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Article

Green Innovation in the Manufacturing Industry: A Longitudinal Approach

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Abstract

Despite substantial growth in eco-innovation (EI) research, most studies rely on cross-sectional data, limiting understanding of the temporal dynamics of EI and its determinants under varying macroeconomic conditions. This study addresses this gap by analysing panel data from Spanish manufacturing firms across three phases of the business cycle: pre-crisis expansion (2004–2007), the global financial crisis (2008–2013), and recovery (2014–2016). We investigate the drivers of two distinct types of eco-innovation: efficiency EI (energy and material savings) and environmental EI (reducing environmental harm), focusing on the role of regulation, institutional interventions, and firm-level innovation capacities. Using a random-effects panel probit model that accounts for unobserved firm heterogeneity, we examine how these drivers operate across different macroeconomic contexts. Our findings reveal that regulation consistently fosters EI, while the influence of subsidies, R&D capacity, and collaborative networks is more context-dependent, particularly during economic downturns. The results highlight the cumulative, path-dependent, and cyclical nature of eco-innovation, providing novel insights into the conditions that enable firms to sustain green innovation over time.

Keywords: eco-innovation drivers; environmental regulation; business cycle dynamics; economic crisis; firm resilience; innovation capabilities; green technology adoption; energy and material saving; sustainability strategies

1. Introduction

The manufacturing sector is increasingly confronted with mounting environmental pressures, as the large volumes of waste generated and the substantial energy required for continuous production cycles, high-temperature treatments, and raw-material processing intensify ecological degradation. These challenges are particularly acute in industries such as chemicals, textiles, and metals, where hazardous by-products, excessive water consumption, and significant particulate emissions remain persistent concerns. Comparable pressures are also evident in food and beverage production, illustrating the systemic nature of these environmental burdens. In this scenario, the scale and persistence of manufacturing-related impacts are prompting firms and policymakers alike to reconsider traditional production models and to incorporate strategies that enhance resource efficiency and reduce environmental harm.

One such strategy is eco-innovation (EI), which has emerged as a central mechanism through which firms can introduce environmentally beneficial products, processes, and organizational practices. Despite its growing relevance, our understanding of the determinants and dynamics of EI—particularly under varying macroeconomic conditions—remains limited. Existing literature reviews (Setyadi et al., 2025; Ren & Mia, 2025) identify manufacturing as a critical context in which

regulatory pressures, competitive forces, and technological demands converge most strongly. Yet empirical work on EI displays important shortcomings. Much of the research remains geographically concentrated, with a predominant focus on China, thereby restricting the generalizability of findings. Moreover, many studies rely on qualitative assessments of policy documents rather than robust, systematic data, while cross-sectional designs dominate empirical analyses. These methodological constraints hinder our ability to understand how environmental regulation, institutional mechanisms, and firm-level capabilities interact to shape EI over time—particularly across different phases of the business cycle, when constraints and incentives may vary markedly (Cai, 2018; Ghisetti & Renning, 2014; Jové-Llopis & Segarra-Blasco, 2018; Siddika et al., 2025; Triguero et al., 2013).

Firms' incentives to undertake eco-innovation (EI) are not static; rather, they fluctuate according to prevailing economic conditions. During downturns, resource scarcity, weakened demand and uncertainty often diminish compliance efforts and reduce consumer sensitivity to environmental considerations (Bowen & Stern, 2010; Cicuéndez-Santamaría, 2024; Kahn & Kotchen, 2011). At the same time, crises may prompt firms—particularly those operating in energy-poor contexts—to adopt energy-saving innovations as a means of containing costs (García-Sánchez & Rama, 2024). Nevertheless, the long-term effectiveness of regulatory frameworks and complementary policy tools, such as subsidies, under shifting macroeconomic conditions remains insufficiently understood. The scarcity of longitudinal datasets represents a significant barrier for researchers, thereby reinforcing calls for analyses that span extended periods to capture how environmental regulation interacts with firms' green behaviour (Cai, 2018; Ghisetti & Rennings, 2014; Jové-Llopis & Segarra-Blasco, 2018; Triguero et al., 2013). Recent literature reviews reiterate this need, emphasizing the importance of panel data for assessing the dynamics and impacts of EI across different phases of the business cycle (Siddika et al., 2025). Indeed, Ghisetti and Rennings (2014) specifically highlight that economic downturns may condition firms' environmental strategies, thereby warranting more nuanced empirical investigation. In line with these perspectives, the present study adopts a longitudinal approach.

To address these gaps, the study pursues two main objectives. First, it examines the dynamic effects of regulation and policy support on EI over time, with particular attention to periods of economic contraction. Second, it analyses firm-level determinants—such as prior EI engagement, firm size, knowledge integration capabilities, and strategic orientations toward market expansion or product quality—and considers how their influence varies across business-cycle phases. Taken together, the longitudinal lens illuminates when and why certain drivers exert influence, thereby enabling more targeted policy design and more resilient managerial decision-making.

These objectives are pursued using panel data from Spanish manufacturing firms, encompassing approximately 97,733 observations from 2004 to 2016. This period includes a phase of economic expansion (2004–2007), the global financial crisis (2008–2013), and the subsequent recovery (2014–2016). Spain presents a particularly salient context, given its structural dependence on imported energy and water resources, alongside the severe contraction in public and private R&D investment following the 2008 crisis (Cruz-Castro et al., 2018; Holl & Rama, 2016). According to Eurostat, Spain is categorized as a “moderate innovator” (https://ec.europa.eu/assets/rtd/eis/2025/ec_rtd_eis-country-profile-es.pdf),. (https://ec.europa.eu/assets/rtd/eis/2025/ec_rtd_eis-country-profile-es.pdf), It is characterized by limited high-technology sectors—especially in ICT-related industries—and a predominance of small firms, which together constrain innovation diffusion and productivity growth (Molero, 2020). Elevated energy prices during downturns further intensify the vulnerability associated with import dependence. Yet, despite structural weaknesses in its National Innovation System (NIS), Spain has emerged as a notable contributor in the field of renewable energy and environmental technology. Patent-based analyses reveal that the country maintains a competitive advantage in several environmental technology domains (Molero & López, 2021), thereby supporting national efforts to reduce reliance on imported fossil fuels. These structural characteristics, many of which are shared by peripheral European and emerging economies, make Spain a compelling comparative case.

