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Patterns of green innovation in the automotive industry: empirical evidence from OECD countries 1990-2018[1]

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Abstract

The aim of the paper is to identify patterns of specialisation in different "green" technologies in the automobile industry. The paper focuses on OECD countries over the last 30 years and analyses the role of systems of innovation in spurring and directing green innovation patterns in the industry, testing which systemic factors drive the detected trends of green specialisation.

The study builds upon a large panel dataset based on green patent data in OECD countries from 1990 to 2018, which allow to depict green specialisation trends for three automotive technologies: green internal combustion engine ("*brownish*"), hybrid ("*greenish*"), electric and fuel cell vehicles ("*green*").

The study reveals that only Japan shows a persistent specialisation in all the three automotive technological solutions and few countries (Italy, France, Sweden, South Korea and USA) are catching up in the cleaner technological domains from 2008 onwards. The majority of the OECD countries display persistent negative levels of specialisation in all the three technological areas.

The econometric analysis, based on a multinomial logit model, shows that the greening of the automotive industry is led both by "*economies of specialisation*" through private R&D investments, and by "*learning economies*" triggered by economic policies oriented towards sustainability goals. The complementarity of the two factors highlights the complexity of the technological and environmental transition and calls for a systemic approach.

Keywords: Automotive, Innovation systems, Technological change, Sustainable transition

JEL Classification: O31; O33; O25; O14

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1. Introduction

The alarming degradation of natural ecosystems (soil, water, air and climate) due to impactful anthropic activities (industrial and transport-related above all) urges a decisive human reaction, which involves significant changes in policies, institutions and practices (MEA, 2005). The so-called "technological transition" has been identified as a pivotal solution to address the contemporary environmental challenges, hinging on a system innovation approach (Hekkert and Negro 2009; Ekins, 2010). As road transports are responsible for 60% of the greenhouse gas (GHG) emissions that mainly come from private cars, the transition to an eco-mobility scenario, which encompasses both individual and collective, public and private solutions that contribute positively to economic and environmental transport performances (Nicolai and Faucheux, 2015), becomes fundamental for transports' decarbonization.

As a consequence, the greening of the automotive industry becomes a crucial component of this transition, with eco-innovations playing a key role in the decarbonization process of the sector.

In the XX century, the automobile industry grew around a highly polluting technological paradigm, the so-called internal combustion engine (ICE), which only in the last decades has been improved with the diffusion of incremental and modular innovations (e.g., catalytic converter, fuel efficient engines, "*green diesel*") and challenged by the development of more ecological solutions (e.g., plug-in hybrid and fully electric engines) (Calabrese, 2016).

Electrification, thus, along with digitalisation, is the most disruptive current technological trend shaping the future the automotive industry (Lüthje, 2021; Wittmann, 2017). The path towards electrification has a long story[2], which can be articulated into four phases: 1) the 1970s-1980s period opens a phase of 'electrical experimentation' in the global automotive industry, characterised by the development of electrical prototypes (Faria and Andersen, 2015); 2) the 1990s mark the introduction of the first modern electric and hybrid-electric engines in the automotive market (Dijk and Yarime, 2010; Faria and Andersen, 2015); 3) a second "*electrical hype*" occurs after 2000, triggered by stringent regional and local eco-policies (Dijk and Yarime, 2010); and 4) the post-2008 crisis "*green spin*" (Faria and Andersen, 2015), which is being accelerated by the current Covid-19 pandemic (ACEA, 2021).

In short, electric engines represent the main propulsive technology alterative to internal combustion, with a long, but niche tradition of prototypes, experiments and tests since the birth of the automobile industry.

The first fully electric models were introduced in the mass auto market only recently: Renault-Nissan, an incumbent original equipment manufacturer (OEM), and Tesla Motors, an emergent one, entered the market with radical technological solutions, respectively *Leaf* in 2010 and *model S* in 2012, "breaking the ice" of a market still fully dominated by fossil-fuelled models, with the introduction of full electric vehicles.

The elements behind this technological innovation are rich and complex and can be depicted by looking at the evolution of green patenting activity of the automotive industry, which has been driven not only by firms' assets heterogeneity (different strategies, knowledge stocks and technological capabilities), but also by a broad array of different elements of the industrial and economic system (technology, consumers' demand as well as institutions and policies) (Covarrubias, 2018; Vazquez et alii, 2018). While automotive has been deeply investigated as a sector *per se* and huge attention has been paid to the actors and factors influencing the internal dynamics of the industry, in relation to the recent adoption of "green" technologies little research and evidence is available on the role of those complementary and systemic elements on the development and diffusion of green technological solutions.

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[2] The first electrical vehicles date back to the last years of the XIX century, to the very birth of the automotive industry. For the seek of simplicity we consider only the most recent story and developments of this technology (IEA, 2013).

Our paper tries to fill this gap. It identifies different green specialisation patterns in automotive industry at the country level and aims to explain these patterns with the characteristics of the different national and sectoral innovation systems.

More specifically, the paper aims at: 1) detecting discontinuities, persistence and catching up patterns of specialisation in different green technologies in the automotive industry, focusing on OECD countries over the last 30 years; 2) analysing the role of systemic factors in spurring and directing green innovation patterns in the sector; 3) testing which kind of economies (e.g., "economies of specialisation" or "economies of learning") associated to those factors drive the detected trends of green specialisation.

Therefore, the present paper aims to expand the existing literature on the greening of the automotive industry which is mainly focused at the firm-level by analysing the dynamics of green innovation in the car industry at the country level, focusing on a large panel dataset.

The paper is structured as follows. Section 2 outlines the framework summarizing the most relevant literature on green innovation in the automotive sector and highlighting the relevance of the theories of innovation system, with special focus on their application to the automobile industry. It also outlines the main research questions. Section 3 presents the data and the empirical strategies, while section 4 shows and discusses the results. Finally, section 5 concludes.

2. Literature review

2.1. The greening of the automotive industry

Economic literature has devoted increasing attention to study the types of innovations able to tackle environmental issues, the so called "green innovations"[3].

Historical factors led the industry to 'lock-in' into an ICE-based dominant design, grounded on the 'creative accumulation' of incremental and modular innovations (Breschi and Malerba, 1993). Yet, in the last decades market stagnation, rising environmental concerns, the emergence of new players and the introduction of stringent eco-policies have driven the industry towards a de-maturity process (Faria and Andersen, 2015; Abernathy et al, 1983), in which the polluting dominant design is challenged by green alternatives developed around radically new and clean, low-carbon technologies.

A wide economic literature has investigated the determinants and barriers of environmental innovation in the automotive industry, highlighting some key facilitating and hampering institutional factors to the development and diffusion of green technological solutions.

Dijk and Yarime (2010) finds that demand, supply and regulations are sources of *lock-in* through path dependence dynamics and drivers of the creation of new clean path through co-evolution; while Gohoungodji et al. (2020) groups all barriers into six blocks respectively related to resources, behaviours, information, technology, laws & regulations and organization, revealing the existence of some causal links between the groups of barriers and emphasizing that the dominant ones are related to behaviours and resources.

Given the importance of such a number of barriers, scholars focused on the analysis of the levers that can overcome such obstacles. In particular, a relevant number of studies has examined the role of environmental policies in the sector[4], providing empirical evidence in support of the so-called

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[3] Green innovation is defined as a type of innovation which can be beneficial in both economic and environmental terms (eco-innovation) or exclusively in environmental ones (environmental innovation) (Ekins, 2010). In this paper we focus on this latter type of green innovation, which is known to exert a relevant effect on the environmental performances of both the automotive industry (Machado and Avila, 2019) and its value chain (Masoumi et al., 2019).

[4] For a critical view of the effects of the policy and regulatory framework in the EU context, see Pardi (2021).

weak version of the "*Porter hypothesis*"[5] (Porter and Van der Linde, 1995; Leewen and Mohnen, 2017).

Hascic et al (2009), for example, shows that environmental regulations exert a greater influence on environmental innovation when they are foreign rather than domestic: domestic eco-policies tend to be anticipated and influenced by domestic car manufactures, while foreign ones act as a real 'shock' for car producers. The study also distinguishes the determinants of "*integrated*" and "*post-combustion*[6]" technologies, revealing that, while the former type innovations is mainly driven by gasoline prices and general propensity to innovation, the latter is primarily affected by "policy shocks", with gasoline prices and the general rate of innovation wielding very little influence.

The forcing power of regulatory interventions has been highlighted also by Berggren and Magnusson (2012), revealing to be decisive in helping car manufactures meeting higher environmental standards, by encouraging the expansion of their technological repertoire with a "long-term oriented, technology-neutral, innovation and competition driving policy, built around stepwise tightening of emissions and incentive levels" (Berggren and Magnusson, 2012, p 29).

The innovation impacts of policies, distinguished into "economic versus regulatory" and "general versus technology specific" (Bergek and Berggren, 2014) illustrates that while general economic tools tend to encourage diffusion and incremental innovation, general regulatory measures enforce significant improvements based on modular innovation; on the other hand, technology-specific tools appear to be required for the development and deployment of radically new technologies, although the fostering of upgrades and cost reductions is necessary for all policies.

Barbieri (2015 and 2016) focuses on the role of post-tax fuel prices, along with that of environmental vehicle taxes, CO2 standards and European emission standards, in the creation of environmental inventions, underlining that post-tax fuel prices influence firms' incentives to reallocate patenting efforts from non-green to green technology fields, contributing to crowding out ICEV inventive activities in favour of alternative propulsion vehicle technologies. This suggests that tax inclusive fuel prices would be effective at unlocking the automotive technological system from dependence on conventional vehicle innovations, confirming the findings of Aghion et al (2015), which empirically proves that higher tax-inclusive fuel prices encourage firms to conduct environmental invention activity and discourage development of dirty inventions.

This broad set of factors stresses the importance to look at the institutional dimension and policy elements that sustain the greening of the car industry. Policies appear to be a major trigger to green innovation, driving the adoption of new technologies and more generally supporting the adoption of new, environmentally-friendly behaviours. Next section aims at introducing the innovation system approach as a useful tool to understand such an institutional and policy dimension.

2.1. The ecological transition of the automobile sector and the role of the innovation system approach

The greening of the automotive industry is part of an eco-mobility scenario, which requires a complex transition to sustainable transport solutions, habits and policies to become a reality. The transition to low-carbon transports involves the development and diffusion of niche innovations, which encompass intermodal travel solutions, cultural and socio-spatial innovations, new forms of demand management, public transport innovations, ICT technologies applications and green propulsion technologies (Geels, 2012).

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[5] The weak version of the PH postulates that environmental regulatory systems do not have a predetermined effect on competitiveness, but always stimulate innovation, which partially offset the loss of competitiveness due to the compliance costs (Jaffe and Palmer, 1997).

