They identify three key sources of innovation lock-ins driven by path dependency: demand, supply, and regulatory lock-ins. Consumers tend to prioritize the lowest price and highest performance, creating demand lock-in. On the supply side, firms face challenges when moving away from their established investments, technologies, and capabilities. Finally, regulatory lock-in occurs when policies continue to favour existing technologies instead of encouraging a shift toward new, more sustainable alternatives.

Bjørnåvold and Van Passel (2017) further illustrate the lock-in effect by analyzing the automotive cooling systems within the European Union. Their research reveals that in this sector, even regulatory policies aimed at environmental goals can create a "snowballing effect" that will lock-in the market, allowing for the dominance of a potentially inferior technology. The authors also argue that the automotive industry may be prioritizing short-term fixes over sustainable, long-term solutions, thus perpetuating technological inertia.

The work of Aghion *et al.* (2016) adds to this discussion by highlighting the presence of path dependency in the innovation activities of automotive firms. Their study notes that companies that are historically innovators in traditional technologies find it more profitable to keep investing in these established technologies despite the incentives for greener alternatives.

Theoretical work suggests that the lock-in situation may be eliminated by a combination of exogenous shocks, regulation, major technological breakthroughs, digital integration, change in consumer behaviour, or the emergence of niche markets, but many are also pessimistic about a relatively rapid transition away from the ICE technological lock-in (Cowan and Hultén, 1996; Unruh, 2002; Christensen, 2011; Bohnsack *et al.*, 2021). Additionally, Oltra and Saint Jean (2009a) argued that fuel cell vehicles might be the most promising option for escaping this lock-in condition in the automobile industry. This should be considered with the contrasting findings of Pantaleone and Fazioli (2022), who, studying hydrogen and fuel cell technologies, found the presence of lock-in effects on fossil fuel policies. Additionally, studying the emergence of fuel cell technologies in the automotive industry, van den Hoed (2007) identifies five potential "change factors" that, combined, may foster the adoption of this radical technological change: new entries, external shocks or crises, performance of the new technology, market changes and industry competition.

The development of low-emission vehicles (LEVs) in the automotive sector represents a textbook case of competing technological trajectories (Mazzei *et al.*, 2023), where diffusion might be either hindered or fostered by socio-economic bottlenecks and opportunities (Dosi, 1988). This scenario illustrates the technological competition between a dominant design and a set of emerging green trajectories (Sierzchula *et al.*, 2012; Karvonen *et al.*, 2016). Recent empirical evidence, based on patent analysis, highlights the presence of very active competition among LEVs (Rizzi *et al.*, 2014; Faria and Andersen, 2017; Yuan and Cai, 2021), yet the ICE technology still represents the dominant design (Dijk and Yarime, 2010; Borgstedt *et al.*, 2017). This suggests the presence of a "sailing ship effect" (Sick *et al.*, 2016), where incumbent firms are only marginally adopting electromobility, focusing instead on incremental innovations within the traditional ICE domain. The concept, also known as the "red queen effect" in biology and applied in industrial contexts (Barnett and Hansen, 1996; Derfus *et al.*, 2008), underscores that competition among alternative designs not only promotes the new but also reinforces the old existing technologies/firms which strive to survive (Snow, 2008; Adner and Snow, 2010).

Feng and Magee (2020) provide a comprehensive analysis of the technological development trajectories in the electric vehicle field by decomposing them into sub-domains. Their research shows that while significant progress has been made in key sub-domains, such as battery technology, the rate of improvement varies significantly across different sub-domains. The study underscores the importance of sustained R&D investments and technological advancements in overcoming the performance limitations of EVs. Moreover, it suggests that to foster the development of EV-related technologies, it is critical to pay attention to the adjustment of business strategies of the key players of each sub-domain: Toyota and Honda in hybrid power electronics, E-One Moli Energy Corp in lithium-ion batteries, Panasonic in Permanent Magnet motors and Toyota in discharging.

Lastly, Novaresio and Patrucco (2022) explore the patterns of green innovation in the automotive industry from a long-term perspective. Their empirical analysis of OECD countries from 1990 to 2018 reveals that two different kinds of economies push the greening of the automotive industry: "economies of specialization" through private R&D and "learning economies" fostered by economic policies. The complementarity of these two suggests the need for a systemic approach. This aligns with Cabigiosu and Lanzini (2023), who provided a detailed overview of the green transition of the automotive industry and highlighted how a combination of government action and heavy R&D investments might smooth current bottlenecks to the green transition.

In conclusion, it remains uncertain which of the highly complex technological solutions will emerge as the next dominant design (Sierzchula *et al.*, 2012), and the current paper seeks to provide further insights into the process of addressing these uncertainties.

2.5 Relevance with the present study and gaps in the literature

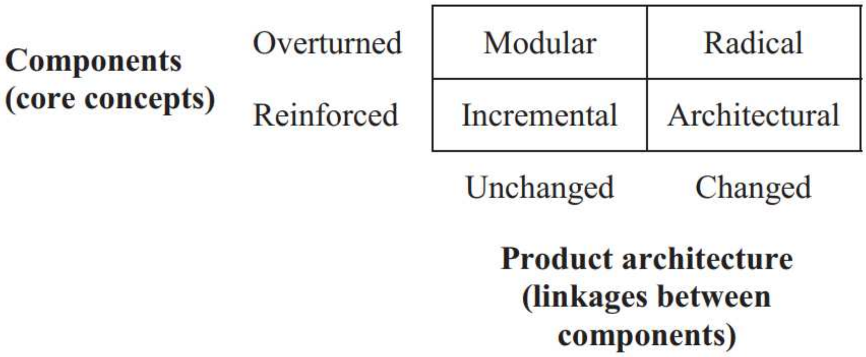
The development of low-emission vehicles (LEVs) is frequently cited in research as a key example of the competition between a set of alternative green technologies (Sierzchula *et al.*, 2012; Karvonen *et al.*, 2016). Previous studies have provided a clear picture of the development of LEVs (Oltra and Saint Jean, 2009a; Borgstedt *et al.*, 2017) and forecasts of technological trends in this sector (Yuan and Cai, 2021).

It is relevant for the scope of the present analysis to highlight that the drivers of eco-innovation in the automotive industry do not necessarily follow a set path. Instead, they can lead to a variety of different outcomes, creating diverse technological pathways. These trajectories vary significantly with respect to their difference and degree of disruption with the dominant design paradigm, which is currently centred around the ICE technology (Oltra and Saint Jean, 2009b; Faria and Andersen, 2017).

In this regard, Bergek *et al.* (2014), using the well-known competence-based typology of innovations of Henderson and Clark (1990), provide four main types of innovation output promoted by different types of environmental policy instruments in the automotive and energy sectors (see Figure 1):

- **Incremental innovations** involving small technological changes aimed at enhancing the standard available technology.
- **Modular innovations** featuring the addition of substantial changes in the core design of one or more components of the standard technology to improve its efficiency and performance.
- **Architectural innovations** entailing the reconfiguration of existing components into the creation of an entirely new design within the established technology.
- **Radical innovations** which are characterized by the introduction of entirely new components that change the product architecture and potentially also the purpose of the established technology, and pave the way for a shift in the technological paradigm and the creation of a new technological trajectory.

Figure 1: Eco-innovation typology, from Bergek et al. (2015, p. 115)



Therefore, based on previous literature, it is recognized that different drivers can stimulate different types of environmental innovations in the automotive sector. For the purpose of this analysis, the possible innovation trajectory outcomes identified by Dijk *et al.* (2013), Bergek *et al.* (2014) and Calabrese (2016) are simplified, and those proposed by Mazzei *et al.*(2023) are adopted, meaning that eco-innovations will be categorized into two possible classes. One class includes all inventions aimed at greening and improving the environmental efficiency of the ICE, representing an incremental innovation trajectory. The other class identifies a competing set of more radical technologies related to hybrid and electric vehicles or fuel cell technologies (HEF)[1], representing a radical competing trajectory[2] in contrast with the ICE one. This approach allows for the examination of a scenario where environmental innovations are paradigm-destroying, pulling away from the ICE paradigm, or a scenario in which eco-innovations stimulate advancements within it, thereby reinforcing the existing technological paradigm in the automotive industry.