The study is theoretically grounded in evolutionary and institutional perspectives. In line with Evolutionary Theory (Nelson & Winter, 1982; Dosi, 1982), green innovation is conceptualized as the result of cumulative learning, path-dependent routines, and the interplay between firm-specific capabilities and network embeddedness, all of which evolve in response to macroeconomic conditions. Institutional theory further suggests that coercive, normative, and mimetic pressures—ranging from regulatory requirements to social expectations and the emulation of leading firms—shape firms' environmental strategies (DiMaggio & Powell, 1983). Together, these frameworks provide a comprehensive analytical foundation for examining EI drivers across varying economic contexts. Accordingly, we posit that while some determinants exert persistent, positive influences on EI irrespective of the business cycle, others function as countercyclical mechanisms that support firms' environmental resilience during challenging periods.

Although the dataset covers 2004–2016, it constitutes the most complete panel currently available for Spanish manufacturing firms. EU-level data on EI remain largely cross-sectional, as Community Innovation Survey (CIS) instruments seldom offer panel structures; the Spanish PITEC survey represents a notable exception in this regard. Given that innovation activity tends to be procyclical—expanding during favourable economic conditions and contracting during downturns (Archibugi et al., 2013)—the dynamics observed during the Great Recession provide valuable insights for understanding firms' responses to subsequent crises, including the ongoing energy crisis in Europe. Consequently, the analysis sheds light on how regulation, other policy support tools and firm capabilities condition eco-innovation under adverse economic circumstances, thereby offering important implications for contemporary policy design.

Section 2 presents the literature review, which establishes the theoretical foundations for the hypotheses. Section 3 details the methodology. Section 4 outlines the contextual setting, Section 5 reports and discusses the empirical findings, and Section 6 provides concluding remarks.

2. Literature Review

This section clarifies the key concepts and definitions associated with eco-innovation (EI) and examines the main determinants identified in the literature, thereby establishing the foundation for the empirical analysis that follows.

2.1. Definitions

In the Community Innovation Survey (CIS) conducted by the European Union, innovation is defined as the introduction of a new or significantly improved product—whether a good or service—or the implementation of a new or significantly improved process within the firm. This definition is particularly relevant, given that the present study draws upon data obtained from a CIS-type survey structure. Within the academic literature, the concept of EI appears under various labels—including “ecological,” “green,” and “sustainable” innovation—reflecting the field's breadth and conceptual diversity (Galera-Quiles et al., 2021). In this article, EI and green innovation are treated as equivalent terms.

Although EI encompasses multiple dimensions, the literature consistently emphasizes two core components: (1) the reduction of negative environmental externalities, particularly through pollution-prevention mechanisms, and (2) the enhancement of resource efficiency, especially regarding energy and water savings. In line with these prevailing conceptualizations, the present study focuses on two types of EI: environmental EI, referring to innovations designed to prevent environmental harm, and efficiency EI, which is associated with technologies and practices that conserve energy and water.

The Eco-Innovation Observatory defines EI as the “introduction of any new or significantly improved product (good or service), process, organizational change, or marketing solution that reduces the use of natural resources (including energy, water, and land) and decreases the release of harmful substances across the whole life cycle.” (<https://ec.europa.eu/eurostat/web/microdata/community-innovation-survey> October 2024). This

definition, widely cited in the literature, reinforces the cross-cutting and multifaceted character of EI. For an extensive synthesis of definitions employed in prior studies, Díaz-García et al. (2015) provide a comprehensive review, while Chaparro-Banegas et al. (2013), drawing on bibliometric techniques, map the evolution of EI terminology across academic domains.

2.2. Conceptual Framework

Following the evolutionary theory of technological change (Nelson & Winter, 1982; Dosi, 1982), green innovation can be interpreted as an outcome of cumulative learning processes, path-dependent routines, and the interaction between firm-specific capabilities and the broader networks in which firms are embedded. Internal capabilities—such as the skills of R&D personnel, accumulated experience, and learning-by-doing—co-evolve with external pressures, shaping firms' ability to adapt their technological trajectories. Simultaneously, access to diverse knowledge sources and strategic cooperation with external partners serve as additional mechanisms of variation and selection, influencing firms' innovation paths over time.

Institutional theory offers a complementary viewpoint, highlighting the role of coercive pressures (e.g., regulatory mandates), normative expectations (e.g., societal demands for sustainability), and mimetic behaviours (e.g., imitation of successful environmental leaders) in shaping firms' green strategies (DiMaggio & Powell, 1983; Scott, 2014). These insights underscore the importance of analysing multiple determinants of EI—including regulatory interventions, knowledge-related factors, and firm-level characteristics—across shifting macroeconomic contexts such as periods of expansion and crisis. A longitudinal perspective is therefore particularly valuable, enabling the assessment of not only which drivers matter, but also how their influence changes as resource availability, regulatory enforcement, and societal priorities evolve over the business cycle.

This integrated theoretical framework informs the review of empirical studies in the subsequent subsections and provides the conceptual basis for the hypotheses developed in this article.

2.3. Drivers of Eco-Innovation: Institutional Intervention

Institutional intervention—manifested through policies and public support for R&D—emerges consistently in the literature as a central mechanism shaping firms' engagement in EI (Siddika et al., 2025). Drawing on institutional theory (DiMaggio & Powell, 1983; Scott, 2014), such interventions are part of the broader institutional environment that conditions firm behaviour, not only through regulation but also via normative expectations and the imitation of peer practices. This perspective underscores the institutional embeddedness of EI and reinforces Horbach's (2008) observation that, owing to the prevalence of negative environmental externalities, EI tends to be less market-driven than other forms of innovation. Consequently, environmental policy is widely viewed as a pivotal determinant of firm-level innovative activity in this domain.