6 Hascic et al (2009) defines "integration" technologies as those aimed at increasing engine's efficiency and the "post-combustion" technologies as those aimed at reducing engine's emissions.

The development and the deployment of green propulsion technologies is a crucial component of such transition, which is actually facing several barriers, causing a systemic inertia around the ICE dominant design (Steinhilbert et al., 2013). Along the same vein, Dijk (2014) has found that from 1990s to 2010s the niche-regime interaction within the automotive has led the industry only to a progressive reorganisation towards a hybridisation model, with electric solutions integrated in the ICE, instead of a real transition to pure electric powertrains.

In this context, the challenges posed by the above-mentioned green transition require a system approach to be appropriately tackled. The innovation system theory can provide a useful analytical frame to translate environmental goals into innovation targets at national, regional and sectoral level (Andersen, 2009).

Innovation being the result of the integration and internalization of complementary elements (i.e., resources, know-how, technologies), systems are, in fact, the bedrock where (green) innovation can stem (Edquist, 1996), making the understanding of their components, frames and functioning crucial.

In line with an evolutionary approach, innovation systems involve the co-evolution of their components, (technology, demand, regulations), as well as the interaction between the different systems, whose characteristics affect each other's development (Castellacci, 2009).

Traditionally, innovation systems can be divided in three major types: 1) National Innovation System, alias NIS (List 1841, Nelson, 1993; Patel and Pavitt, 1994; Lundvall, 1992), 2) Regional Innovation System, alias RIS (Cooke et al, 1997; Cooke, 2008), and 3) Sectoral Innovation System, alias SIS (Malerba, 2002 and 2005). While NIS focuses on the nation-wide dimension of innovation, RIS considers the regional milieu where innovation stems and SIS describes the specific sector-based characteristics of the inventive activities

In addition to this well-known three types, an emerging and cross-cutting fourth classification includes the so-called Green Innovation System, alias GRINS (Andersen, 2009), which stems from the greening process of the other three and is clearly particularly relevant for the present analysis.

A green innovation system specifically should embed environmental elements in its multi-layered structure, which are expressed in terms of ecological practices, policies and attitudes, leading to a 'green learning economy' able to create an environment favouring green innovations (Andersen, 2009).

An early example of the sectoral approach applied to the automotive sectors is offered by Breschi and Malerba (1993), which depicted the "traditional" automotive innovation system as characterized by high appropriability, cumulativeness, spatial density, few innovators and a 100-year-old technological paradigm, which make the sector particularly resistant to radical innovations and new technological patterns.

More recently, a pioneering work that provides a first theoretical and empirical contribution on the application of the notion of GRINS to the automotive industry is Hübner et al. (2001), which shows the opportunities and the obstacles to a technological change triggered by the greening of innovation system.

The results of this study highlight that the selection of innovations, like fuel cells, in the automotive industry by the German innovation system is hurdled by a wide range of factors: the higher costs of the new technology, the lack of complementary technologies (fuel infrastructures), the uncertainty related to consumers' acceptance and to the real environmental relief deriving from the new technological solutions, and the absence of a comprehensive national energy strategy. However, rising gasoline eco-taxes, self-sustaining environmentally oriented innovation dynamics and a 'second-best' scenario making fuel cell cars a palatable urban mobility option, represent the main drivers to innovation adoption.

Following the way paved by those seminal contributions, we adopt a 'system approach' to examine whether there are different green innovation patterns in the automotive industry and to explore the impact of different systems of innovation on the green specialisation of the automobile sector at country level.

Therefore, in the next section we will identify the various main factors bringing back to the different types of innovation systems.

In particular, we will compare factors associated to the sectoral innovation system and the green innovation system and test if and how these affect the different greening processes adopted by the industry in OECD countries, in order to test whether sectoral or policy effects are prevailing.

3. Methodology

3.1. Data description

Our study is based on data covering 27 OECD countries over the time period between 1990 and 2018, and is built upon a strongly balanced panel dataset featuring the variables summarised in Table 1. The choice of the temporal span, stretching from 1990 to 2018, is grounded both empirically and theoretically. This period, in fact, is suitable as the 1990s mark the introduction of the first modern electric or hybrid-electric engines in the automotive market (Dijk and Yarime, 2010; Faria and Andersen, 2015), which was followed by a second "electrical hype" after 2000, triggered by new eco-policies (Dijk and Yarime, 2010) and the post-2008 crisis "green spin" (Faria and Andersen, 2015).

To capture the propensity to introduce green innovation in the automotive industry, we use green patents, which are widely employed as proxy of environmental innovations (Oltra et al., 2008b; Hascic and Migotto, 2015), despite the usual drawbacks of patents as measure of innovation (Pavitt, 1985; Pake, 1986; Hascic and Migotto, 2015).

The choice to use green patents is motivated by the fact that they allow not only to proxy for the level of eco-innovation activity, but also to analyse changes in the technological trajectory of a given sector, especially in medium-high tech industries such as the automotive industry (Faria and Andersen, 2015).

The data on green patents from the automotive industry are retrieved from OECD Environment database (OECD, 2021) - employed by recent studies on green innovation, e.g., Ghisetti and Quatraro (2017)- and divided in three technological domains: 1) "brownish" technologies, which stands for green internal combustion engines (ICE); 2) "greenish" technologies, representing hybrid engines; 3) "pure green" technologies, which includes electric solutions[7]. Green patents included are of family size 2 or greater, which assures that only high-value inventions (that have sought patent protection in at least two jurisdictions) are used for the study[8].

The analysis is then based on a normalised Relative Technological Specialisation Index derived from Relative Specialisation index (Balassa, 1963; Brusoni and Geuna, 2005; Nesta and Patel, 2005; Chang, 2012), which is commonly used as an indicator of international specialisation, in order to

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[7] The first category of the so-called 'brownish' technologies includes patents of the CPC class Y02T10/10-40, while the second category of the so-called 'greenish' technologies includes patents of the CPC class Y02T10/62 and the third category of the so-called 'green' technologies includes patents of the CPC class Y02T10/64-72.

Please refer to EPO patent search to browse among the specific patents included in each patent class: https://worldwide.espacenet.com/classification?locale=en_EP#!/CPC=Y02T10/72

[8] The OECD statistics is based on the concept of a patent family which is defined as all patent applications protecting the same 'priority' (as defined by the *Paris Convention*), also referred to as 'simple patent family' (see *Martinez 2010*). The patent family concept is applied to all statistics presented here, including counts of patent families by inventor country (as a measure of technology development) and by jurisdictions where patent protection for these inventions has been sought (as a measure of technology diffusion). Therefore, each country counts for green patents developed by national firms and institutions as well as those deposited by international companies/institutions. To avoid double counting, if a patent lists inventors from three countries, each country will obtain a count of 0.33.

measure the evolution of firm's or country's specialisation in a given technological area. The index RTS index is given as follows:

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

Where *Pij* represents the number of patents from technology *j* on the patent portfolio of firm or country *i*.

In our case, the relative specialisation index compares the share of a given green automotive technology *j* within the green technological portfolio of country *i* with the share of the same technology for the whole sample of countries as a measure of relative technologic specialization. We normalized the index in order to simplify and compare symmetrically the results (Nesta and Patel, 2005):

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

This index is used for two purposes in the paper: first, to examine patents trends over time in the descriptive section of the paper; second, to test the impact of a selection of factors related the countries' systems of innovation on countries' green automotive specialisation.

The dataset also features three groups of proxies, respectively for the "Sectoral Innovation System" (SIS), the "Green Innovation System" (GRINS) and "National Innovation System" (NIS).

The SIS group includes "*public R&D expenditures for transports*" and "*automotive R&D expenditures*", which capture the "*ideas production*" in the transport and automotive sector at country level (Stern et al, 2000), as well as "*auto sales*", which proxy for the classical demand-pull effect.

The GRINS group features "*public green R&D expenditures*", "*public renewable energy R&D expenditures*" and "*public fossil fuel energy R&D expenditures*", which proxy for a country's specific green and non-green ideas production and spillovers; it includes also the "*Environmental Policy Stringency*[9]" (EPS), which captures the magnitude of country's green policies, and "*BEV sales*", which proxies for green demand pull in automotive sector.

The dataset also includes "*Patent Stock*[10]" and "*GDP per capita*", which is a proxy for innovation demand-pull and the ability of the country to translate its knowledge into a realised economic state (Stern et al, 2000).

Please insert Table 1 here.

The summary statistics of the variables is shown in Table 2 in the Appendix.

3.2 Empirical strategy

Our empirical strategy encompasses two steps:

i. the graphical analysis of the countries' specialisation in the automotive green technologies, by comparing a relative index (RTSI n) with an absolute one (patents over country's population);

ii. the econometric analysis, investigating the impact of different systems of innovation on green patents specialisations, through a multinomial logit model (Greene, 2000).

A multinomial logit model is commonly expressed as:

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[9] EPS indicator summarises indexes of green policies mostly devoted to reduce air pollution. See: https://stats.oecd.org/Index.aspx?DataSetCode=EPS

[10] The variable "Patents Stock" is taken in the logarithmic form in order to smooth data displaying extreme values and to make them approaching a normal distribution.

$$\Pr\{Y_i=j\} = \exp(\beta_j^{T} X_i) / 1+\sum_k \exp(\beta_k^{T} X_i) \qquad \text{for } j = 2, 3, \ldots, J$$

$$\Pr\{Y_i=1\} = 1 / 1+\sum_k \exp(\beta_k^{T} X_i) \qquad \text{for } j = 1$$

where *Yi* is the set of *j* green specialisation clusters, *Xi* is the vector of explanatory variables (the variables pointed out in Table 1), and *bj* is a vector of estimated coefficients specific to group *j*. The objective of the multinomial logit model estimation is to identify the most important drivers associated with each eco-innovation trajectory (*brownish, greenish, green*), enabling assessment of the relative importance of policies, demand-side and country-specific factors within the systems of innovation framework. The choice of this model, an extension of the binary logistic regression that allows to predict the probability of category membership on a dependent variable that has more than two categories, is backed by previous innovation literature, which is consistent with the nature and the purpose of the current study (Castellacci and Lie, 2017; Castellacci, 2009).

While the graphical analysis allows to provide an overview of countries' specialisation in green automotive technologies trends and evolution, the choice of the econometric model is due to the aim of examining the relation between the innovation systems and the level and type of green specialisation in automotive techs.