[1] Although product HEF trajectory appears highly heterogeneous, commonalities exist regarding the underlying technologies. For example, hydrogen and electric solutions are becoming more complementary and integrated (Mazzei *et al.*, 2023).
[2] Regarding product design, HEF vehicles could represent what Henderson and Clark (1990) define as a modular innovation, in which the architecture remains almost unchanged, whereas the components (engine) are modified. Although the transmission system remains almost unaltered, HEF technologies radically modify the energy generation process. Therefore, the term radical is used to contrast the notion of incremental technological solutions to mitigate ICE emissions. This approach is aligned with, and inspired by, the one used by Mazzei *et al.* (2023, p. 827).

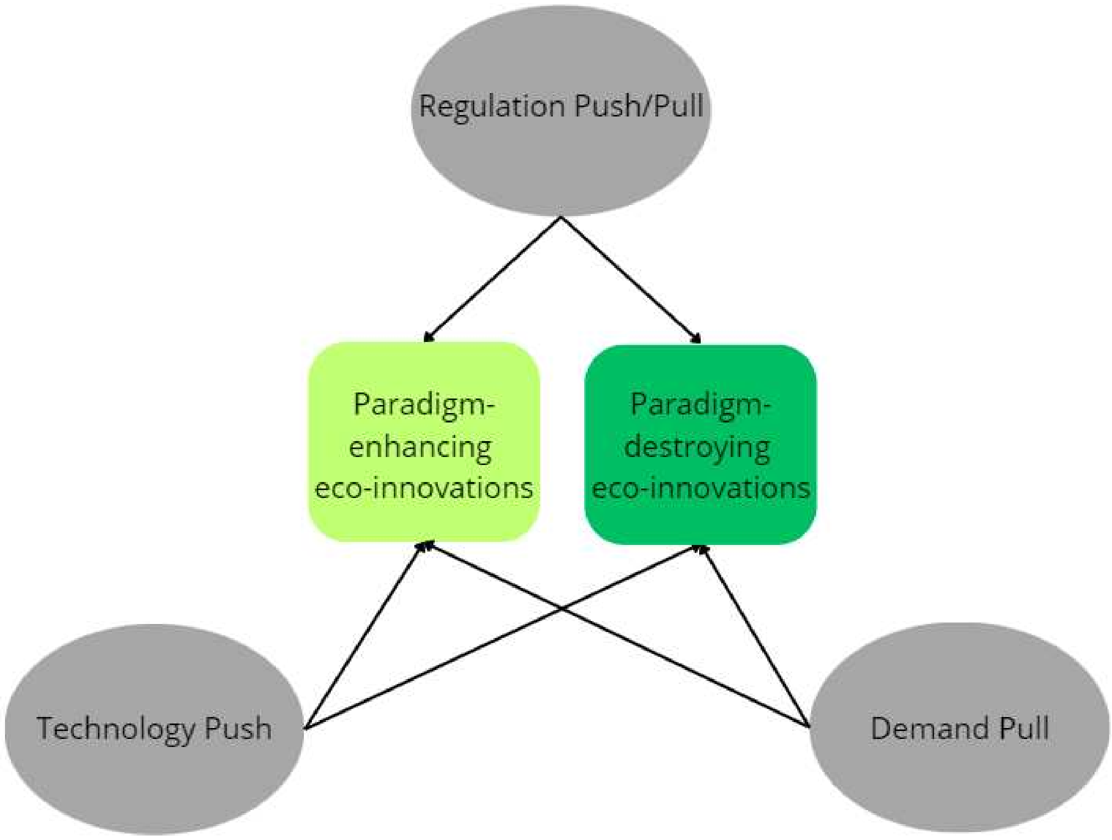
According to Dijk *et al.* (2013), the key factors driving the emergence of an electric mobility trajectory vis à vis a traditional ICE paradigm are the following:

- Changes in the global car market and a variation in the mobility utility (**demand pull** factors).
- Shifts in the fueling infrastructures, an evolution of energy prices, and developments in the electricity sector (**technology push** factors).
- The impact of climate policies (**regulatory** factors).

Therefore, the present work intends to empirically assess whether these three major drivers of eco-innovation are prompting a paradigm change in the automotive sector, evidenced by a decrease in ICE-related innovations and an increase in EV-related ones, or whether they are leading to a greening of the existing paradigm, resulting in an increase in ICE-related innovation, with no substantial impact on EV-related technologies (see Figure 2).

To sum up, the present study aims to examine the role of each of the specific drivers discussed in either enhancing or destroying the existing technological paradigm, an area that, to the best of the available knowledge, has not yet been addressed fully by the current literature. Additionally, this analysis will be conducted across a broad range of countries and over an extended time span, with the goal of producing findings that are more widely applicable. This approach contrasts with much of the existing literature, which typically focuses on individual countries or shorter periods.

Figure 2: Theoretical model of the analysis



3. Methodology

3.1 Research approach

A quantitative approach was selected to address the present analysis's research question, specifically employing statistical regressions as the primary analytical tool. This choice is rooted in the strengths of quantitative research and the nature of the research problem. Quantitative research methodologies enable the systematic measurement and analysis of data, facilitating the identification of patterns and testing of hypotheses regarding the effects of regulatory push/pull, technology push, and demand pull factors on innovation outcomes (Creswell, 2017).

Furthermore, quantitative methods are characterized by their precision and objectivity, which are crucial for offering a systematic framework for analyzing data, minimizing the influence of researcher bias and enhancing the credibility of the research (Saunders *et al.*, 2009; Johnson and Christensen, 2024). In examining the impact of policies and other factors on eco-innovation, this precision allows for a more accurate and reliable assessment of the effectiveness of different interventions.

Finally, the choice of this methodological approach aligns with the broader objectives of producing research that is not only descriptive but also explanatory and predictive. By quantifying the relationships between variables, with this approach the present study aims to contribute to the existing literature with findings that are generalizable and that can inform both theory and practice in the field (Polit and Beck, 2010).

3.2 Dataset construction

Data on OECD countries over 17 years have been collected to investigate green patenting activity as a function of regulatory pressure, technology push, and demand pull.

The dataset has been created using several OECD databases to collect different variables related to patenting activity (OECD STI Micro-data Lab: Intellectual Property Database, 2023), environmental policy stringency (OECD Climate Actions and Policies Measurement Framework (CAPMF), 2024), environmental-related innovation and technology measures (OECD Green Growth, 2024), green consumption (U.N. Environment Programme (UNEP) Global Material Flows Database, 2023), and information about the country's GDP (OECD NAAG Chapter 1, 2024) and population (OECD Historical Population Data, 2023).

Moreover, in addition to the OECD datasets mentioned, data has also been retrieved from the International Organization of Motor Vehicle Manufacturers (OICA) (OICA, 2023) dataset for information on the automotive market and from the International Energy Agency (IEA) datasets (IEA, 2024a, 2024b) for information regarding the electric vehicle market and energy prices.

All OECD countries have been considered except Colombia and Costa Rica because of their too recent OECD membership accession and Latvia and Lithuania for high presence of missing data. The result is a balanced panel dataset of 34 OECD countries from 2005 to 2021.

The missing values (5.6833% of the total) are imputed using Breiman's Random Forest method (Breiman, 2001) because they appear to have a random distribution over countries, years and variables, i.e. *Missing at Random,* which implies that the likelihood of a value being missing is influenced solely by the values that are observed, and not by those that are unobserved (Schafer and Graham, 2002). The random forest method has been shown to generate significantly more accurate predictions than traditional parametric methods (Muchlinski *et al.*, 2016, Tang and Ishwaran, 2017), and in the present study, it will be applied with the Multiple Imputation by Chained Equations method (MICE).