The debate surrounding institutional drivers of EI is longstanding and far from settled. Porter and van der Linde's (1995) "win-win" hypothesis posits that stringent environmental regulation may stimulate innovation by compelling firms to identify efficiency gains and new technological opportunities. While influential, this hypothesis has generated mixed empirical findings (Siddika et al., 2025). Institutional theory helps explain this heterogeneity: although regulation exerts coercive pressure, firms also respond to normative expectations—such as industry standards or environmental activism—and mimetic forces under uncertainty. Empirical contributions reflect these varied influences. Several studies, especially in European contexts, identify regulation as a decisive driver of EI (Bossle et al., 2016; Costa-Campi et al., 2015; Doran & Ryan, 2012; García-Sánchez & Rama, 2024; Hojnik & Ruzzier, 2016; Jové-Llopis & Segarra-Blasco, 2018; Demirel & Kesidou, 2011; Horbach, 2008; Triguero et al., 2013). Evidence from China similarly highlights strong positive links between institutional pressures and green innovation (Ning et al., 2021), and studies across Asia reviewed by Ren & Mia (2025) confirm the centrality of regulation. Yet, other analyses point to mixed outcomes (Guo et al., 2018), suggesting that regulation alone seldom suffices. Its effectiveness may depend on complementary conditions, such as public R&D funding (Guo et al., 2018; Yi et al., 2021), societal

pressures—often expressed through pollution complaints (Sun et al., 2022)—or alignment with broader policy frameworks (Cecere et al., 2014; Criscuolo & Menon, 2015; Ning et al., 2021). Moreover, Demirel & Kesidou (2011) note that highly innovative firms may pursue EI independently of regulatory inducement, highlighting potential trade-offs between internal capabilities and external policy stimuli.

Regional variation adds complexity to this landscape. Mora-Sanguinetti et al. (2024) find that national-level renewable energy regulations in Spain significantly increase expenditures on both green and non-green innovation, while regional measures show negligible effects—possibly reflecting regulatory fragmentation or qualitative differences in policy design. Supranational EU policies introduce an additional institutional layer that further shapes firm behaviour.

Financial support mechanisms—particularly subsidies—have likewise attracted substantial scholarly attention, yet their contribution to EI remains contested (Siddika et al., 2025). The effects of subsidies vary considerably across regional, sectoral, and firm-level contexts. For example, in Eastern Europe, subsidies appear to function as essential enablers, helping firms overcome financial constraints and pursue green innovation (Horbach, 2016). Evidence from Chinese manufacturing firms similarly reveals positive effects on patent-based indicators of EI, with subsidies easing financial pressures and signalling credibility to external investors (Sun et al., 2022). From an institutional perspective, subsidies also enhance legitimacy by signalling conformity with policy priorities. In Spain, however, the evidence is more ambiguous. Jové-Llopis and Segarra-Blasco (2018) report limited impacts of financial support on EI, while Cuerva et al. (2014) find that subsidies in Castilla-La Mancha's food and beverage small-and medium-enterprises (SMEs) tend to promote non-eco-innovations instead. Biggi et al. (2023) further show that subsidies significantly influence environmental EI—aimed at preventing environmental harm—but exert no meaningful effect on efficiency EI, which focuses on conserving energy and other resources. Supranational funding introduces an additional layer of variation: among Spanish food and beverage firms, EU-level R&D finance exhibits a stronger positive effect on EI, particularly during periods of economic stress, exceeding the influence of national support (García-Sánchez & Rama, 2024). Collectively, these findings suggest that subsidies are neither universally effective nor homogeneous in their influence; rather, their impact depends on their source, regional context, sectoral composition, and the type of EI targeted. The present study examines these three layers of institutional tools.

Other institutional instruments remain comparatively understudied. Caravella & Crespi (2020) emphasize the importance of distinguishing among diverse financial tools, as their effectiveness and target profiles vary. Notably, public-private R&D contracts—despite their potential to promote sustained innovation and facilitate knowledge transfer—have received relatively limited attention (García-Sánchez & Rama, 2024). Addressing this gap, the present study considers the role of such contracts in sustaining EI, particularly under conditions of economic uncertainty.

The rationale for adopting a longitudinal approach arises from several interrelated considerations. Sociological research indicates that crises may erode environmental concern (Cicuéndez-Santamaría, 2024), with reductions in public awareness or shifting consumer priorities weakening firms' incentives to comply with environmental regulations. Macroeconomic downturns amplify these dynamics by intensifying policy uncertainty, dampening firms' and investors' willingness to invest in green initiatives, and heightening resistance to environmental measures (Noailly et al., 2022; Kahn & Kotchen, 2011; Bowen & Stern, 2010). Conversely, other studies suggest that regulation can continue to encourage EI during crises. Bowen & Stern (2010) emphasize that policy interventions may either mitigate or exacerbate the effects of crises depending on their design and implementation. During the 2008–2014 financial crisis and early recovery, regulatory pressure still supported EI among Spanish manufacturing firms (Jové-Llopis & Segarra-Blasco, 2018), and European SMEs that perceived regulation as a key driver were more likely to engage in EI (Triguero et al., 2018). While these analyses highlight the potential of regulation to sustain EI during crisis periods, their focus on in-crisis intervals limits understanding of how institutional drivers operate across the full business cycle.

Building on institutional theory, we conceptualize regulatory and financial interventions as dynamic pressures—coercive, normative, and mimetic—whose influence on EI evolves with macroeconomic conditions. By adopting a longitudinal perspective, the present study examines how these institutional drivers shape EI across boom, crisis, and recovery phases.

Based on the preceding discussion, we propose the following hypotheses:

H1. *Dynamic Regulation Hypothesis*. Regulation positively influences firms' eco-innovation in boom, crisis, and recovery periods.

H2. *Countercyclical Support Hypothesis*. Regulation positively influences environmental innovators in boom, crisis and recovery, while financial support mechanisms become particularly influential during challenging times, with public R&D funding providing countercyclical reinforcement.

H3. *Regulatory Dominance Hypothesis*. Efficiency EI is primarily driven by regulation and is not significantly influenced by other policy instruments across the business cycle.

Throughout the article, the term challenging times refers to both the crisis and recovery periods. This designation reflects the fact that, in Spain, recovery unfolded more slowly and severely than in many other EU countries, as evidenced by its GDP trajectory (García-Sánchez & Montes-Luna, 2022).