The econometric model is the following:

$$\mathit{Special} = \alpha + \beta 1\mathrm{SIS} + \beta 2\mathrm{GRINS} + \beta 3\mathrm{NIS} + \varepsilon$$

Special is a categorical variable representing the type of countries' specialisation in automotive green technologies (*brownish, greenish and green*), which can be negative, neutral or positive[11]. The variable *Special* has been constructed by clustering data in three groups using the *k-means* algorithm over the three separate green automotive specialisation indexes (GREENICE_RTSI_N, HYBRID_RTSI_N, ELECTRIC_RTSI_N): the result is gioven by three categorical variables (BROWNISH_Special, GREENISH_Special and GREEN_Special) taking value 1 where specialisation index is *negative* (negative specialisation), 2 when the specialisation index is *positive* (positive specialisation), and 3 when the index is *mildly negative/positive* (mildly negative/positive specialisation).

The motivation for the construction of this variable is based on data observation revealing that countries tend to display three main *patterns* of specialisation within the three different types of technology, which can be labelled as *negative, neutral and positive*.

These patterns, highlighted in Figures 1.1, 1.2 and 1.3 in Appendix, can be interpreted as countries' '*attitudes*' towards automotive green technologies with respect to all green technologies, which can be *negative,* as long as countries lag behind in the production of automotive-specific green patents with respect to the development of patents in all green domains, *neutral,* as far as countries do not display nor a strong under-specialisation nor an evident specialisation in automotive green technologies (the index lies between positive and negative values, representing a mild under- or over- specialisation), and *positive,* when countries have a relative comparative advantage (specialisation) in the automotive-specific green technologies.

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[11] These categories correspond to a *below-average, on average* and *above-average* comparative advantage of the countries in the abovementioned automotive-specific green technologies, Emerging from the data analysis.

Tables 3.1, 3.2 and 3.3 in Appendix depict, for each automotive-specific technological category (brownish, greenish and green), the characteristics of the clusters with respect to the specialisation indexes, supporting the use of a multinomial logit model.

SIS is a vector of the variables related to the *Sectoral Innovation System*, *GRINS* is a vector of the variables related to the *Greening of the Innovation Systems* and *NIS* is a vector of the variables related to the *National Innovation System*. All the explanatory variables are lagged by 1 year to mitigate possible endogeneity issues.

Table 4 in the Appendix shows the correlation matrix of the variables in the model.

The error term is assumed to be robust to serial correlation and heteroskedasticity[12].

4. Results

4.1. Data analysis

First, the study analyses countries' evolution in their auto green specialisation, with respect to both their absolute and relative auto green specialisation for three different green technological categories, *brownish* (green ICE), *greenish* (hybrid) and *pure green* (electric) technologies, over three "time frames", 1990-1999, 2000-2008 and 2009-2018.

The plots depicted in Figure 2.1 outline the evolution of countries' specialisation in *brownish* technologies, revealing that most of the countries have persistent low levels of both absolute and relative specialisation, while only Germany and Japan show persistent high level of absolute and relative specialisation in this technological domain.

The graphical analysis also points out a catching up process concerning Sweden, Austria, France, Italy and USA, which display rising levels of technological specialisation in the *green ICE* over time.

Please insert Fig 2.1 here

The plots depicted in Figure 2.2 outline the evolution of countries' specialisation in *greenish* technologies, showing Japan as the only one country with a very high level of relative and absolute specialisation in this technological domain. The graphical inspection highlights a strong catching up by Germany, Sweden and Austria, whose technological evolution moves the countries from low to very high levels of absolute and relative specialisation in automotive greenish techs.

France and USA, followed by Italy and South Korea, also display a relevant catching up, going from low levels of absolute a relative specialisation to a medium level of relative specialisation in this technological domain.

Please insert Fig 2.2 here

The plots depicted in Figure 2.3 outline the evolution of countries' specialisation in *green* technologies, revealing that Japan is always the only country with persistent very high levels of absolute and relative specialisation, while the other countries show a persistent low level of absolute and relative specialisation in this technological domain.

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[12] The application of sandwich-estimator or Huber-White standard errors satisfies the assumption that our results are robust to heteroskedasticity and serial correlation, according to the most econometric literature (Woolridge, 2010). Moreover, the simulations by Munizaga et al (2000) aimed at testing to which extent different discrete choice models (including MNL) applied to transport studies, can handle heteroskedasticity, reveal that MNL is a fairly robust model to some violations of homoskedasticity.

Germany and South Korea are the only two countries displaying a relevant catching up in the last time frame, when their levels of absolute and relative specialisation rise from low to very high.

Please insert Fig 2.3 here

These analyses provide some evidence in support of the hypothesises that early specialisations tend to persist over time, confirming that the automotive sector is prone to path dependence, as highlighted by previous studies, e.g., Aghion et al (2015).

Nonetheless, the results seem to show that between 2009 and 2018, the time frame characterized by the introduction of the first electric vehicles in the mass market, there has been a catching up process among some OECD countries with early low levels of specialisation in the greenest solutions, especially those with the longest tradition in the automotive industry.

The graphical inspection also reveals that China displays a high level of relative specialisation in all three technological domains (*brownish, greenish and green*) between 1990 and 1999, which disappears in the following time periods. It looks clear that this peak coincides with the period before China enters the WTO (2001), when the country had to meet international patent standards.

These findings, summarised in Table 5, are substantially confirmed by the sensitivity analysis over different 'time windows', namely 1990-1995, 2000-2005 and 2013-2018 (see Fig. 3.1, 3.2 nd 3.3 in the Appendix).

Please insert Table 5 here

4.2. Econometric analysis

The econometric model aims to analyse the role of the factors associated to the sectoral system of innovation (SIS) and the green innovation system (GRINS) respectively, in spurring and directing the green innovation patterns depicted in the previous section. The main outcomes of the model are summarised in Table 6.

First, the econometric results reveal that the Sectoral Innovation System (SIS) is positively associated with countries' *mildly green* specialisations in the automotive industry, since the increase in the amount of the business-funded R&D expenditures in the automotive sector and the car sales pushes up the multinomial log-odds for positive specialisation rather than strongly negative specialisation (baseline category 1) in brownish and greenish patents, respectively by 0.0057 and 0.0111 unit.

Second, the results concerning the relation of Green Innovation System (GRINS) with the countries' green specialisation in the automotive industry largely provide a more diversified picture.

In fact, the analysis shows that, while environmental government-funded R&D expenditures are negatively associated with the country's positive specialisation in green (-0.54) patents, the Environmental Policy Stringency index (EPS) is positively linked with brownish (0.75), greenish (0.88) and pure green (1.21) patents positive specialisation.

These findings seem to suggest that countries investing more resources in the green domains tend to devote less funds and effort to the greening of their automotive sector, while those that introduce more stringent environmental policies are more likely to have a positive specialisation in brownish and pure green technological solutions in the automotive sector, revealing both a "*technology-following*" and "*technology-forcing*" attitude.

The study also confirms the positive role of the patent ecosystem in the process of greening the automobile industry, since the amount of patent stock is positively associated with the positive specialisation in hybrid (1.25) and electric (0.87) solutions.

The analysis may suggest that the green paradigm shift in the automotive industry is driven both by "*economies of specialisation*", fostered by factors related to the Sectoral Innovation System, and "*economies of learning*" through the factors specific to the Green Innovation System, even though green policies appear to be the most significant determinant of the investigated green turn, at least in terms of magnitude.

Our key findings are substantially confirmed by running an equivalent multinomial model on imputed data, whose results are reported in Table 7 in Appendix.

Moreover, the results are robust to the exclusion of Japan –a country behaving as an outlier - and to the inclusion of China from 2001 onwards (see Table 8 and Table 9 in Appendix).

The main difference between the outcomes of the baseline regression and those of the robustness checks[13] is that, in the latter, the eco-policies do impact only brownish patents, exerting no influence on greener solutions, thus revealing that environmental regulations tended to have a more "*technology-following*" nature.

Please insert Table 6 here

Conclusions

The paper aimed to examine the dynamics and drivers governing the greening of the sector.

As a matter of fact, a wide strand of economic literature has investigated the determinants (and barriers) of green innovation in the automotive industry, highlighting the role of eco-policies (Hascic et al, 2009, Berggren and Magnusson, 2012; Bergek and Berggren, 2014, Barbieri 2015), fuel prices (Barbieri 2015, 2016), path dependence and lock-in dynamics (Aghion et al, 2015; Gohoungodji et al, 2020) and the new path creation driven by the co-evolution of supply and demand (Dijk and Yarime, 2010) as the main driving (or hampering) forces of the environmental innovation patterns in this industrial sector.

However, only few studies have explored green trajectories of the main car manufacturers (Oltra and Saint Jean, 2009a; Faria and Andersen 2015, 2017a, 2017b) and none, except Oltra and Saint Jean (2009b) examined the impact of systemic factors on green specialisation of the automobile sector at country level.

The present paper aimed at filling this gap by: 1) detecting discontinuities, persistence and catching up patterns of specialisation in the different automotive green technological domains, by focusing on OECD countries over the last 30 years; 2) analysing the role of systemic factors in spurring and directing green innovation patterns in automotive sector; 3) in particular testing whether the detected trends of green specialisation are driven by factors specific to the sectoral innovation system, or are instead triggered by factors associated to green policies and institutions.

Firstly, the analysis of the countries' specialisation patterns reveals that only Japan shows a persistent specialisation in *brownish, greenish and green* automotive technological solutions, while few countries, namely Italy, France, USA, Sweden and South Korea, catch up in some of the three technological domains from 2008 onward and the rest of the OECD countries display persistent negative levels of specialisation in the examined automotive technological areas.

These results may reflect and be consistent with the current technological heterogeneity of alternative engines and the evidence that the industry find it hard to converge towards a different, new dominant design (Fujimoto, 2017).

Secondly, the study provides evidence in support of the hypothesis that early low or high levels of specialisation in a technological field are followed by persistent specialisation patterns in the initial domain, confirming findings of Aghion (2015) about path dependence patterns in the automotive industry and that the introduction of the first fully electric models in the auto market has steered only a moderate acceleration of the specialisation in electric solutions among the OECD countries, with only few of them experiencing relevant catching up processes in the cleanest technological domain by 2018.

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[13] As a robustness check, we also tested our model controlling for the "number of employees in auto sector" (OECD-STAN, 2021), finding that it captures the effect of "private R&D expenditure in the automotive sector", which is strongly correlated with.

Finally, the econometric analysis, based on a multinomial logit model, reveals that both the group of factors related to the "*sectoral innovation system*" (SIS) and the so-called "*green innovation system*" (GRINS) lead countries to the specialisation in cleaner automotive technological solutions. We argue that the former group of factors associated to SIS triggers "economies of specialization" that support green innovation patterns, while the latter group of factors linked to GRINS ignite "economies of learning" that may support the adoption of more radical change.

The paper shows that while the business-funded R&D expenditures in the automotive sector and the car sales positively relate with the specialization in green ICE and hybrid patents, stringent eco-policies have a dual effect on countries' specialisation in automotive sector, stimulating the development of patents in both brownish and pure green solutions. However, this dual effect is not fully confirmed by our robustness checks, which suggest that eco-policies have had a more *technology-following* nature, spurring only incremental types of innovation during the time period considered.