The MICE method, used with the fully conditional specification (FCS) approach because of its flexibility and effectiveness (Van Buuren, 2007), allows for the imputation of each variable's missing values based on its own conditional distribution, and also employing all the other variables in the dataset as predictors (Shah *et al.*, 2014).

3.3 Variables description

3.3.1 The dependent variables

OECD (OECD STI Micro-data Lab: Intellectual Property Database, 2023) outlines seven technological classes of green patents within the automotive sector. These have been organized into categories inspired by the frameworks of Aghion *et al.* (2016) and Agnelli *et al.* (2023), which typically utilize a three-tier classification system: dirty, grey, and clean. However, for the purposes of this study, a two-tier system, similarly to Mazzei *et al.* (2023), was preferred: greenish and green. This classification is based on the role of the technologies in enhancing or disrupting existing paradigms. Innovations classified as "green" are paradigm-destroying; they challenge the traditional internal combustion engine (ICE) paradigm by integrating electric or fuel cell systems, entailing both architectural and radical changes. On the other hand, "greenish" innovations are paradigm-enhancing; they represent an evolutionary development of the ICE system toward a more sustainable model and are generally more incremental. Table 1 categorizes in detail these technological classes based on their role as either paradigm-enhancing or paradigm-destroying, thereby indicating their respective shades of green.

Patents have been used as an indicator of innovative activity for decades (Scherer, 1965; Schmookler, 1966). This approach has become the predominant method for assessing the innovative output of companies, industries, and nations (Braun *et al.*, 2011). More recently, patents have also been widely employed as a proxy variable of eco-innovation (Oltra *et al.*, 2010; Haščič and Migotto, 2015), despite their acknowledged limitations (Oltra *et al.*, 2010; Braun *et al.*, 2011; Haščič and Migotto, 2015; Reeb and Zhao, 2020). In particular, in the automotive industry, patents accurately reflect the innovative activity as they play a strategic, reputational, and essential role in this "complex product sector" (Blind *et al.*, 2006), and because it is one of the industries with the highest proportion of firms protecting their innovations with patents (Oltra *et al.*, 2010).

Figure 3 and Figure 4 display the trends in greenish and green patents over time, segmented by country. It can be observed that OECD countries, with the exceptions of the Czech Republic and Switzerland, exhibit a rather constant or declining trend in greenish patents over the examined period. Conversely, the trend for green patents is steady or rising, except in Greece and New Zealand.

Figure 5 and Figure 6 illustrate the trends of greenish and green patents per capita for the countries with the highest patent production in the automotive sector, namely France, Germany, Japan, Korea, the UK and the USA. It is observed that Germany, Korea and Japan are the countries with the highest green patenting per capita, and Korea stands out as the country with the most significant positive difference between green and greenish patenting.

Table 1: Technologies by transport eco-innovation class

Technology	**Paradigm-position**	**Shade of Green**	**Patent Class**
Internal Combustion Engine (ICE)	PAR ENHANCING	GREENISH	Y02T 10/00
Emissions abatement from mobile sources	PAR ENHANCING	GREENISH	Y02T10/80
Fuel efficiency-improving vehicle design	PAR ENHANCING	GREENISH	Y02T10/12
Hybrid vehicles	PAR DESTROYING	GREEN	Y02T10/62
Electric vehicles	PAR DESTROYING	GREEN	Y02T10/64
Electric charging systems	PAR DESTROYING	GREEN	Y02T90/10
Fuel cell systems	PAR DESTROYING	GREEN	Y02T90/16