2.4. Drivers of Eco-Innovation: Knowledge Factors

Although EI is often portrayed as a response to regulatory or economic pressures, a growing body of research shows that its underlying drivers are considerably broader. Oltra and Saint-Jean (2009) argue that EI cannot be reduced to a mechanical reaction to regulation; instead, firms' knowledge bases—and particularly their access to external knowledge—play a decisive role. Horbach et al. (2012) similarly contend that while regulation and cost-saving incentives remain central, a wider set of supply-side factors, including technological capabilities, must also be considered.

A key concept in this regard is firms' absorptive capacity, commonly proxied by R&D investment. Ren and Mia's (2025) review indicates that technological resources and the ability to assimilate external knowledge both exert a positive influence on green innovation. Empirical work supports this view: Cai (2018), studying Chinese firms, finds that strong technological capabilities significantly encourage EI, and Horbach (2008) likewise reports that R&D engagement fosters EI, though with uneven effects across contexts (Horbach, 2016). Spanish evidence echoes this pattern: Jové-Llopis and Segarra-Blasco (2018) show that both internal and external R&D were positively associated with EI during the 2008 crisis and early recovery, a result consistent with Biggi et al. (2023). Yet, contrasting findings persist—Cainelli et al. (2015) and Costa-Campi et al. (2015) detect no significant link between R&D and EI. Despite these contributions, Chaparro-Banegas et al.'s (2013) bibliometric analysis highlights that absorptive capacity remains relatively underexplored in the EI literature, a gap also emphasized by Ren & Mia (2025).

Relatedly, most studies privilege formal R&D while overlooking alternative innovation pathways. Biggi et al. (2023) offer an exception, showing that lagged product and process innovations positively affect efficiency EI but not environmental EI. Beyond formal R&D, mechanisms such as learning-by-doing, cumulative experience, and collaborative knowledge exchange may be equally important. Prior EI engagement, for instance, strongly predicts future EI, reflecting path dependency and the development of persistent routines (Arranz et al., 2021; Horbach, 2008; Jové-Llopis & Segarra-Blasco, 2018; García-Sánchez & Rama, 2024; Triguero et al., 2013; see also Nelson & Winter, 1982; Dosi, 1982).

Cooperation with external partners—including clients, suppliers, universities, and industry associations—emerges as another critical knowledge source. Collaboration often provides access to complementary expertise and reduces the costs associated with technological constraints (Biggi et al., 2023). In their review, Araújo and Franco (2021) find a generally positive effect of cooperation, though

outcomes depend on choosing appropriate partners. Ren & Mia's (2025) synthesis similarly highlights the consistent benefits of collaboration. Still, empirical findings remain mixed: while Horbach (2008, 2016) and Cainelli et al. (2015) report positive effects, Jové-Llopis and Segarra-Blasco (2018) detect none. Some evidence suggests that specific forms of cooperation matter more than others; Triguero et al. (2013), for example, find a particularly strong impact of university and research-centre collaboration among European SMEs. These authors also show that the breadth of external information sources significantly increases environmental EI, especially during the severe economic conditions studied.

Spillovers represent another potential EI driver frequently cited in theory but seldom validated empirically (Jové-Llopis & Segarra-Blasco, 2018; García-Sánchez & Rama, 2024). Access to external knowledge can also be reflected in the acquisition of technological inputs. Although the Oslo Manual conceptualizes the acquisition of equipment, software, and external knowledge as legitimate innovation activities, empirical work on their role in EI is scarce (https://www.oecd.org/en/publications/oslo-manual-2018_9789264304604-en.html October 2025). Cainelli et al. (2012) note this gap in their study of Italian firms, while Demirel & Kesidou (2011) find that investments in machinery recurrently support EI among British firms. This points to a broader issue: several potential EI drivers remain understudied, warranting further empirical attention—an issue this study seeks to address.

Despite offering valuable insights, much of the existing research focuses on “normal” periods of the business cycle or on macroeconomic contexts with similar characteristics, such as crisis and early recovery (Costa-Campi et al., 2015; Jové-Llopis & Segarra-Blasco, 2018). Consequently, little is known about how knowledge-related drivers of EI evolve across distinct macroeconomic environments. Addressing this gap is crucial to understanding the dynamics governing firms' innovative behaviour across boom, crisis, and recovery.

Based on the previous discussion, we propose the following hypotheses:

H4. *Persistence Hypothesis*. Firms with prior EI experience are more likely to engage in EI across boom, crisis, and recovery.

H5. *Continuous Innovation Hypothesis*. Firms engaged in continuous joint product and process innovation are more likely to eco-innovate across boom, crisis, and recovery.

H6. *Knowledge Integration Hypothesis*. Access to diversified external knowledge and internal R&D-related factors positively influences EI during challenging times, but not necessarily during expansive phases.

2.5. Drivers of Eco-Innovation: Firm Characteristics and Market Dynamics

Beyond institutional and knowledge-related drivers, the literature identifies a range of additional determinants of EI, notably market-related and firm-specific factors. Market-oriented and organizational theories posit that competitive dynamics and a firm's market position significantly influence EI adoption. For instance, Demirel & Kesidou (2011), analysing the United Kingdom, find that while regulatory pressure constitutes an important stimulus, market-related factors—particularly the pursuit of cost reduction—serve as strong motivators for EI. Similarly, Horbach (2008), using German panel data, demonstrates that cost savings constitute a central driver, highlighting the reinforcing role of economic incentives alongside policy measures. In line with these findings, Ren & Mia (2025), synthesizing prior studies, identify market competition as a recurrent catalyst of green innovation across diverse empirical contexts.

Evidence from Spain, however, paints a more nuanced picture. Jové-Llopis and Segarra-Blasco (2018) report that demand-pull factors exert limited influence: coefficients capturing the importance of maintaining or expanding market share, or entering new markets, are largely non-significant, suggesting that such factors are not decisive in driving EI adoption. Similarly, Brunnermeier & Cohen

(2003), analysing 146 U.S. industries between 1981 and 1991, observe that market structure—proxied by the concentration ratio of the four largest firms—has only a modest effect on EI once industry fixed effects are accounted for. Horbach et al. (2012) further report that competitive pressures play a negligible role in Germany, as firms' eco-innovative activities rarely aim at market expansion. Arranz et al. (2019) add that market saturation may act as a constraint on EI. Taken together, these findings suggest that while market incentives such as cost savings and competition can stimulate EI, their influence varies across institutional, sectoral, and national contexts.