Our empirical results, both descriptive and econometrically, are in line with the main findings of the existing automotive literature, confirming that until 2018 the sector was characterized by a scattered and slow green transition, strongly influenced by path dependence dynamics (Aghion et al, 2015; Dijk, 2014).

From a policy-making viewpoint, the paper highlights the importance of an industry-based focus (Alochet and Midler, 2019): in particular, complementary investments in R&D and eco-policies are shown to have the potential to accelerate the move to cleaner automotive technological solutions, helping countries lagging behind in their production (and commercialisation) to catch up and specialise in low carbon automotive techs too.

Further attention and future research effort should be devoted to the investigation of the determinants and dynamics of green innovation uptake and diffusion.

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Appendix

Table 1. The variables in the dataset

THE VARIABLES				
Variable	**Definition**	**Source**	**Literature**	**Role**
GREENICE_RTSI_N	Normalised specialisation index in Green "Internal Combustion Engine" patents	OECD ENV-TECH	Faria and Anderson (2015, 2017a, 2017b)	Dependent var.
HYBRID_RTSI_N	Normalised specialisation index in "Hybrid Vehicles" patents	OECD ENV-TECH	Faria and Anderson (2015, 2017a, 2017b)	Dependent var.
ELECTRIC_RTSI_N	Normalised specialisation index in "Electric Vehicles" patents	OECD ENV-TECH	Faria and Anderson (2015, 2017a, 2017b)	Dependent var.
BERD_AUTO	Private/Business-funded expenditures for R&D in automotive sector (Motor Vehicles, trailers and semi-trailers)	OECD Stat	Automotive literature	Explanatory var. (SIS)
CAR_SALES	Numbers of car sales	OICA	Automotive literature	Explanatory var. (SIS)
GREEN_GOV_FUND_R&D	Environmentally related government R&D budget (% total gov. R&D)	OECD Stat	New	Explanatory var. (GRINS)
REN_EN_PUB_R&D	Renewable energy public RD&D budget (% total energy public RD&D)	OECD Stat	New	Explanatory var. (GRINS)
FOSS_FUEL_R&D_R&D	Fossil fuel public RD&D budget -excluding CCS- (% total energy public RD&D)	OECD Stat	New	Explanatory var. (GRINS)
BEV_SALES	Number of Battery Electric Vehicles sales	EAFO - OECD	New	Explanatory var. (GRINS)
EPS	Environmental Policy Stringency	OECD Stat	Wang et al (2020) Wolde-Rufael, and Weldemeskel (2020)	Explanatory var. (GRINS)
PATENT_STOCK (log)	The logarithm of the total amount of patents	OECD Stat	Innovation Literature	Control (NIS)
GDP_PC	Gross Domestic Product per capita	OECD Stat	Stern et al (2000)	Control (NIS)

Table 2. Summary statistics of the variables in the dataset[14]

VarName	mean	sd	xtsdb	xtsdw	min	xtminb	xtminw	max	xtmaxb	xtmaxw	xtn	obs
GREEN_ICE_RTSIN	-0.3	0.4	0.3	0.3	-1.0	-1.0	-1.0	0.8	0.2	1.0	28	812
HYBRID_RTSIN	-0.5	0.5	0.3	0.4	-1.0	-1.0	-1.6	1.0	0.2	1.3	28	812
ELECTRIC_RTSIN	-0.4	0.5	0.3	0.4	-1.0	-0.9	-1.2	1.0	0.2	1.2	28	812
BERD_AUTO	3216.2	7017.1	6626.4	3176.8	0.0	2.6	-8431.0	35466.1	22169.5	21433.0	27	513
CAR_SALES	103.0	44.4	32.3	30.5	9.4	52.3	-50.4	382.9	230.6	255.3	27	719
GREEN_GOV_RD	2.4	1.3	1.0	1.0	0.0	0.6	-2.4	10.3	4.9	8.8	27	685
REN_EN_PUB_RD	23.0	14.6	10.7	10.1	0.0	6.3	-11.8	81.6	42.8	84.6	26	627
FOSS_FUEL_PUB_RD	10.3	12.9	9.8	8.5	0.0	0.7	-16.1	90.0	35.8	70.8	26	590
BEV_SALES	4.3	37.4	33.9	31.3	0.0	0.0	-171.9	815.9	176.7	643.5	27	761
EPS	1.8	0.9	0.4	0.8	0.2	0.9	0.1	4.1	2.6	4.2	28	659
Log_PATENT_STOCK	7.1	2.8	2.1	1.8	-9.2	2.5	-4.5	11.4	11.0	15.7	28	812
GDP_PC	29137.0	13649.3	9288.1	10164.1	975.3	5893.0	3486.8	84575.4	44079.5	75159.8	28	803

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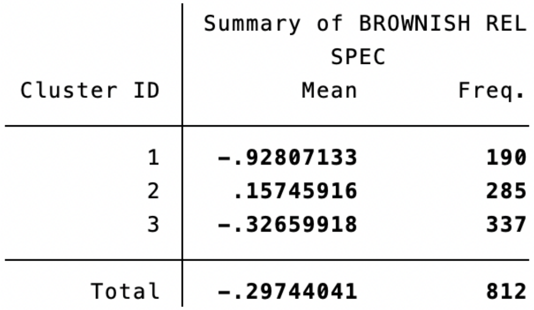
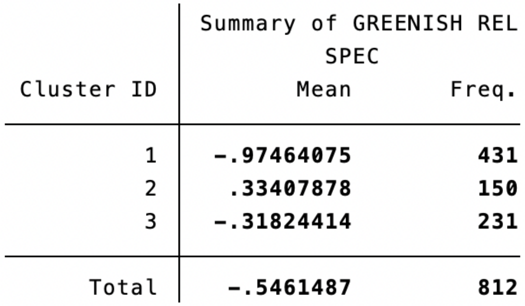
[14] Table 2 shows the relevant statistics of the dataset's variables, including: mean, standard deviation (basic, between and within the panels), minimum and maximum value (basic, between and within the panels), number of panels and observations.



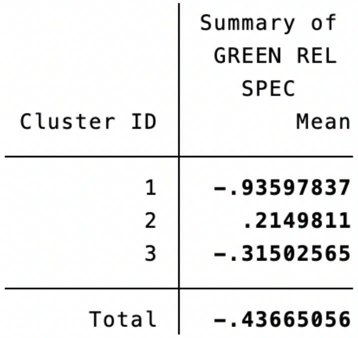
```
             │  Summary of BROWNISH REL
             │           SPEC
  Cluster ID │       Mean        Freq.
─────────────┼──────────────────────────
           1 │ -.92807133          190
           2 │  .15745916          285
           3 │ -.32659918          337
─────────────┼──────────────────────────
       Total │ -.29744041          812
```

Table 3.1. Summary of the brownish (green ice) RTSI - N by cluster



```
             │  Summary of GREENISH REL
             │           SPEC
  Cluster ID │       Mean        Freq.
─────────────┼──────────────────────────
           1 │ -.97464075          431
           2 │  .33407878          150
           3 │ -.31824414          231
─────────────┼──────────────────────────
       Total │  -.5461487          812
```

Table 3.2. Summary of the greenish (hybrid) RTSI - N by cluster



```
             │  Summary of
             │   GREEN REL
             │     SPEC
  Cluster ID │       Mean
─────────────┼─────────────
           1 │ -.93597837
           2 │   .2149811
           3 │ -.31502565
─────────────┼─────────────
       Total │ -.43665056
```

Table 3.3. Summary of the green (electric) RTSI- N by cluster

Table 4. Correlation matrix[15]

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
(1) L.BERD_AUTO	1.000											
(2) L.CAR_SALES	-0.014	1.000										
(3) L.GREEN_GOV_RD	-0.319	0.143	1.000									
(4) L.REN_EN_PUB_RD	-0.174	-0.054	0.190	1.000								
(5) L.FOSS_FUEL_PU~D	-0.093	-0.059	0.081	-0.252	1.000							
(6) L.EPS	0.030	-0.174	0.060	0.299	-0.340	1.000						
(7) L.BEV_SALES	0.351	-0.042	-0.163	-0.033	-0.086	0.181	1.000					
(8) L.Log_PATENT_S~K	0.701	-0.063	-0.311	-0.350	-0.141	0.152	0.264	1.000				
(9) L.GDP_PC	0.215	-0.213	-0.226	0.014	0.060	0.573	0.338	0.358	1.000			
(10) BROWNISH_SPEC	-0.006	-0.034	0.048	-0.104	0.060	0.034	-0.065	0.184	0.133	1.000		
(11) GREENISH_SPEC	0.249	-0.024	-0.015	-0.199	-0.000	0.174	0.134	0.534	0.255	0.229	1.000	
(12) GREEN_SPEC	0.149	-0.128	-0.016	-0.107	-0.119	0.135	0.066	0.406	0.102	0.162	0.433	1.000

Table 5. Countries' specialisation patterns

PATENTS/ SPECIALISATION	**PERSISTENT LOW-REL & ABS-**	**CATCHING UP - RELATIVE-**	**CATCHING UP ABSOLUTE-**	**PERSISTENT HIGH -REL & ABS-**
BROWNISH	Most of the countries	Czech, France, Italy, USA	Austria, Sweden	Germany, Japan
GREENISH	Most of the countries	France, USA, Italy, South Korea	Austria, Germany, Sweden	Japan
GREEN	Most of the countries	None	Germany, South Korea	Japan

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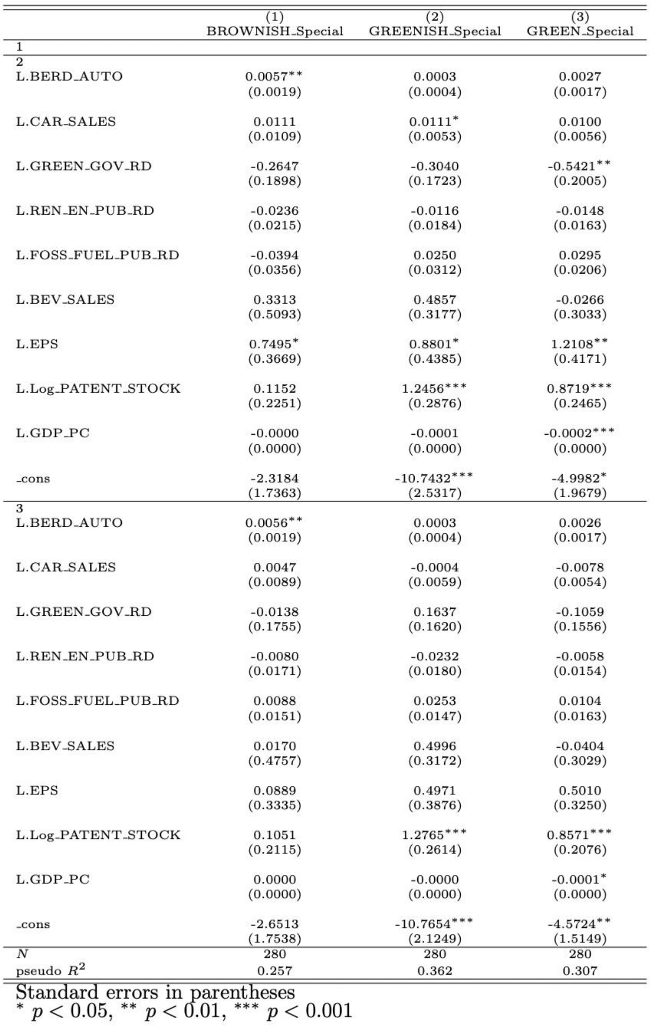
[15] Table 3 shows the correlation matrix between the factors related to the systems of innovation (SIS, GRINS, NIS) and the categorical variables built upon the specialization index (RTSI norm) and used as dependent variables in the econometric model