Figure 3: Greenish patents by Country

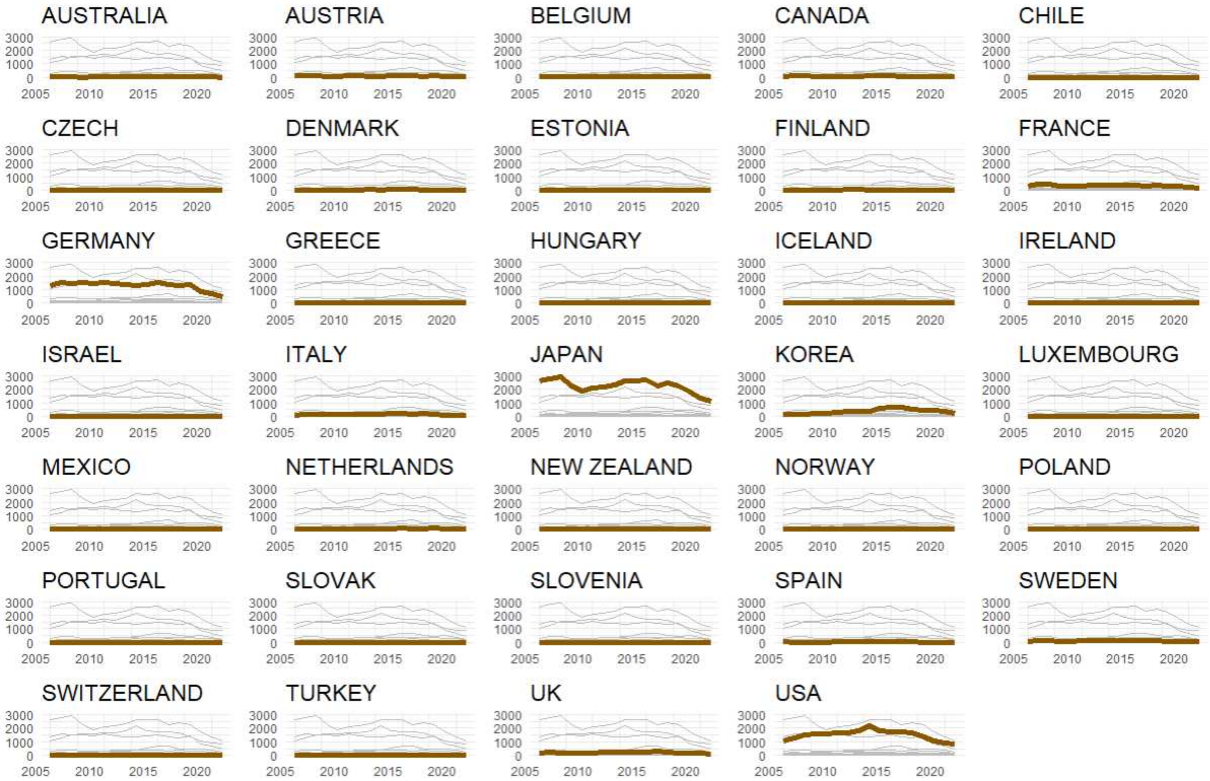


Figure 4: Green patents by Country

Figure 5: Greenish patents per capita – Most Innovative Countries

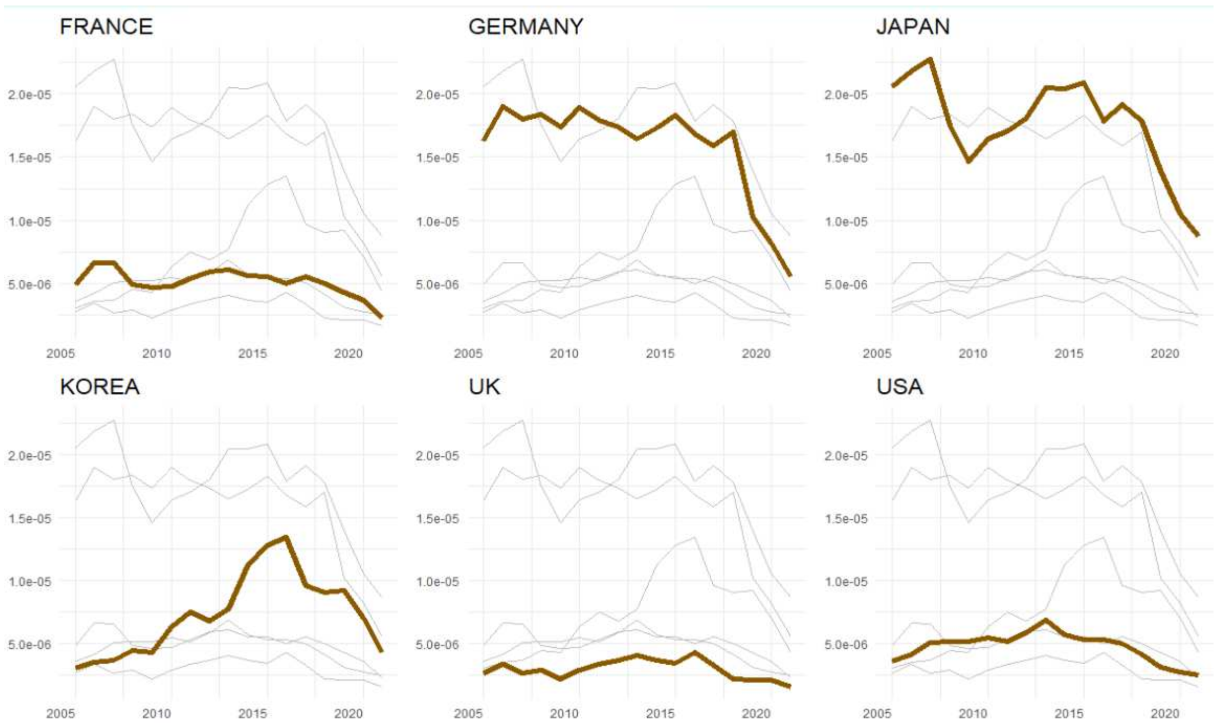
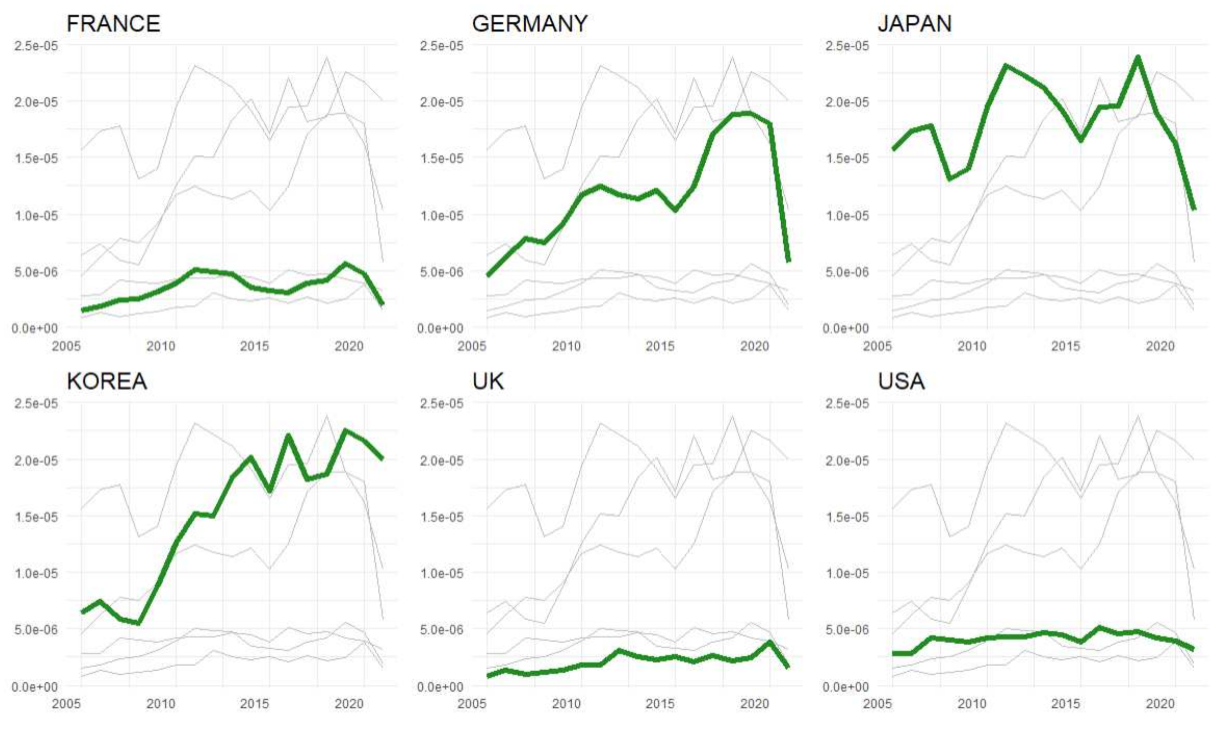


Figure 6: Green patents per capita – Most Innovative Countries



3.3.2 The independent variables

The explanatory variables employed in this study are three traditional determinants of eco-innovations: regulation push/pull, technology push and demand pull (Rennings, 2000; Horbach *et al.*, 2012).

The effect of regulation is captured through the Environmental Policy Stringency Index (EPS) developed by OECD (OECD Climate Actions and Policies Measurement Framework (CAPMF), 2024). The EPS, built by Botta and Koźluk (2014), is an internationally comparable index covering 40 countries, including all the 34 OECD countries analyzed in the current study, and 13 policy instruments, focusing predominantly on climate change and air pollution policies. The unit of measure is an index of stringency of environmental policies ranging from 0 (absence of policies in place) to 6. In the present research, the updated version of the EPS will be used, the EPS21, developed by Kruse *et al.* (2022), which considers market, non-market and technology-support policies instruments. The EPS captures the level of policy stringency across several sectors, including the transport ones. For the purpose of this study, also the impact of specific components within the EPS is investigated: Diesel Tax, NOx Tax, NOx Limit, Particulate Matter (PM) Limit, and Sulphur content limit in diesel fuel, to explore their influence on green innovative activity in the automotive sector.

Additionally, the present study considers two aggregate stringency transport-specific indexes from the OECD Climate Actions and Policies Measurement Framework (2024): transport market instruments and transport non-market instruments. Market-based mechanisms incorporate emissions trading scheme (ETS[3]), carbon tax[4], fuel excise taxes[5], fossil fuel support (FFS)[6] and congestion charges[7] (Nachtigall *et al.*, 2022); whereas non-market-based mechanisms encompass bans and phase-outs[8], fuel economy standards[9], mandatory energy

[3] Data is based on IPAC data collection drawing on data from the Global Status reports of the International Carbon Action Partnership (ICAP) and the World Bank's Carbon Pricing Dashboard.
[4] Data is based on IPAC data collection drawing on the World Bank's Carbon Pricing Dashboard and IEA's energy tax data.
[5]Data is mostly based on IEA's energy tax data, with some IPAC data collection for some countries drawn on OECD's PINE database..
[6] Data on FFS is based on the OECD Inventory on Support for fossil fuels. See Table Annex B1 in the CAPMF working paper for a more detailed description of and caveats related to the use of OECD fossil fuel support data.
[7] Data was collected by the OECD IPAC, drawing primarily on Croci, 2016 and complemented with other sources.
[8] Data was collected by the OECD IPAC, drawing on various data sources such as the International Council on Clean Transportation (ICCT).
[9] The underlying data on fuel economy standards for passenger cars is courtesy of the policy tracking activities of the Energy Efficiency and Inclusive Transitions Office at the IEA. Data on fuel economy standards for heavy-duty vehicles comes from the RISE database developed by the World Bank's Energy Sector Management Assistance Program.

labels[10], rail public infrastructure[11] and speed limits[12] (Nachtigall *et al.*, 2022). This is done to examine the effects of regulation that may be falling outside the scope of the EPS21 and to account for the potential difference of influence between market-based and non-market-based policy. It has been found, in fact, that in recent years, non-market-based policy instruments have generally seen the most significant absolute increase in stringency across the OECD (Kruse *et al.*, 2022).