Firm-level characteristics, particularly firm size, have also been extensively examined as determinants of EI. Larger firms are often argued to possess superior financial resources, organizational capacities, and absorptive abilities, which facilitate investment in green technologies and processes. Empirical evidence generally supports this claim. Sun et al. (2022), studying Chinese firms, find that larger firms enjoy a comparative advantage in EI, with economies of scale enabling lower R&D costs. Similarly, Costa-Campi et al. (2015) and Jové-Llopis & Segarra-Blasco (2018), focusing on Spanish firms, document a positive association between firm size and EI, a relationship also observed by Triguero et al. (2013) among European SMEs. Biggi et al. (2023) report that firm size positively influences efficiency EI but not environmental EI, whereas Arranz et al. (2019) find that size affects environmental EI but not efficiency EI; both studies draw on Spanish samples. In contrast, Horbach (2008), examining German data, finds no significant effect of firm size on EI adoption. Collectively, these mixed findings underscore the complexity of the relationship between firm size and EI, suggesting that contextual, sectoral, and institutional factors may moderate this association.

Based on the preceding discussion, we formulate the following hypotheses:

H7. *Baseline Size Effect Hypothesis*. Larger firms are more likely to engage in eco-innovation in boom, crisis, and recovery.

H8. *Cyclical Sensitivity of Smaller Firms Hypothesis*. The likelihood of EI among smaller firms increases during economic expansions but diminishes during challenging times.

H9. *Market Expansion Hypothesis*. Firms pursuing market expansion or entry into new markets are more likely to eco-innovate across boom, crisis, and recovery.

H10. *Quality Hypothesis*. Firms emphasizing product quality are more likely to eco-innovate across boom, crisis, and recovery.

3. Context Setting

Following the recommendations of Arranz et al. (2019) and the bibliometric review by Chaparro-Banegas et al. (2023), which underscore the value of studying EI within the framework of the NIS, this section situates Spanish manufacturing in a broader comparative and institutional context. This is critical for interpreting firm-level EI and for drawing lessons applicable to similar economies.

Spanish manufacturing operates within a European environment marked by the long-term decline of industrial activity (Braña & Molero, 2020; Pianta et al., 2016; OECD, 2015). Relative to the EU average, Spain's industrial structure shows a lower share of technology-intensive sectors and a predominance of low-technology industries, limiting the diffusion of advanced knowledge and constraining the transition toward innovation-driven and sustainable production models. According to Eurostat, Spain is categorized as a "moderate innovator", a classification that include those countries whose overall innovation performance reaches 70%–100% of the EU average (https://ec.europa.eu/assets/rtd/eis/2025/ec_rtd_eis-country-profile-es.pdf). They typically have solid human capital and digital capabilities, and their firms often introduce incremental innovations, but they generally show weaker R&D investment, fewer high-tech, and less developed innovation linkages than leading innovators.

Structural characteristics further shape Spain’s innovative potential. The small average size of firms restricts productivity, international competitiveness, and their ability to generate and absorb new technologies, including environmental innovations (Molero, 2020). Foreign participation plays a significant role: subsidiaries of multinational enterprises account for a large share of industrial output and exports, particularly in high-technology sectors (Instituto Nacional de Estadística, 2019), <https://www.ine.es/dynt3/inebase/index.htm?type=pcaxis&path=%2Ft37%2Fp227%2Fp01%2Fa2019%2Fe01%2F&file=pcaxis&L=0>. Yet, their presence has not fully delivered expected spillover effects to strengthen domestic technological capabilities (Álvarez & Molero, 2005; García-Sánchez et al., 2016; Guimón & Salazar-Elena, 2015).

Several aspects of the Spanish NIS are particularly relevant for understanding firms’ capacity for green innovation (European Commission, 2025). Innovation intensity remains modest, and the proportion of innovative firms is well below the EU average—33% in Spain versus 57% in the EU and around 70% in leading innovation countries. Spanish companies invest less frequently in R&D, introduce fewer product innovations, and rely minimally on intellectual property mechanisms, including patents. Only 11.8% of firms conduct R&D, compared with 26.6% in the EU. Innovation cooperation is limited, concentrated mainly among domestic partners, with comparatively low engagement with universities and public research organizations.

These structural patterns reflect broader systemic constraints. Gaps in human capital—stemming from mismatches between education and labor-market needs, weak vocational training, and limited continuous professional development—reduce firms’ capacity to adopt and integrate advanced environmental technologies. Financial barriers, including banks’ risk aversion, restricted venture capital, and scarce early-stage funding, further constrain innovation. Complex and fragmented regulation, coupled with slow administrative procedures, increases both the cost and uncertainty associated with new projects.

Overall, Spain’s industrial and innovation landscape combines technological, organizational, and institutional limitations that shape the environment in which green innovation emerges. These conditions help explain the challenges faced by Spanish manufacturing firms in pursuing EI and underscore the need for a detailed, context-sensitive analysis.

4. Methodology

4.1. Data

The present study draws on the PITEC survey, Spain’s contribution to the EU’s Community Innovation Survey (CIS) framework (https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736176755&menu=resultados&secc=1254736195616&idp=1254735576669#_tabs-1254736195616; 20 December 2024). Unlike most CIS-type surveys, PITEC provides panel data collected within a mandatory survey framework, offering anonymized firm-level microdata on technological innovation activities across all major sectors of the Spanish economy. For this analysis, the panel is restricted to manufacturing firms that remained continuously active throughout the 2004–2016 period, as data for 2017 and subsequent years are not yet publicly available.

The panel structure allows for the observation of technology adoption behaviour over time, facilitating the examination of both the timing and persistence of eco-innovation and their interaction with external shocks, including the 2008 financial crisis. The dataset comprises 97,733 firm-year observations, ensuring robust sample coverage. Consistent with the trajectory of Spanish GDP (García-Sánchez & Montes-Luna, 2022), the study period is divided into three sub-periods: 2004–2007 (boom), 2008–2013 (crisis), and 2014–2016 (recovery). The analysis differentiates between efficiency EI—focused on reducing material and energy use per unit of output—and environmental EI—aimed at minimizing environmental harm.