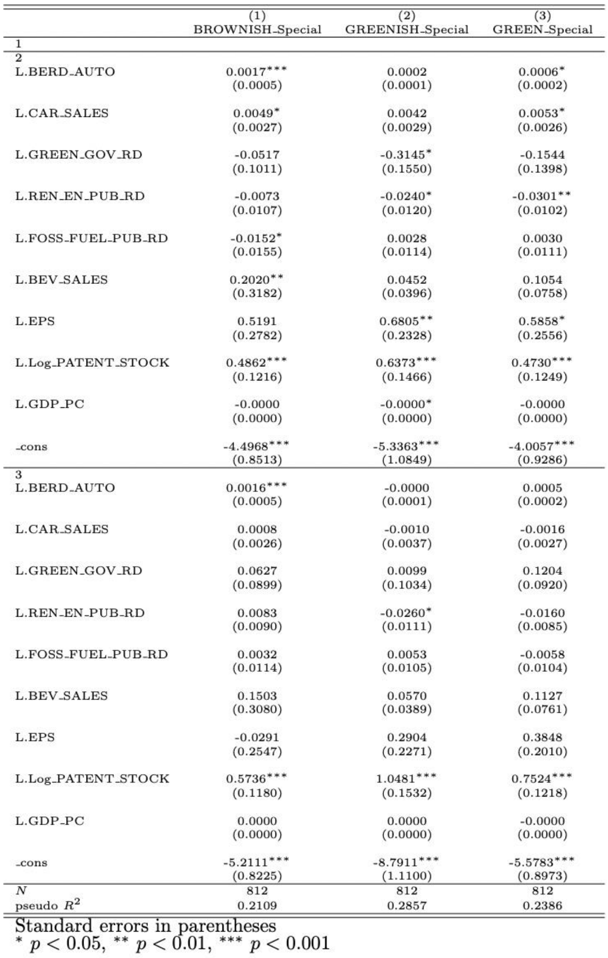
Table 6. The main results of the econometric model



	(1) BROWNISH_Special	(2) GREENISH_Special	(3) GREEN_Special
1			
2			
L.BERD_AUTO	0.0057**	0.0003	0.0027
	(0.0019)	(0.0004)	(0.0017)
L.CAR_SALES	0.0111	0.0111*	0.0100
	(0.0109)	(0.0053)	(0.0056)
L.GREEN_GOV_RD	-0.2647	-0.3040	-0.5421**
	(0.1898)	(0.1723)	(0.2005)
L.REN_EN_PUB_RD	-0.0236	-0.0116	-0.0148
	(0.0215)	(0.0184)	(0.0163)
L.FOSS_FUEL_PUB_RD	-0.0394	0.0250	0.0295
	(0.0356)	(0.0312)	(0.0206)
L.BEV_SALES	0.3313	0.4857	-0.0266
	(0.5093)	(0.3177)	(0.3033)
L.EPS	0.7495*	0.8801*	1.2108**
	(0.3669)	(0.4385)	(0.4171)
L.Log_PATENT_STOCK	0.1152	1.2456***	0.8719***
	(0.2251)	(0.2876)	(0.2465)
L.GDP_PC	-0.0000	-0.0001	-0.0002***
	(0.0000)	(0.0000)	(0.0000)
_cons	-2.3184	-10.7432***	-4.9982*
	(1.7363)	(2.5317)	(1.9679)
3			
L.BERD_AUTO	0.0056**	0.0003	0.0026
	(0.0019)	(0.0004)	(0.0017)
L.CAR_SALES	0.0047	-0.0004	-0.0078
	(0.0089)	(0.0059)	(0.0054)
L.GREEN_GOV_RD	-0.0138	0.1637	-0.1059
	(0.1755)	(0.1620)	(0.1556)
L.REN_EN_PUB_RD	-0.0080	-0.0232	-0.0058
	(0.0171)	(0.0180)	(0.0154)
L.FOSS_FUEL_PUB_RD	0.0088	0.0253	0.0104
	(0.0151)	(0.0147)	(0.0163)
L.BEV_SALES	0.0170	0.4996	-0.0404
	(0.4757)	(0.3172)	(0.3029)
L.EPS	0.0889	0.4971	0.5010
	(0.3335)	(0.3876)	(0.3250)
L.Log_PATENT_STOCK	0.1051	1.2765***	0.8571***
	(0.2115)	(0.2614)	(0.2076)
L.GDP_PC	0.0000	-0.0000	-0.0001*
	(0.0000)	(0.0000)	(0.0000)
_cons	-2.6513	-10.7654***	-4.5724**
	(1.7538)	(2.1249)	(1.5149)
N	280	280	280
pseudo R^2	0.257	0.362	0.307

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

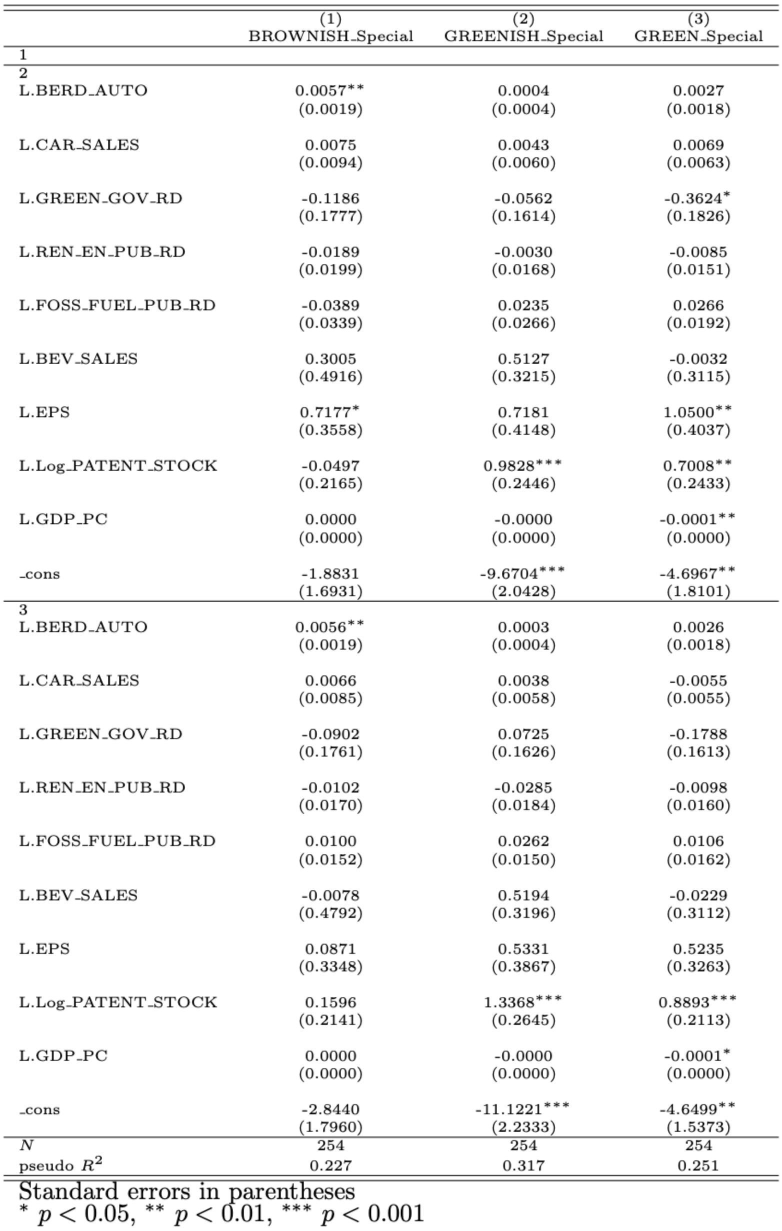
Table 7. The results of the base regressions with imputed values (arbitrary random pattern)



	(1) BROWNISH_Special	(2) GREENISH_Special	(3) GREEN_Special
1			
2			
L.BERD_AUTO	0.0017*** (0.0005)	0.0002 (0.0001)	0.0006* (0.0002)
L.CAR_SALES	0.0049* (0.0027)	0.0042 (0.0029)	0.0053* (0.0026)
L.GREEN_GOV_RD	-0.0517 (0.1011)	-0.3145* (0.1550)	-0.1544 (0.1398)
L.REN_EN_PUB_RD	-0.0073 (0.0107)	-0.0240* (0.0120)	-0.0301** (0.0102)
L.FOSS_FUEL_PUB_RD	-0.0152* (0.0155)	0.0028 (0.0114)	0.0030 (0.0111)
L.BEV_SALES	0.2020** (0.3182)	0.0452 (0.0396)	0.1054 (0.0758)
L.EPS	0.5191 (0.2782)	0.6805** (0.2328)	0.5858* (0.2556)
L.Log_PATENT_STOCK	0.4862*** (0.1216)	0.6373*** (0.1466)	0.4730*** (0.1249)
L.GDP_PC	-0.0000 (0.0000)	-0.0000* (0.0000)	-0.0000 (0.0000)
_cons	-4.4968*** (0.8513)	-5.3363*** (1.0849)	-4.0057*** (0.9286)
3			
L.BERD_AUTO	0.0016*** (0.0005)	-0.0000 (0.0001)	0.0005 (0.0002)
L.CAR_SALES	0.0008 (0.0026)	-0.0010 (0.0037)	-0.0016 (0.0027)
L.GREEN_GOV_RD	0.0627 (0.0899)	0.0099 (0.1034)	0.1204 (0.0920)
L.REN_EN_PUB_RD	0.0083 (0.0090)	-0.0260* (0.0111)	-0.0160 (0.0085)
L.FOSS_FUEL_PUB_RD	0.0032 (0.0114)	0.0053 (0.0105)	-0.0058 (0.0104)
L.BEV_SALES	0.1503 (0.3080)	0.0570 (0.0389)	0.1127 (0.0761)
L.EPS	-0.0291 (0.2547)	0.2904 (0.2271)	0.3848 (0.2010)
L.Log_PATENT_STOCK	0.5736*** (0.1180)	1.0481*** (0.1532)	0.7524*** (0.1218)
L.GDP_PC	0.0000 (0.0000)	0.0000 (0.0000)	-0.0000 (0.0000)
_cons	-5.2111*** (0.8225)	-8.7911*** (1.1100)	-5.5783*** (0.8973)
N	812	812	812
pseudo R^2	0.2109	0.2857	0.2386