As a proxy for technology push, the variables employed in the analysis are designated to signal a country's level of green technological competencies both absolutely and relatively to other countries. To this extent, the development of green patents as a percentage of domestic inventions and the index of relative technological advance in environmentally-related technologies are utilized. Furthermore, a key element of technology push is government investment in R&D (Ren and Albrecht, 2023). This investment compensates for the underinvestment by private firms and mitigates the private costs of innovation (Jaffe *et al.*, 2002; Nemet, 2009), which stem from the 'double externality problem' (Rennings, 2000). Therefore, the analysis includes environmental-related public R&D as a percentage of the government's R&D budget, as well as, Fossil Fuel R&D and Renewables R&D budgets as percentages of the public energy R&D budget.

To capture the demand pull, it is used the total vehicles sales and its share of battery electric vehicles (BEV), plug-in hybrid electric vehicles (PHEV) and fuel cell electric vehicles (FCEV), to measure the propensity towards the purchase of green vehicles, and the material footprint per capita, to assess the propensity for green consumption. This approach is based on the findings of Guerzoni (2010), who found that as the market size gets bigger and its user more sophisticated, there is an incentive to invest in green innovations.

Finally, two control variables are included: GDP per capita, inspired by the study on eco-innovation, green investments and CO2 emissions in China by Hordofa *et al.* (2023), and road fuel price, which has been shown to be a key factor in the automotive sector for the development of innovations (Gallagher and Muehlegger, 2011; Aghion *et al.*, 2016; Agnelli *et al.*, 2023).

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[10] The underlying data on labels is courtesy of the policy tracking activities of the Energy Efficiency and Inclusive Transitions Office at the IEA.
[11] Data comes from OECD ITF's Investment Spending in Transport Infrastructure.
[12] Data was collected by the OECD, drawing on OECD ITF's Road Safety Annual Reports and WHO's Global Status Report on road safety.

Table 2 and Table 3 are reported to assist the reader in navigating through the analysis. The former provides a summary of the statistics for each variable, whereas the latter details the variables' names, definitions, and proxies they represent.

Table 2: Variable's statistics

Variable	Mean	Variance	Min.	Max.	N. Obs
Greenish	194.40	249,158.17	0.00	2,909.50	578
Green	181.73	233,034.31	0.00	3,023.08	578
EPS	2.72	0.90	0.00	4.89	578
DieselTax	3.26	1.97	0.00	6.00	578
NOx Tax	0.92	3.59	0.00	6.00	578
NOx Lim	4.33	2.86	0.00	6.00	578
PM Lim	4.22	4.57	0.00	6.00	578
Sulphur Lim	5.60	0.55	0.00	6.00	578
Transp Mkt Instr	2.62	2.18	0.00	6.29	578
Transp NonMkt Instr	2.84	1.65	0.00	6.67	578
Env Perc of Inv	11.55	14.47	0.96	27.12	578
Rel Env Tech Adv	1.03	0.10	0.08	3.02	578
Green RD	2.62	4.61	0.00	17.66	578
Renewables RD	24.94	215.13	0.00	66.80	578
Fossil RD	7.40	256.33	-61.62	96.96	578
Vehicle Mkt Size	1,294,207.38	1,379,971.98	2,471	17,865,773	578
Green Vehicles Perc	0.019	0.004	0.00	0.681	578
Material Footprint	27.61	172.55	9.18	86.76	578
GDP PC	41.24	313.02	11.91	137.95	578
Fuel Prices	1.79	0.38	0.62	4.27	578

Table 3: Variables overview

Variables	Description	Proxy
Greenish	Number of paradigm-enhancing patents	ECO-INNOVATION
Green	Number of paradigm-destroying patents	ECO-INNOVATION
EPS	Environmental Policy Stringency Index	REGULATION
Diesel Tax	Diesel tax (stringency index)	REGULATION
NOx Tax	NOx tax (stringency index)	REGULATION
NOx Limit	NOx emission limit (stringency index)	REGULATION
PM Limit	PM emission limit (stringency index)	REGULATION
Sulphur limit	Limit of sulphur content in diesel fuel (stringency index)	REGULATION
Transp Mkt Instr	Transport - Market-based instruments (stringency index)	REGULATION
Transp NonMkt Instr	Transport - Non market-based instruments (stringency index)	REGULATION
Env Perc of Inv	Development of environmental related technologies -% of domestic inventions	TECHNOLOGY PUSH
Rel Env Tech Adv	Index of relative technological advantage in environmental related tech	TECHNOLOGY PUSH
Green RD	Environmental related R&D -% government R&D budget	TECHNOLOGY PUSH
Renewables RD	Renewables R&D -% energy public R&D	TECHNOLOGY PUSH
Fossil RD	Fossil Fuel R&D -% energy public R&D	TECHNOLOGY PUSH
Vehicles Mkt Size	Total Vehicle Sales	DEMAND PULL
Green Vehicles Perc	Green vehicles (BEV+ PHEV+ FCEV) sales -% vehicles sales	DEMAND PULL
Material Footprint	Material Footprint -tonnes per capita	DEMAND PULL
GDP PC	Gross Domestic Product per capita	CONTROL
Fuel Prices	Road Fuel Price	CONTROL

3.4 Empirical analysis and model specification

The purpose of the present empirical analysis is to explore the relationship between the two categories of eco-innovations specified above (paradigm-enhancing and paradigm-destroying) and three factors, i.e. regulation push/pull, technology push and demand pull, to determine whether they act as drivers, or barriers, for greenish and/or green innovations. As it can be noted in Figure 7, the statistics for greenish and green patents are highly skewed with few outliers, therefore a logarithmic transformation has been applied, significantly improving the linear fit of the distributions, as shown by Figure 8.

Figure 7: Scatterplot of Patent Number and EPS for paradigm-enhancing and paradigm-destroying technologies

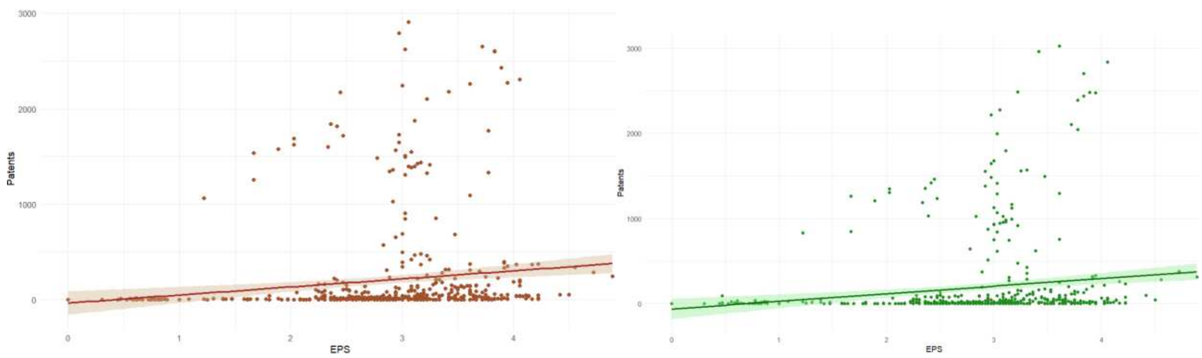
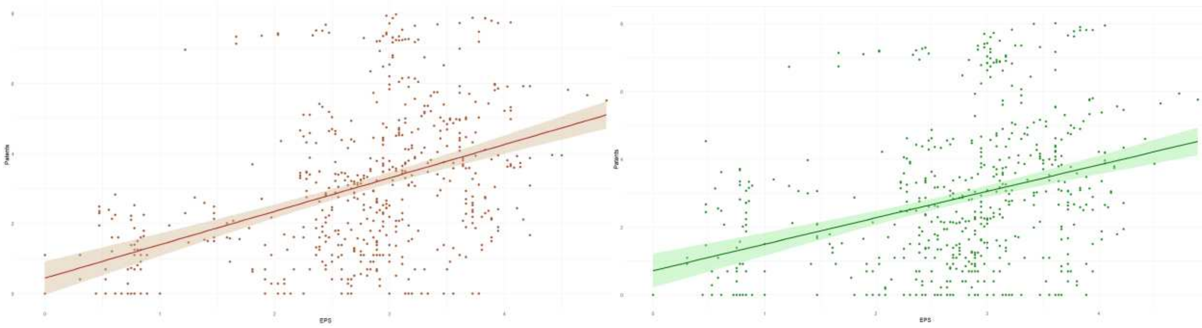


Figure 8: Scatterplot of LOG Patent Number and EPS for paradigm-enhancing and paradigm-destroying technologies



The statistical method employed in this analysis is the Ordinary Least Squares (OLS) regression with fixed effects estimation, which focuses on within units' variation rather than between units, in order to control for unobserved heterogeneity across cross-sectional units. This approach, applied to the panel data created as described above, allows to effectively control for all time-invariant characteristics of each country, removing the potential bias caused by omitting these characteristics from the model, which is a major concern of this analysis.