Within the PITEC survey, innovation is defined broadly, encompassing both innovations that are new to the market and those that are novel only to the firm, even if similar solutions already exist

elsewhere. While the latter category may more accurately reflect technology adoption, the term “innovation” is employed here to maintain consistency with the data source.

Although some prior studies on EI exclude micro-firms (≤ 10 employees) from their analyses (Arranz et al., 2019), we retain them in the sample, as they represent approximately 9% of our dataset. This inclusion allows for at least a partial assessment of micro-firms’ green behaviour, contributing to a more complete understanding of the Spanish manufacturing landscape.

Despite its advantages, the PITEC dataset presents certain limitations for studying green technology adoption. Information on EI is self-reported, reflecting firms’ perceptions regarding the importance of green considerations in their innovation activities. To capture actual green innovation rather than aspirational statements, the sample is restricted to firms classified as innovators under the PITEC framework—those that introduced innovations in the previous two years, had ongoing innovation projects, or experienced failed innovation attempts. This approach aligns with the Oslo Manual definition of innovation, which recognizes innovation as a process inclusive of both successful and unsuccessful outcomes.

Within this subset, eco-innovators are identified as firms reporting that environmental considerations were either very important or moderately important in their innovation processes. By focusing on active innovators, the analysis excludes firms that claim environmental technologies are highly important but report no innovation activity, reducing noise and aligning the sample with firms demonstrating tangible capacity or intent to adopt new technologies. Although this restriction narrows the scope of inference to innovative firms within the Spanish manufacturing sector, it provides a more accurate basis for examining the determinants and temporal dynamics of EI, consistent with methodologies employed by Costa-Campi et al. (2015) and García-Sánchez & Rama (2024).

A further challenge, noted by Horbach (2016), is that CIS-type surveys, including PITEC, do not provide specific information on R&D dedicated to green innovation. Consequently, researchers must rely on general R&D and innovation data, a limitation that applies to the present study as well.

4.2. Variables

4.2.1. Dependent Variables

The PITEC questionnaire captures firms’ prioritization of regulatory compliance, energy and water savings, and the prevention of environmental harm within their innovation activities. Firms’ perceptions of the importance of green innovation are measured on a four-point Likert-type scale (high importance, moderate importance, reduced importance, not relevant). Consistent with the approach outlined in Section 4.1, we classify innovative firms as eco-innovators if they report that environmental considerations were either very important or moderately important in their innovation processes (corresponding to responses 4 and 3 on the Likert scale).

Two dependent variables are constructed to capture distinct dimensions of eco-innovation:

EcoEffic_innov: A dummy variable coded as 1 if the firm’s innovation objectives over the past two years were primarily or moderately oriented toward saving energy and water per unit of output. This variable reflects consistent engagement in efficiency EI across both years, rather than in only one.

EcoEnviron_innov: A dummy variable coded as 1 if the firm’s innovation objectives over the past two years were primarily or moderately aimed at reducing environmental impact. This variable indicates whether the firm consistently pursued environmental EI across both years.

4.2.2. Independent Variables

Table A1 provides a comprehensive description of all variables. Below, we focus on the independent variables of primary theoretical interest and those requiring further clarification, guided by the conceptual framework developed in the Literature Review.

Regulation. Firms were asked whether environmental, health, and safety regulations were considered in their innovation activities, measured on the same 4-point Likert scale (high, moderate, reduced, not relevant). The econometric models include three variables: *high-regul*, *moderate-regul*, and *non-relevant regul*, with the “reduced” category serving as the reference group. A stronger perception of regulatory importance is expected to positively influence EI, whereas “not relevant” may have a negative effect.

Other Policy Tools:

RD_EU_funding: Dummy variable equal to 1 if the firm received EU funding for R&D in the preceding two years.

RD_GovSubs_funding: Dummy variable equal to 1 if the firm received R&D subsidies from the Spanish central government in the preceding two years.

RD_RegSubs_funding: Dummy variable equal to 1 if the firm received R&D subsidies from regional or local governments in the preceding two years.

RD_GovContr_funding: Dummy variable equal to 1 if the firm received R&D funding through contracts from the Spanish central government in the preceding two years.

RD_RegContr_funding: Dummy variable equal to 1 if the firm received R&D funding through contracts from regional or local governments in the preceding two years.

Persistence Variables

PersistEcoEffic: Dummy variable equal to 1 if the firm engaged in efficiency EI in both $t-1$ and $t-2$.

PersistEcoEnviron: Dummy variable equal to 1 if the firm engaged in environmental EI in both $t-1$ and $t-2$.

These persistence variables are “double-lagged” composites: coded as 1 only when both prior periods indicate active engagement (1) and 0 otherwise, capturing the sustained nature of eco-innovation over time.

Control Variables

Size: Included as a categorical variable to avoid multicollinearity. Firms are classified as micro (≤ 10 employees), small (11–49 employees), medium (50–249 employees), medium–large (250–999 employees), and large (≥ 1000 employees), with small firms serving as the reference category.

Ownership: Distinguishes between domestic and foreign capital (*multinational*).

Group Affiliation: Captured by a dummy variable for independent firms (*independent*), with domestic business groups (DBG) as the reference category.

Industry effects: Controlled using dummy variables comparing each firm’s data to the two-digit industry average.

4.3. Models

The model specification employs a random-effects panel probit framework that accounts for unobserved firm heterogeneity and allows for the estimation of eco-innovation drivers across different business cycle phases. The models are globally significant ($\text{Prob} > \chi^2 = 0.000$) and the correlation matrix indicates no serious problems of multicollinearity (available upon request). Sample sizes remain robust across sub-samples.

It is important to note that the explanatory variables in the model differ in their measurement scales: some are categorical (e.g., perceived importance of regulation), some are binary (e.g., innovation persistence), and others are intensity-based. Consequently, the purpose of reporting the marginal effects is to indicate the direction and statistical significance of each determinant rather than to establish relative effect sizes between predictors measured on different scales.