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

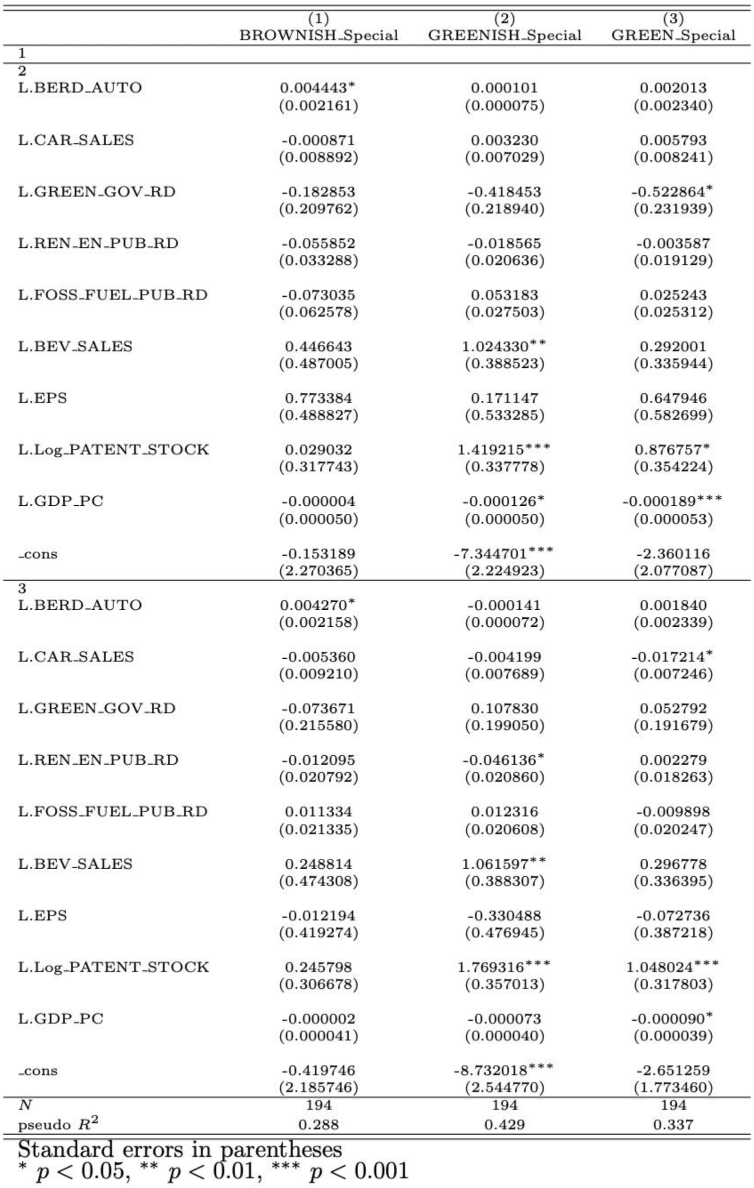
Table 8. The results of the regressions without Japan and China



	(1) BROWNISH_Special	(2) GREENISH_Special	(3) GREEN_Special
1			
2			
L.BERD_AUTO	0.0057^{**}	0.0004	0.0027
	(0.0019)	(0.0004)	(0.0018)
L.CAR_SALES	0.0075	0.0043	0.0069
	(0.0094)	(0.0060)	(0.0063)
L.GREEN_GOV_RD	-0.1186	-0.0562	-0.3624^{*}
	(0.1777)	(0.1614)	(0.1826)
L.REN_EN_PUB_RD	-0.0189	-0.0030	-0.0085
	(0.0199)	(0.0168)	(0.0151)
L.FOSS_FUEL_PUB_RD	-0.0389	0.0235	0.0266
	(0.0339)	(0.0266)	(0.0192)
L.BEV_SALES	0.3005	0.5127	-0.0032
	(0.4916)	(0.3215)	(0.3115)
L.EPS	0.7177^{*}	0.7181	1.0500^{**}
	(0.3558)	(0.4148)	(0.4037)
L.Log_PATENT_STOCK	-0.0497	0.9828^{***}	0.7008^{**}
	(0.2165)	(0.2446)	(0.2433)
L.GDP_PC	0.0000	-0.0000	-0.0001^{**}
	(0.0000)	(0.0000)	(0.0000)
_cons	-1.8831	-9.6704^{***}	-4.6967^{**}
	(1.6931)	(2.0428)	(1.8101)
3			
L.BERD_AUTO	0.0056^{**}	0.0003	0.0026
	(0.0019)	(0.0004)	(0.0018)
L.CAR_SALES	0.0066	0.0038	-0.0055
	(0.0085)	(0.0058)	(0.0055)
L.GREEN_GOV_RD	-0.0902	0.0725	-0.1788
	(0.1761)	(0.1626)	(0.1613)
L.REN_EN_PUB_RD	-0.0102	-0.0285	-0.0098
	(0.0170)	(0.0184)	(0.0160)
L.FOSS_FUEL_PUB_RD	0.0100	0.0262	0.0106
	(0.0152)	(0.0150)	(0.0162)
L.BEV_SALES	-0.0078	0.5194	-0.0229
	(0.4792)	(0.3196)	(0.3112)
L.EPS	0.0871	0.5331	0.5235
	(0.3348)	(0.3867)	(0.3263)
L.Log_PATENT_STOCK	0.1596	1.3368^{***}	0.8893^{***}
	(0.2141)	(0.2645)	(0.2113)
L.GDP_PC	0.0000	-0.0000	-0.0001^{*}
	(0.0000)	(0.0000)	(0.0000)
_cons	-2.8440	-11.1221^{***}	-4.6499^{**}
	(1.7960)	(2.2333)	(1.5373)
N	254	254	254
pseudo R^2	0.227	0.317	0.251

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 9. The results of the regressions with China from 2001



	(1) BROWNISH_Special	(2) GREENISH_Special	(3) GREEN_Special
1			
2			
L.BERD_AUTO	0.004443*	0.000101	0.002013
	(0.002161)	(0.000075)	(0.002340)
L.CAR_SALES	-0.000871	0.003230	0.005793
	(0.008892)	(0.007029)	(0.008241)
L.GREEN_GOV_RD	-0.182853	-0.418453	-0.522864*
	(0.209762)	(0.218940)	(0.231939)
L.REN_EN_PUB_RD	-0.055852	-0.018565	-0.003587
	(0.033288)	(0.020636)	(0.019129)
L.FOSS_FUEL_PUB_RD	-0.073035	0.053183	0.025243
	(0.062578)	(0.027503)	(0.025312)
L.BEV_SALES	0.446643	1.024330**	0.292001
	(0.487005)	(0.388523)	(0.335944)
L.EPS	0.773384	0.171147	0.647946
	(0.488827)	(0.533285)	(0.582699)
L.Log_PATENT_STOCK	0.029032	1.419215***	0.876757*
	(0.317743)	(0.337778)	(0.354224)
L.GDP_PC	-0.000004	-0.000126*	-0.000189***
	(0.000050)	(0.000050)	(0.000053)
_cons	-0.153189	-7.344701***	-2.360116
	(2.270365)	(2.224923)	(2.077087)
3			
L.BERD_AUTO	0.004270*	-0.000141	0.001840
	(0.002158)	(0.000072)	(0.002339)
L.CAR_SALES	-0.005360	-0.004199	-0.017214*
	(0.009210)	(0.007689)	(0.007246)
L.GREEN_GOV_RD	-0.073671	0.107830	0.052792
	(0.215580)	(0.199050)	(0.191679)
L.REN_EN_PUB_RD	-0.012095	-0.046136*	0.002279
	(0.020792)	(0.020860)	(0.018263)
L.FOSS_FUEL_PUB_RD	0.011334	0.012316	-0.009898
	(0.021335)	(0.020608)	(0.020247)
L.BEV_SALES	0.248814	1.061597**	0.296778
	(0.474308)	(0.388307)	(0.336395)
L.EPS	-0.012194	-0.330488	-0.072736
	(0.419274)	(0.476945)	(0.387218)
L.Log_PATENT_STOCK	0.245798	1.769316***	1.048024***
	(0.306678)	(0.357013)	(0.317803)
L.GDP_PC	-0.000002	-0.000073	-0.000090*
	(0.000041)	(0.000040)	(0.000039)
_cons	-0.419746	-8.732018***	-2.651259
	(2.185746)	(2.544770)	(1.773460)
N	194	194	194
pseudo R^2	0.288	0.429	0.337

Standard errors in parentheses
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Figure 1.1 The distribution of the specialisation in brownish technologies