Multicollinearity has been identified among some variables related to regulation, particularly with the EPS, which shows a high Variance Inflation Factor (VIF). This was expected because, as explained in Section 3.2, Diesel Tax, NOx Tax, NOx limit, PM limit and Sulphur limit are components of the EPS index. Additionally, both market-based and non-market-based transport instruments share common elements with the EPS index. Therefore, the following models will consider either EPS alone or its components when a more detailed analysis is required. By doing so, the VIF is effectively lowered to levels that are no longer concerning. This adjustment aligns with expectations and ensures the integrity of the model's results.

The correlation matrix highlights the high correlation between proxies of technologies push, specifically between "Environmental-related Percentage of Inventions" and "Relative Environmental-related Technology Advantage" index, as well as, “Green R&D” and “Renewables R&D”. These associations were anticipated given the similar nature of these variables. To prevent biased outcomes, these variables are analyzed in separate models. Since both sets of variables yield similar results and the same intuitions, only the models featuring the "Relative Environmental-related Technology Advantage" index and the Renewables R&D variable will be reported to facilitate readability.

Furthermore, given that the studentized Breusch-Pagan test revealed heteroskedasticity in the residuals, White's heteroskedasticity-consistent standard errors have been employed. Additionally, the errors have been clustered to mitigate the effects of serial correlation.

The final estimated model equation is as follows:

$$\text{Patents}_{i,t} = \alpha_i + \beta_1 X_{i,t} + \beta_2 C_{i,t} + \epsilon_{i,t}$$

where:

- $\text{Patents}_{i,t}$ represents the logarithm of the number of greenish or green patents in the automotive sector in country i at time t.
- α_i captures the country-specific time-invariant characteristics.
- $X_{i,t}$ is the set of covariates that incorporates regulation push/pull, technology push and demand pull.
- $C_{i,t}$ is the matrix of controls.
- $\epsilon_{i,t}$ stands for the idiosyncratic error, which captures random fluctuations in patent numbers that are not explained by any other element of the model.

It is useful to outline the models' specifications to guide the reader in the following analyses. Model 1, presented in columns 1 and 2, broadly investigates the impact of regulation using the EPS index. Model 2, detailed in columns 3 and 4, delves into the specific components of the EPS index to explore their individual roles more thoroughly. Model 3, shown in columns 5 and 6, incorporates the technology push variables, while Model 4, reported in columns 7 and 8, represents the final model since it also includes the demand pull effect.

The models are then analysed with several variations to explore potential insightful differences and check the robustness of the results.

The dependent variable was lagged by one and two years in the analysis. This was done because patents are the output of a long process and results of inventive activity, so there may be a lag between patenting and regulation, technology and demand influences (Kleinknecht and Verspagen, 1990). This methodology is supported by findings from several studies on eco-innovations and the automotive sector, which found the presence of lag effects (e.g. Costantini *et al.*, 2015; Agnelli *et al.*, 2023). The lagged models yielded the same intuitions, and, due to better performance, only the results with a two-year lag are reported and displayed in Table 4.

Table 5 details the results from models incorporating a two-way fixed effect specification, to control for time specific unobserved heterogeneities, thus accounting for potential trends and/or shocks that might affect all economies similarly during the same period, such as global economic fluctuations, international policy shifts, and technological breakthroughs.

Finally, Table 6 adjusts the models to consider the population of each country, calibrating the dependent variable to per capita terms to ensure comparability across different national contexts.

4. Results

Model 1 (Table 4) reveals no statistically significant correlation between countries' environmental policy stringency and the production of paradigm-enhancing innovations. However, a significant positive correlation is found with the production of paradigm-destroying innovations. This suggests that stringent environmental policies may be more effective in promoting radical technological changes rather than incremental ones.

Model 2 (Table 4) delves deeper by examining the transport-specific components. It identifies that non-market instruments have a significant positive correlation with the development of green innovations. Other components, including market-based instruments, do not show statistically significant effects. Consistent with the previous model, no policy instrument significantly correlates with the development of greenish innovations.

Model 3 (Table 4) incorporates the technology push element into the analysis and demonstrates that public R&D budgets related to renewable energy and to fossil fuels are significantly and positively correlated with the development of greenish innovations. Interestingly, it is discovered that no technology push variable significantly affects green innovations. Additionally, this model reinforces the findings from Model 1 by showing that the EPS index has a statistically significant positive effect on green patents development.

Model 4 (Table 4) includes demand pull factors and reveals that the percentage of green vehicles has a statistically significant effect on both types of innovations: a negative impact on greenish innovations and a positive one on green innovations. Moreover, the total vehicle sales size in a country is found to have a significant negative impact on greenish patents.

Furthermore, both Model 3 and Model 4 indicate that the development of paradigm-enhancing innovations positively influences the development of paradigm-destroying innovations, whereas the reverse relationship is not statistically significant. Finally, it is observed that GDP per capita has a positive statistically significant impact on green patents.

Similar insights are obtained when controlling for time-fixed effects and adjusting the dependent variables to per capita terms, as it can be observed in Table 5 and Table 6.

It is worth noting that when standardizing the dependent variable of patent counts to per capita terms, the material footprint per capita is found to have a significant negative effect on paradigm-destroying innovations. This suggests that a greener consumption pattern and a greater green propensity among the population may positively influence green patenting activity in the automotive sector, reinforcing the findings on the impact of the demand pull factor suggested by Table 4.

Table 4: Y=LOG X=LAG$_{t-2}$

	Dependent Variable:							
	Greenish (1)	Green (2)	Greenish (3)	Green (4)	Greenish (5)	Green (6)	Greenish (7)	Green (8)
EPS	0.0407	0.2919**			0.0477	0.3018**	0.1048	-0.0002
	(0.0885)	(0.1015)			(0.0815)	(0.1010)	(0.0963)	(0.0876)
Diesel Tax			-0.0349	0.0071				
			(0.0272)	(0.0406)				
NOx Tax			0.0121	-0.0388				
			(0.0192)	(0.0489)				
NOx Limit			0.0848	-0.1262				
			(0.0694)	(0.0674)				
PM Limit			-0.0472	0.0771				
			(0.0358)	(0.0412)				
Sulphur Limit			0.1237	0.1273				
			(0.0725)	(0.0766)				
Transp Mkt Instr			-0.0045	0.0162				
			(0.0307)	(0.0423)				
Transp Non-Mkt Instr			-0.0608	0.1921*				
			(0.0457)	(0.0755)				
Green					-5.31e-05		6.95e-05	
					(0.0003)		(0.0003)	
Greenish						0.0004*		0.0006**
						(0.0002)		(0.0002)
Rel Env Tech Adv					-0.1172	-0.0259	-0.1172	-0.0394
					(0.1009)	(0.1788)	(0.1050)	(0.1542)
Renewables RD					0.0064**	0.0016	0.0058**	0.0020
					(0.0021)	(0.0031)	(0.0019)	(0.0025)
Fossil RD					0.0046*	0.0019	0.0036	0.0034
					(0.0020)	(0.0032)	(0.0020)	(0.0025)
Vehicles Market Size							-4.52e-08*	4.25e-09
							(2.07e-08)	(3.12e-08)
Green Vehicles Perc							-2.029**	3.110*
							(0.6894)	(1.3071)
Material Footprint PC							-0.0011	0.0008
							(0.0070)	(0.0113)
GDP PC							-0.0081	0.0315***
							(0.0051)	(0.0073)
Fuel Prices							0.1254	0.0035
							(0.1374)	(0.2145)
N. Observations	510	510	510	510	510	510	510	510
R^2	0.0014	0.0442	0.0353	0.1546	0.0334	0.0509	0.0737	0.2031
Adj. R^2	-0.0701	-0.0242	-0.0470	0.0825	-0.0446	-0.0257	-0.0118	0.1296
F Statistic	0.2114	8.2723**	1.4631	8.9830***	3.1131**	2.3458	6.7008***	5.7144***