The models following seek to identify variations in the influence of drivers across different phases of the business cycle, while controlling for other factors. To this end, the sample was segmented into three periods: boom (2004–2007), crisis (2008–2013), and recovery (2014–2016). Six models ([1]–[6]) were then estimated, focusing on efficiency EI and environmental EI during the

boom, crisis, and recovery periods, respectively. Each type of EI was examined through three models, corresponding to the three phases of the business cycle.

$$P(EcoEffic_innov = 1 | X_{it}^{3T0}, \beta^{3T0}, \alpha_i) = \Lambda(\alpha_i + X_{it}^{3T0} \beta^{3T0}) \tag{1}$$

$$P(EcoEffic_innov = 1 | X_{it}^{3T1}, \beta^{3T1}, \alpha_i) = \Lambda(\alpha_i + X_{it}^{3T1} \beta^{3T1}) \tag{2}$$

$$P(EcoEffic_innov = 1 | X_{it}^{3T2}, \beta^{3T2}, \alpha_i) = \Lambda(\alpha_i + X_{it}^{3T2} \beta^{3T2}) \tag{3}$$

$$P(EcoEnviron_innov = 1 | X_{it}^{3T0}, \beta^{3T0}, \alpha_i) = \Lambda(\alpha_i + X_{it}^{3T0} \beta^{3T0}) \tag{4}$$

$$P(EcoEnviron_innov = 1 | X_{it}^{3T1}, \beta^{3T1}, \alpha_i) = \Lambda(\alpha_i + X_{it}^{3T1} \beta^{3T1}) \tag{5}$$

$$P(EcoEnviron_innov = 1 | X_{it}^{3T2}, \beta^{3T2}, \alpha_i) = \Lambda(\alpha_i + X_{it}^{3T2} \beta^{3T2}) \tag{6}$$

Our sets of independent variables denoted as X_{it}^{3Tj} comprise the full set of drivers in both types of EI. The phases of the business cycle are represented by $j=0,1,2$, with the corresponding parameters denoted as β^{3Tj}

To account for potential autocorrelation and heteroscedasticity, all models employ robust panel standard errors. Additionally, a “persistence adjustment” is applied as an instrument to correct for autocorrelation effects arising from repeated observations of the same firm over time. Alternative model specifications were also tested, including the introduction of lags of the persistence variables and additional lagged independent variables. These robustness checks indicate that the statistical significance of the primary results remains stable, confirming the reliability of the baseline specifications.

4.4. Descriptive Statistics

Table 1 presents the distribution of firms by size, highlighting the predominance of SMEs. This distribution is particularly relevant, as firm size has been identified as a key determinant of how organizations perceive and respond to EI, as discussed in Sections 2.4 and 2.5.

Table 1. Distribution of the sample by size of the firm, 2004-2016.

Size	No. of employees	%
Micro firm	< 10	8.6
Small	10-49	40.9
Medium	50-249	35.7
Medium-large	250-999	12.6
Large	>1000	2.2

Source: Authors’ own elaboration based on PITEC data.

Approximately 54% of firms in the sample regard compliance with regulation as either highly or moderately important (responses 4 and 3 on the Likert scale, Table 2, Column 1). The chi-square test reported at the bottom of the table confirms a statistically significant association between firm size and the perceived importance of regulation. Additional inferential analyses, including ANOVA and Bonferroni pairwise comparisons, support this interpretation. Overall, smaller manufacturing firms appear to prioritize environmental compliance more strongly than larger firms.

Table 2. Firms’ Views on the Importance of Environmental Aspects (1).

Firm Size	Comply with Regulation (%)	Save Energy / Water (%)	Avoid Harming Environment (%)
Micro	42.93	60.24	38.19
Small	50.96	53.49	45.60
Medium	54.97	56.35	52.85

Medium-Large	61.54	64.34	63.04
Large	67.90	71.45	74.27
Total	53.82	56.87	50.94

Source: Author’s own elaboration based on PITEC data. Notes: (1) Percentage of firms rating each aspect as 'High' or 'Moderate' in importance when they innovate. Pearson χ^2 and Cramér’s V; - Regulation: $\chi^2 = 857.35$, $V = 0.0740$; - Efficiency: $\chi^2 = 1.4 \times 10^3$, $V = 0.0853$; - Avoid Harm: $\chi^2 = 1.6 \times 10^3$, $V = 0.1011$.

Column 2 of Table 2 presents the importance that sample firms assign to energy and water savings in their innovation activities. Overall, 57% of firms rate this objective as highly or moderately important. Both Pearson and Cramér’s V tests indicate a statistically significant relationship with firm size, reinforced by additional inferential analyses (available upon request). The distribution reveals a negative size gradient: as firm size increases, the mean importance assigned to energy and water efficiency declines. Micro and small firms appear to view efficiency gains as central to their innovation strategies, likely because these gains offer a direct avenue for cost reduction and short-term competitiveness. This pattern is consistent with Spain’s high dependence on imported energy, which may amplify firms’ emphasis on energy-saving measures.

Column 3 reports firms’ perceptions regarding the reduction of environmental impact. Approximately 51% of firms rate this objective as highly or moderately important. The association between firm size and the emphasis on environmental impact reduction is statistically significant. Larger firms demonstrate stronger concern for environmental protection, likely reflecting heightened reputational exposure and broader stakeholder pressures, including regulatory scrutiny, investor expectations, and consumer demand for sustainable practices.

Collectively, these descriptive statistics illustrate that both firm size and strategic priorities influence the relative weight assigned to efficiency and environmental objectives in innovation processes. These patterns provide important context for the subsequent econometric analysis, which examines how regulatory, knowledge, and firm-level factors shape eco-innovation across different phases of the business cycle.

5. Results and Discussion

Table 3 presents the drivers of EI, reporting only the marginal effects of statistically significant variables. As outlined previously, the analysis is disaggregated across the three phases of the business cycle—boom (2004–2007), crisis (2008–2013), and recovery (2014–2016)—and distinguishes between efficiency EI and environmental EI. A statistically significant coefficient, whether positive or negative, indicates that the corresponding driver either increases or decreases the probability of a firm engaging in EI. The reported marginal effects capture the extent of this likelihood.