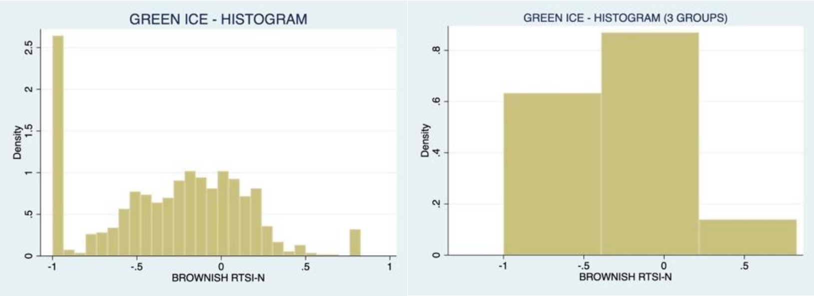


Figure 1.2 The distribution of the specialisation in greenish technologies

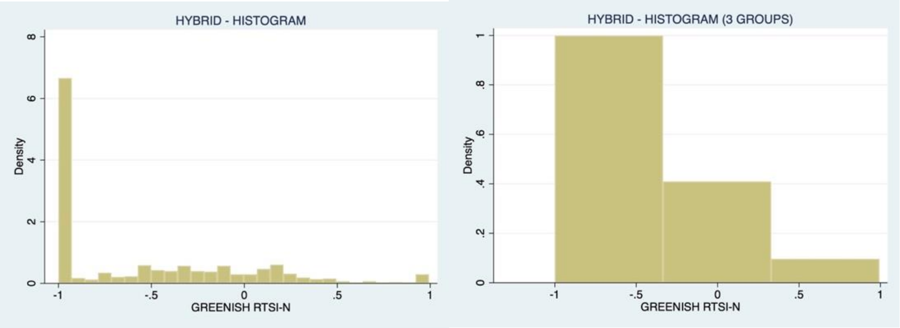


Figure 1.3 The distribution of the specialisation in green technologies

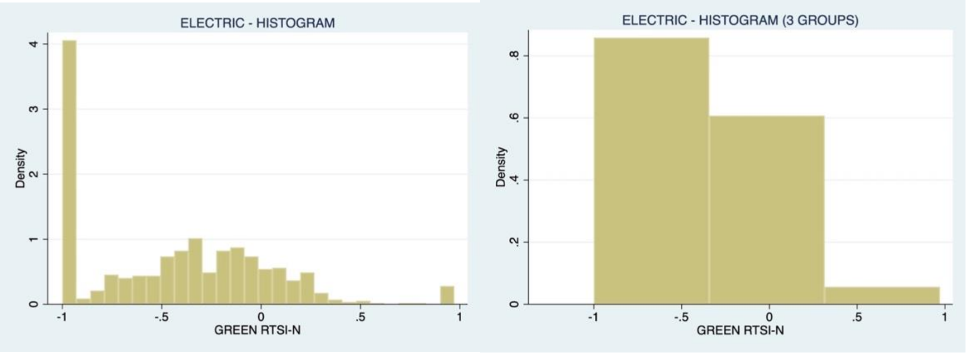


Fig. 2.1. Absolute vs. relative specialisation in *brownish* patents (1990-1999 / 2000-2008 / 2009-2018)

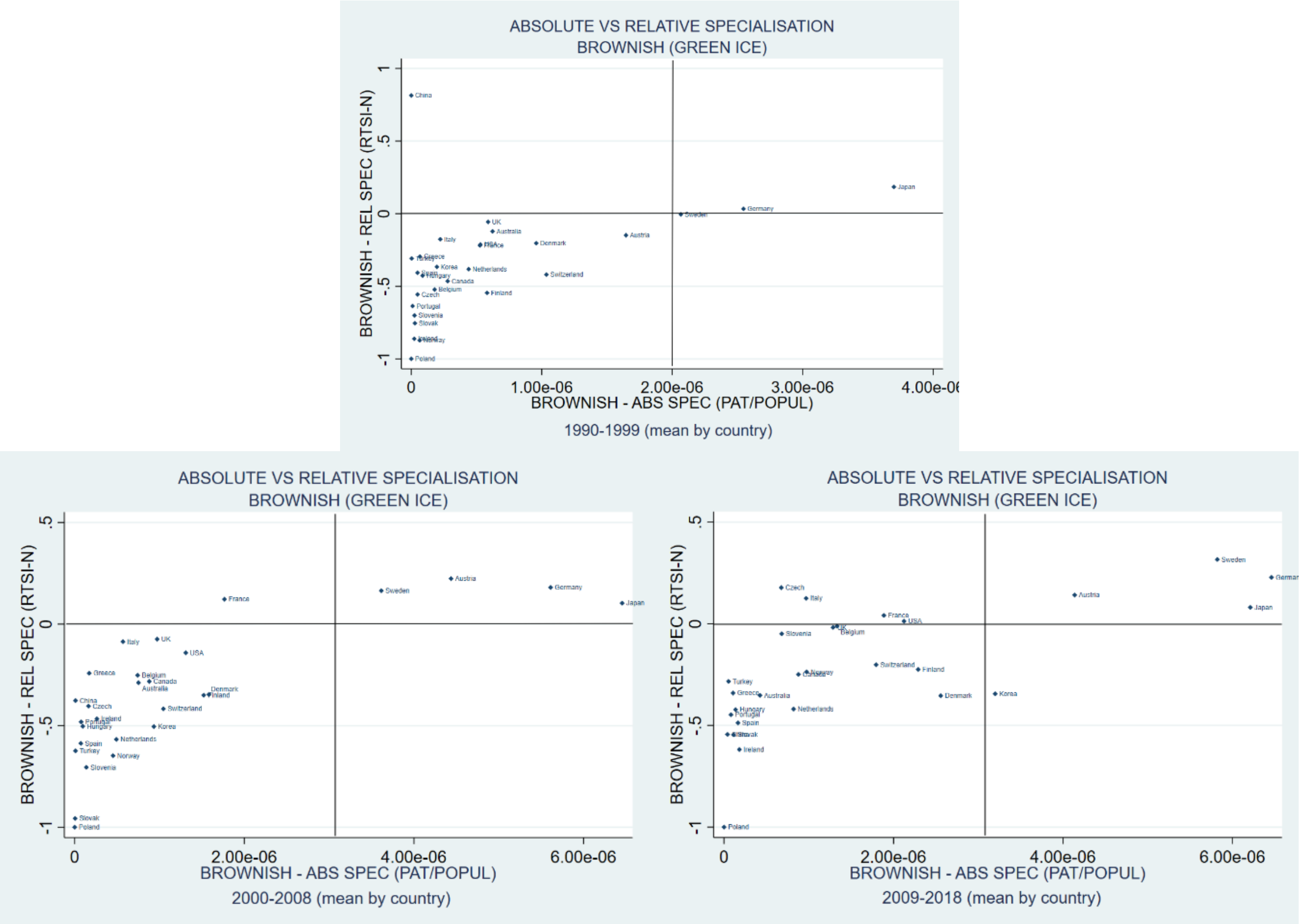


Fig. 2.2. Absolute vs relative specialisation in *greenish* patents (1990-1999 / 2000-2008 / 2009-2018)

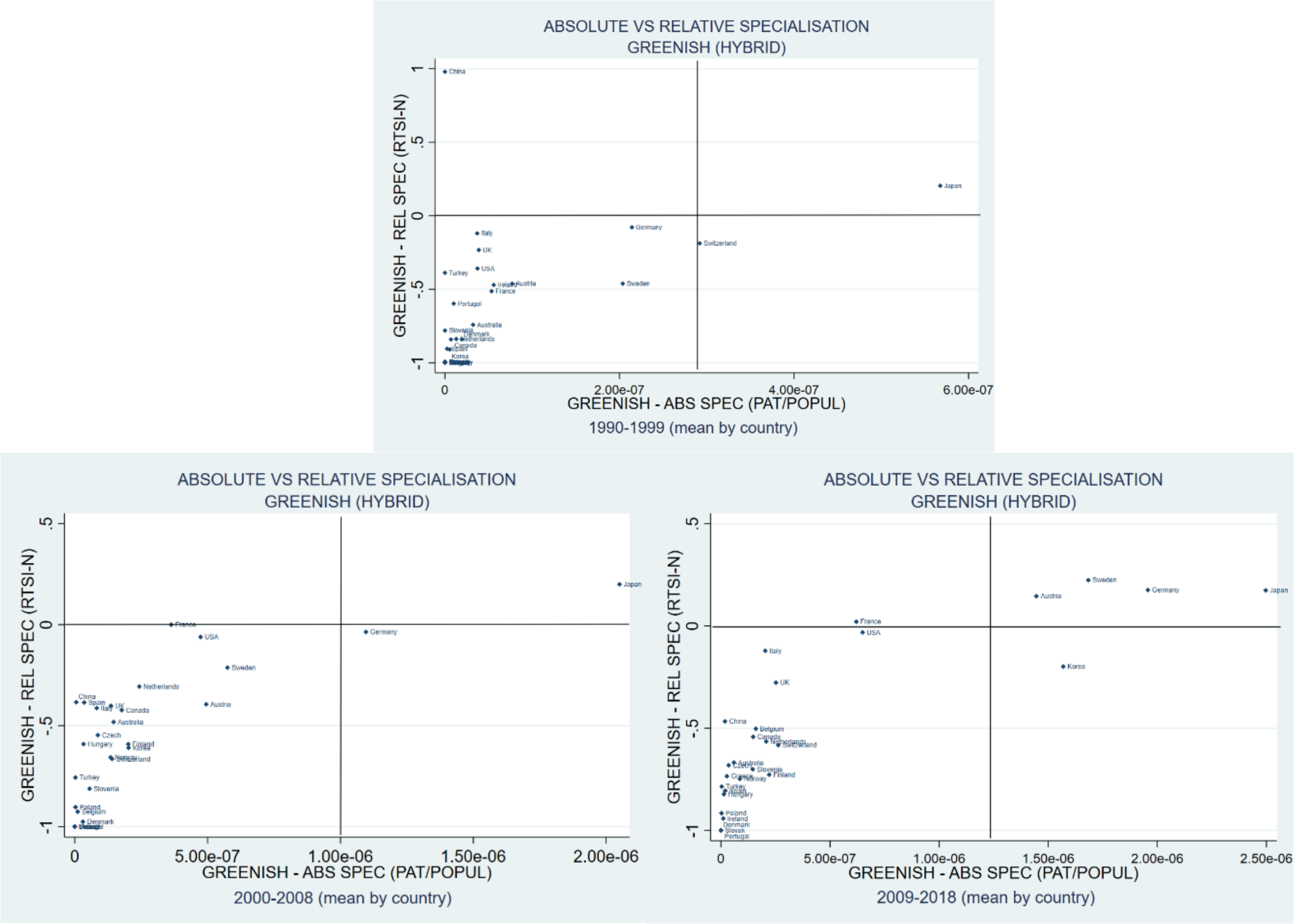


Fig. 2.3 Absolute vs relative specialisation in *green* technologies (1990-1999 / 2000-2008 / 2009-2018)