Note: *$p<0.05$; **$p<0.01$; ***$p<0.001$

Table 5: Y=LOG X=LAG, Temporal Fixed Effect

	Dependent Variable:	
	Greenish	Green
	(1)	(2)
EPS	0.0030***	-0.1613*
	(0.0984)	(0.0798)
Green	4.2301e-05	
	(2.6846e-04)	
Greenish		4.1240e-04**
		(1.3284e-04)
Rel Env Tech Adv	-0.0694	-0.0278
	(0.0728)	(0.1670)
Renewables RD	0.0039*	0.0021
	(0.0024)	(0.0025)
Fossil RD	0.0036*	0.0029
	(0.0017)	(0.0024)
Vehicles Market Size	4.4791e-09	1.0139e-08
	(2.6879e-08)	(2.8851e-08)
Green Vehicles Perc	-0.4799	3.5982**
	(0.4780)	(1.2697)
Material Footprint PC	0.0015	0.0080
	(0.0064)	(0.0113)
GDP PC	0.0135**	0.0276**
	(0.0052)	(0.0089)
Fuel Prices	0.1599	0.1099
	(0.2155)	(0.3721)
N. Observations	510	510
R^2	0.0337	0.0867
Adj. R^2	-0.0881	-0.0285
F Statistic	2.4434**	9.0461***

Note: *p<0.05; **p<0.01; ***p<0.001

Table 6: Y=PAT/POP X=LAG

	Dependent Variable:	
	Greenish	Green
	(1)	(2)
EPS	2.7244e-07	-1.3587e-07
	(3.1190e-07)	(3.4412e-07)
Green	-2.5598e-10	
	(2.9844e-09)	
Greenish		3.5161e-09*
		(1.7194e-09)
Rel Env Tech Adv	-4.4430e-07	2.3876e-07
	(3.2647e-07)	(4.2448e-07)
Renewables RD	1.8115e-08*	9.8641e-10
	(8.1076e-09)	(8.0799e-09)
Fossil RD	5.3283e-09	9.0712e-09
	(4.6793e-09)	(5.0713e-09)
Vehicles Market Size	1.0525e-13	1.6219e-13
	(2.0344e-13)	(2.2519e-13)
Green Vehicles Perc	-6.3752e-06	7.0079e-06***
	(3.5025e-06)	(2.0258e-06)
Material Footprint PC	-2.1682e-08	-4.3369e-08*
	(2.0891e-08)	(2.1116e-08)
GDP PC	-4.6316e-08*	8.7172e-08**
	(2.1481e-08)	(3.3416e-08)
Fuel Prices	1.0527e-07	-2.1160e-07
	(3.8156e-07)	(4.4757e-07)
N. Observations	510	510
R^2	0.0635	0.1364
Adj. R^2	-0.0229	0.0567
F Statistic	1.4314	5.3702***

Note: *p<0.05; **p<0.01; ***p<0.001

5. Discussion

The above findings highlight the different ways in which the factors analyzed influence the development of paradigm-enhancing and paradigm-destroying eco-innovations in the automotive sector. The implications of these results could be a helpful tool for policymakers, industry stakeholders, and researchers aiming to foster sustainable innovation in the automotive sector.

It is observed that the regulation push/pull factor positively impacts the green patenting activity. This aligns with the "weak" version of the Porter Hypothesis, which states that stringent and well-designed environmental regulations can trigger innovation and the introduction of cleaner technologies (Porter, 1996), which was further supported by several empirical studies, most of them reported in a literature review study by Ambec *et al.* (2013), which confirmed that environmental regulations could indeed enhance innovations with improved environmental outcomes.

Interestingly, it appears that non-market instruments, such as standards and limits, are found to be the ones driving this effect. In contrast, market-based instruments like taxes and subsidies do not show statistically significant results. This could be due to the fact that, according to Rennings (2000), non-market instruments are less influenced by market fluctuations and other economic variables, thus providing clearer and more stringent signals, compared to market-based instruments, which can create a more predictable environment for firms to invest in new technologies. This finding aligns with Carraro (2000), which highlights the effectiveness of non-market-based policies in driving environmental innovation under imperfect competition.

Therefore, regarding environmental policies, the present study suggests that to foster green innovations in the automotive sector, it may be critical to develop robust regulatory frameworks, strengthening especially non-market instruments, and ensuring stability and predictability to provide clear and consistent signals to the industry.

Moreover, it is shown that demand pull is another significant factor driving eco-innovations in the automotive sector. It is observed, in fact, that the green vehicles market size and the automobile market size negatively affect greenish innovations. Conversely, the market demand for green vehicles and the lower material footprint, which entails a greener consumption pattern by citizens, positively influence green patent counts. This underscores the critical role of consumer behaviour and market demand in encouraging green innovations in the automotive sector.

It is well known in the literature that market demand acts as a powerful source of innovation (Di Stefano *et al.*, 2012), and this relationship is rooted in the "strong" version of induced innovation theory by Acemoglu (2002), which argues that a shift in the market can stimulate firms to develop new technologies to meet these changing preferences.

Moreover, the present analysis suggests that when consumers are more environmentally conscious and reduce their material footprint, a market for sustainable products is created, thereby driving innovation in this direction. Research supports the idea that environmentally conscious consumers can significantly impact market dynamics. For example, it is highlighted that consumers' growing awareness and concern for environmental issues lead to increased market shares for green products (The Nielsen Company, 2015). This consumer behaviour not only fosters a market for sustainable products but also encourages firms to differentiate themselves by investing in green technologies (Ottman *et al.*, 2006).

Based on these findings, it is suggested to consider strategies to leverage the power of the demand pull to drive innovation in green technologies, fostering a more sustainable automotive sector. Examples include enhancing consumer awareness and education about the environmental impact of their consumption choices. In this way, consumers may be more likely to demand green products, driving innovation in that direction. Moreover, offering subsidies, tax breaks, or similar instruments to consumer who purchase environmentally friendly products such as electric vehicles, lowers the upfront cost barriers and may encourage consumers to opt for greener choices. Additionally, supporting the green consumer market through infrastructure development and policies could be an effective strategy. For instance, expanding the charging infrastructure for electric vehicles may render EVs more attractive to consumers, thus increasing demand.

Furthermore, an interesting result is found for the technology-push factors, which are found to have a significant positive impact on greenish innovations but no significant effect on green innovations. This differentiation highlights the role of public R&D investments in fostering paradigm-enhancing rather than paradigm-destroying eco-innovations in the automotive sector.

This may be due to the fact that while the green capabilities and knowledge necessary for innovation and paradigm transition in the automotive sector are already in place, the supporting elements, such as demand and regulation, are lacking. This creates a situation of "lock-in", or

"Regime Resistance" (Geels, 2014), and path dependency on the traditional ICE paradigm, hindering the full potential development of green innovations.