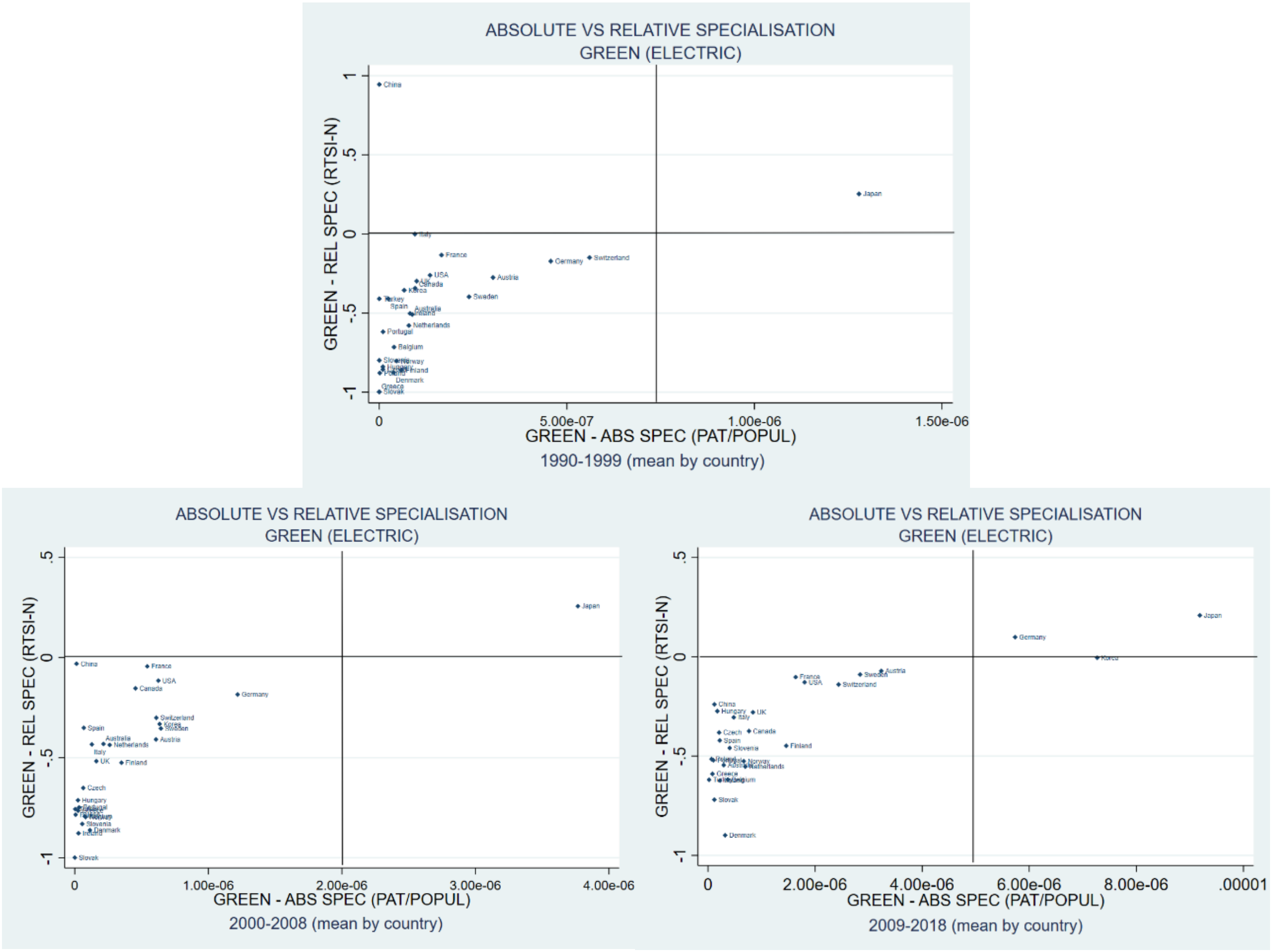


Fig. 3.1 Absolute vs relative specialisation in *brownish* technologies (1990-1995 / 2000-2005 / 2013-2018)

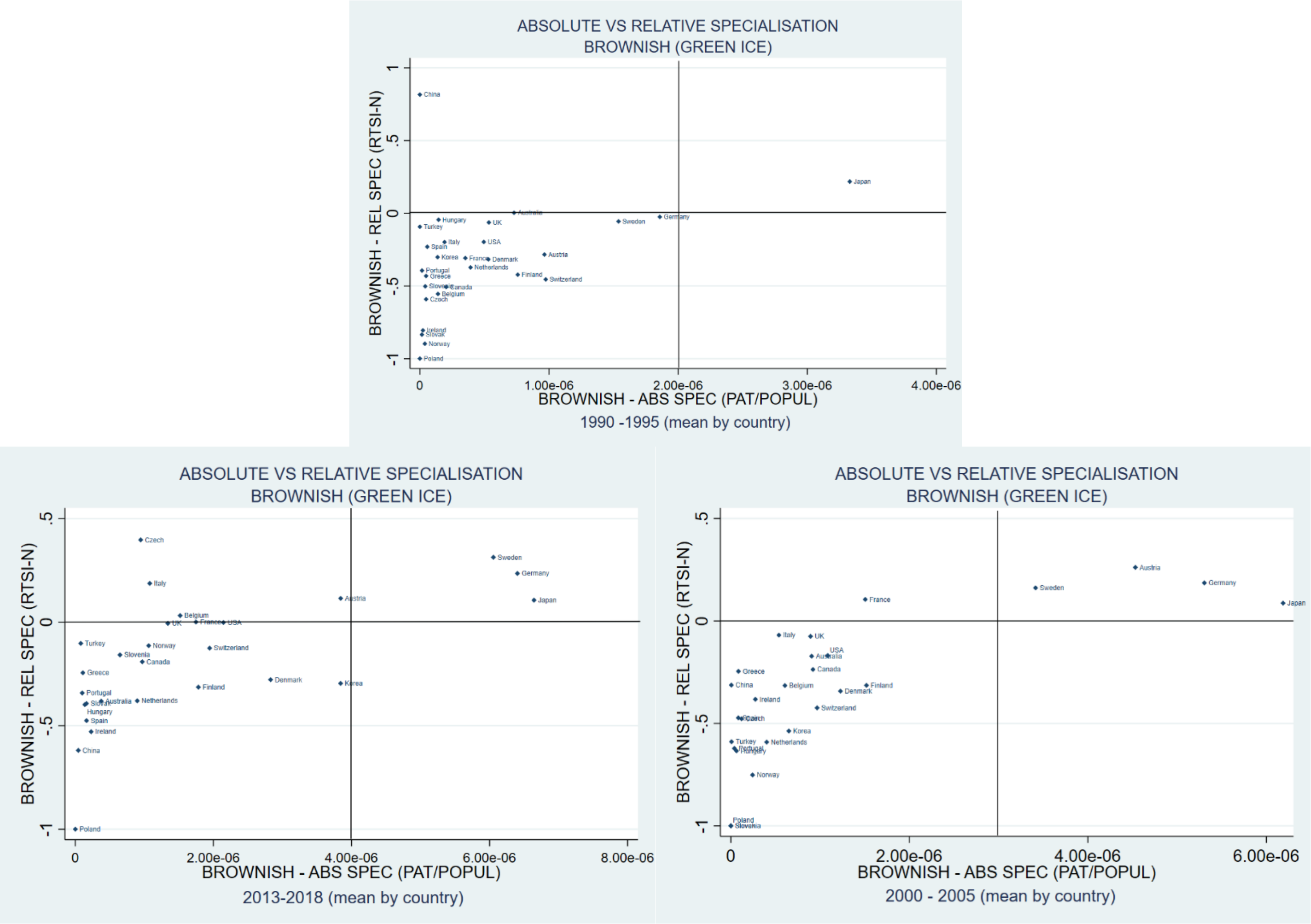


Fig. 3.2 Absolute vs relative specialisation in *greenish* technologies

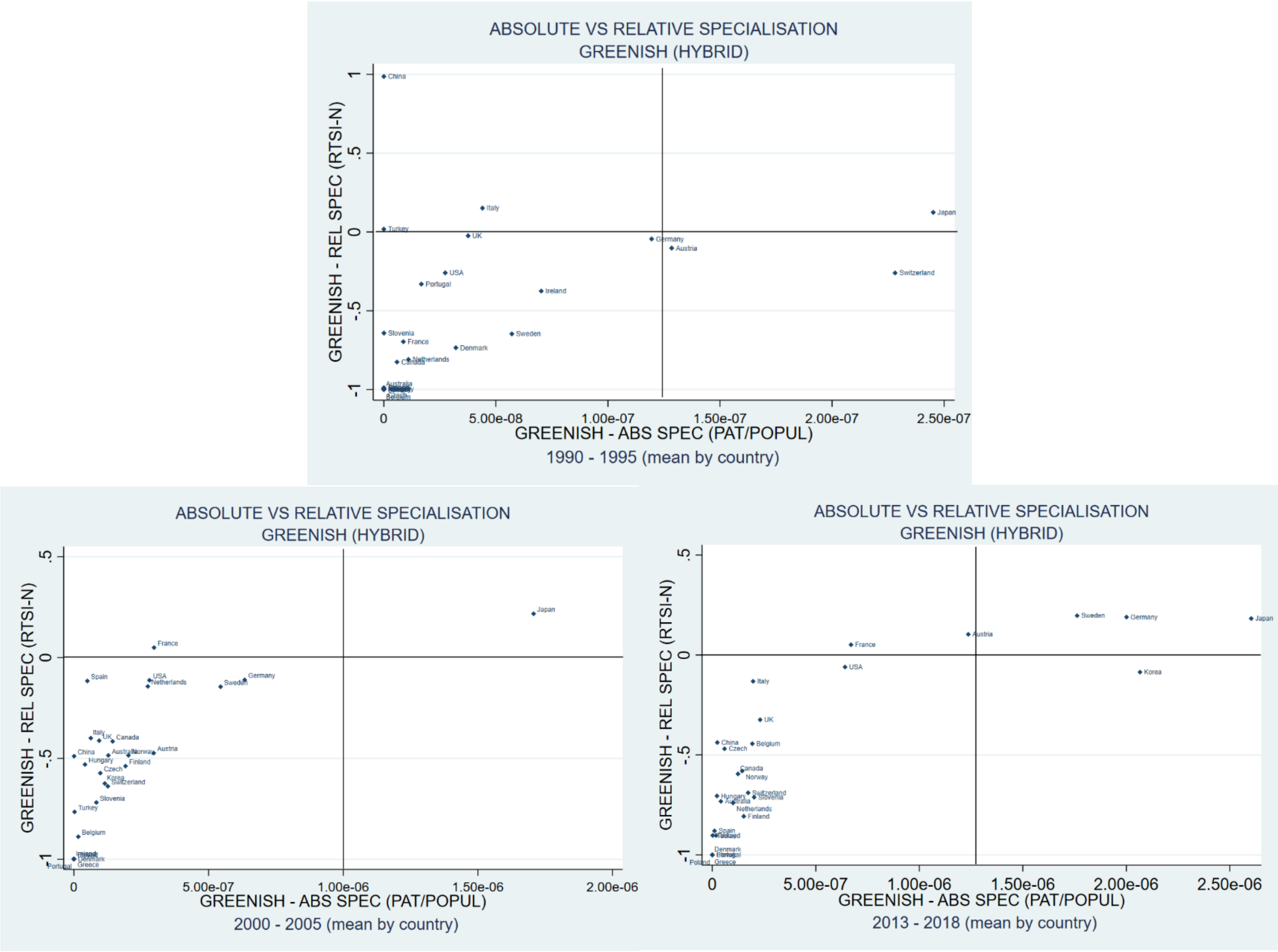


Fig. 3.3 Absolute vs relative specialisation in *green* technologies