This hypothesis is supported by several studies discussing the readiness of technological capabilities versus the lag in regulatory and market support. Unruh (2000) argues that although existing technological capabilities for low-carbon solutions are present, systemic inertia, or "carbon lock-in", including regulatory and market failures, prevents their widespread use and adoption. Similarly, Foxon and Pearson (2008) highlight that technological systems often outpace the development of supportive institutional frameworks and market structures, which are not sufficiently developed to facilitate a transition.

Based on these findings, it is suggested to not only sustain and enhance R&D public investments, especially in high-impact areas as renewable energy and sustainable transportation, but also to put frameworks and mechanisms in place to ensure they are complemented by a robust policy framework and a strong market demand adopting a holistic strategy that considers all these elements together to drive a more comprehensive and effective green transition in the automotive sector. It is critical to find the optimal policy mix of technology and demand to effectively spur innovation, as it has already been argued in several studies (March, 1991; Nemet, 2009; Costantini *et al.*, 2015).

Finally, it is observed that the development of greenish innovations positively influences the development of green ones. The reason behind this could be that in the automotive industry the accumulated knowledge in incremental innovation domains fosters the technological positioning of firms in the disruptive innovation domains. This finding aligns with Mazzei *et al.* (2023), who, with a study on the patenting activity of automotive firms at the United States Patent and Trademark Office (USPTO) between 2001 and 2018, found that "brown" knowledge denotes leadership in green technological trajectories.

The present study reveals both convergences and divergences with the reported literature in Section 2, thus the remaining of this Section will be devoted to examining the areas where the findings align with existing literature and where they diverge, providing a comprehensive overview of the consistencies and discrepancies observed.

This thesis found that non-market instruments play a crucial role in driving green patenting activity. This aligns with the literature suggesting that non-market instruments can provide clear and stable signals, promoting innovation more effectively than market-based instruments (Carraro, 2000; Rennings, 2000). At the same time, however, this intuition contrasts with studies like those by Jaffe *et al.* (2000), Popp (2003) and Costantini *et al.* (2015), which argue that market-based instruments are more capable of fostering eco-innovations.

Interestingly, this study's findings regarding the impact of technology push factors diverge from a large body of the literature reported in Section 2. This could be attributed to the fact that previous studies typically did not differentiate between greenish and green eco-innovation. The present study observes that technology push factors positively impact greenish innovations but do not significantly affect green innovations. While many studies, as mentioned in Section 2, argue that technological capabilities acquired through R&D play a critical role in driving eco-innovation (Blum-Kusterer and Hussain, 2001; Löschel, 2002; Horbach, 2008; Popp *et al.*, 2009, 2011a, 2011b; Johnstone *et al.*, 2012). The lack of impact on green innovations observed by the present analysis suggests that the presence/readiness of green capabilities alone may not be sufficient to drive disruptive innovations without supportive market and regulatory conditions. This supports the views of Louis and Felice (2009) and Demirel and Kesidou (2019), who argue that technological capabilities must be supported by, and aligned with, a coherent regulatory environment and market mechanisms to effectively stimulate green innovations.

Regarding the impact of demand pull, this thesis's findings mainly align with the literature since it highlights the role of market demand and consumer behaviour in driving eco-innovation. The positive influence of demand pull factors on green innovations reflects the dynamics described by Newell *et al.* (1999 and 2006), Popp (2002), Beise and Rennings (2005), and Johnstone *et al.*(2010), who underscore the criticality of market demand as an incentive for innovation. In addition, the present analysis's finding that environmentally oriented consumer behaviour, reflected in lower material footprints, promotes green innovations is consistent with a large body of literature emphasizing the role of the value placed by consumers on green products/services in encouraging firms to pursue eco-innovation (Rehfeld et *al.*, 2007; Kammerer, 2009; Dangelico and Pujari, 2010; Grunwald, 2011; Wagner and Llerena, 2011; Doran and Ryan, 2012; Horbach *et al.*, 2012). Furthermore, the current study adds to the existing literature by identifying a negative impact of market demand on the development of greenish innovations, suggesting that consumer-driven demand could also be impactful in transitioning from greenish to green innovations.

6. Conclusions

In this study, a country-level analysis was performed to explore the impact of the key innovation drivers on eco-innovation activities within the automotive industry. The innovation determinants examined are regulation push/pull, technology push and demand pull, with various proxy variables employed to represent these drivers. Meanwhile, the eco-innovation activity was measured by analyzing automotive patent data in detail. The main contribution of this analysis is categorizing eco-innovations into radical, paradigm-disrupting, “green” innovations and into incremental, paradigm-enhancing, “greenish” ones and examining the respective influence of the drivers on these two subsets.

The empirical analysis draws on an extensive dataset, which integrates data from several OECD, IEA and OICA datasets. The panel dataset created, covering multiple OECD countries over an extended period, provided a solid foundation for a thorough evaluation. Statistical regressions were used to assess the impact of the drivers mentioned above on “greenish” and “green” patent development while controlling for relevant factors such as GDP per capita and fuel prices. The robustness and reliability of results are ensured through various methods, addressing potential issues related to missing values, heteroscedasticity and multicollinearity. Additionally, fixed effects estimation models are used to control for unobserved country-specific characteristics, and two additional models examined both time-specific characteristics and per capita translations of the model’s specification to check for potential differences in results and ensure reliability.

The results revealed that regulation push/pull factors, particularly non-market-based mechanisms, as well as demand pull factors, including both market forces and consumer orientation toward greener choices, have a positive effect on the development of paradigm-destroying innovations. On the other hand, technology push factors seem to foster greenish innovations that enhance the existing ICE paradigm.

Thus, the title question of whether the future of automotive is green or greenish, i.e. whether the industry is transitioning from ICE-related technologies to EV-related ones, remains partially unsolved as incremental advancements in the ICE technology coexist with emerging green innovations. However, the present study sheds some light on the critical factors influencing this transition and underscores the need for a multi-faceted approach to potentially achieve a technological paradigm shift in the automotive sector. Specifically, the findings highlight the need for the implementation of frameworks and mechanisms to ensure that green R&D and technological capabilities are efficiently leveraged and complemented by robust non-market-based regulations and strong market demand. By adopting a holistic strategy that integrates these elements, it may be possible to drive a more comprehensive and effective green transition in the automotive sector. Therefore, the present research suggests that focusing on precise, reliable and coordinated policy actions, consumer incentives and other mechanisms that stimulate market demand, and sustained technological development could accelerate the shift toward a more sustainable automotive future.

It is essential to acknowledge the limitations characterizing this study to offer the reader the possibility of a thorough evaluation, even though some mitigation strategies for the following constraints were already implemented, as discussed in Section 3.1 and Section 3.4.

Firstly, this study relies on proxy variables, such as patent data, which were used to represent broader factors, such as eco-innovation. However, these proxies may not fully capture the complete range of effects and activities associated with a given factor. Additionally, the study's scope is geographically limited to OECD countries; hence, the results may not be fully generalizable to non-OECD nations where the innovative ecosystem, regulatory frameworks, and market conditions may differ. Another limitation lies in the potential for unobserved variables not accounted for in the study to influence the impact of the analyzed factors.

The present paper paves the way for stimulating future research avenues, which could address the limitations mentioned above and/or broaden the scope of the current analysis. For example, expanding the analysis beyond patent data to include additional metrics, such as innovation surveys, firm-level data, and new product introductions, could capture a wider range of dynamics related to environmental innovation activities that may not result in formal patent applications.

Secondly, future studies could extend the analysis of the automotive eco-innovation trends by including emerging economies, such as BRICS countries, where the automotive industry and green technologies solutions are rapidly expanding. These regions' unique characteristics and growth patterns may reveal distinct dynamics of eco-innovation activities, providing valuable insights that differ from those observed in OECD countries.

Lastly, future research could investigate the effectiveness of various policy mixes in more depth to identify and propose optimal solutions for fostering a green transition in the automotive sector.

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