Table 3. Determinants of Propensity to Eco-Innovate (Marginal Effects). Eco-innovation types by business cycle phase.

Variable	ECO-efficiency			ECO-environmental		
	Boom	Crisis	Recovery	Boom	Crisis	Recovery
Size (1)						
Micro (<10)	-0.01776	0.01365	0.00667	-0.01198	-0.00364	-0.02500
Medium (50–249)	0.01853	0.02641**	0.02764+	0.01586	0.03243***	0.00125
Medium-Large (250–999)	0.04962*	0.05996***	0.07231**	0.08518***	0.04111**	0.04505*
Large (≥1000)	0.13374**	0.05755+	0.12902**	0.09789**	0.08201**	0.07271+
Ownership						

Independent	-0.01409	-0.02161*	–	-0.01549+	-0.01693	–
Multinational	0.05654**	0.04550***	–	0.02916*	0.03455*	–
Persistence						
PersistEcoEffic	0.27792***	0.19299***	0.24303***	0.05660***	0.04691***	0.03091**
PersistEcoEnviron	-0.04184+	-0.02346*	–	0.16699***	0.10599***	0.12191***
Institutional.Intervention						
High-regul (2)	0.18573***	0.20971***	0.20277***	0.52006***	0.48799***	0.55883***
Moderate-regul	0.12954***	0.15719***	0.19958***	0.41631***	0.39034***	0.48959***
Non-relevant-regul	-0.12004***	-0.15557***	-0.13895***	-0.12952***	-0.14952***	-0.09224***
RD_EU_funding	–	–	–	–	0.10302***	0.05608*
RD_Gov_Contrfunding	–	–	–	–	0.05712**	0.09742+
RD_EU_funding	-0.03496*	–	–	0.02452+	0.02566**	–
Market (3)						
Local/regional	–	-0.05093+	–	–	–	–
EU & EFTA	–	-0.02612+	–	–	–	–
Rest of the World	–	-0.00959	–	–	–	–
h_objectmarket	0.04666***	0.06185***	0.06678***	0.02065*	0.02388***	0.02942**
h_incum_dom	–	–	–	–	0.02317+	–
h_objectrange	-0.02324*	–	–	-0.02070*	–	–
h_objectqualit	0.11167***	0.07793***	0.05940***	0.05270***	0.05233***	0.03028**
h_DemandUncertain	–	0.01976*	–	–	–	–
h_prev_innov	–	–	–	-0.06544*	-0.06362***	-0.07353*
R&D and Investment (3)						
i_invest_pw	–	–	–	0.01959**	–	0.02575*
i_RDownfunds	–	0.01696+	–	–	–	–
i_Innov_Effort	0.02747*	–	–	–	–	–
i_Machine_Effort	0.02797*	0.01569+	0.04331*	0.02170*	–	–
i_Knowledgee_Eff	–	–	–	-0.04829*	–	–
i_Traininge_Eff	–	-0.01960+	–	–	–	–
i_RDpers_pw	–	–	0.02746**	–	–	–
Cooperation/ Spillovers						
CoopVariety	–	–	–	0.00819**	–	–
ContCoopSuppl	–	–	–	0.04805*	–	–
ContCoopClient	-0.07789*	–	–	–	–	–
Spill_suppl	0.06512***	0.05329***	0.04410***	0.03245***	0.02030**	0.02059+
Spill_compet	0.04138***	0.04655***	0.02283+	–	0.01229+	–
SpillProfAssoc	0.05178***	0.05433***	0.06534***	0.04523***	0.05446***	0.06102***

Type of innovation

Product	-0.10491***	-0.09319***	-0.09149***	-0.04689***	-0.03010***	–
Process	0.11705+	–	–	-0.02451	–	–
Novelty	0.02098+	–	–	0.03597***	0.01628*	–
Novelent	–	0.02168*	–	-0.01416+	-0.03474*	–
Constant	***	***	***	***	***	**
Insig2u	*	***	***	***	***	**
Prob > chi2	0.000	0.000	0.000	0.000	0.000	0.000
N. of cases	7430	16648	5565	7430	16648	5565
sigma_u	1.21824	1.67318	1.61295	2.41367	2.51270	3.22441
Rho	0.31087	0.45974	0.44159	0.63910	0.65743	0.75963

Source: Authors’ own elaboration based on PITEC data provided by Spanish National Institute of Statistics (INE). **Notes:** + p<0.10, * p<0.05, ** p<0.01, *** p<0.001. Base references: (1) Firm size: small firm (11–49 employees). (2) Regulation: reduced importance. (3) Variables with an “i” prefix indicate intensity compared to the two-digit industry- (4) Variables with an “h” prefix indicate high priority of this objective in the firm’s innovative activities.

5.1. Regulation and Other Policy Tools

The coefficients for the *high-regul* and *moderate-regul* dummy variables display consistently strong positive effects across both types of EI and all phases of the business cycle, whereas the *non-relevant-regul* variable is consistently negative. Firms that assign high importance to regulation in their innovation activities are 18–20% more likely to implement efficiency-oriented innovations (material and energy savings) and 48–55% more likely to engage in environmental EI (reducing environmental harm) compared with peers that regard regulation as less relevant.

For environmental EI, the marginal effect of *high-regul* decreases slightly during the crisis but rebounds sharply in the recovery period. In contrast, efficiency EI shows an increase in marginal effects even during the crisis relative to the boom period. This pattern suggests that efficiency EI is perceived not only as environmentally beneficial but also as economically advantageous. These findings resonate with Bowen and Stern (2010), who argue that economic downturns can provide strategic windows for green investment, underscoring the potential role of policy in leveraging such periods to promote sustainable development.

Contrary to the commonly cited assumption that firms resist environmental regulation during downturns (see Literature Review), our results indicate that regulation acts as a structural driver of EI, shaping firm behaviour consistently over time. Firms comply with regulatory standards irrespective of the business cycle, confirming the deeply institutionalized nature of these pressures. These results align with prior empirical evidence identifying regulation as a central determinant of EI (Bossle et al., 2016; Bitencourt et al., 2020; Fernández et al., 2017; García-Sánchez & Rama, 2024; Horbach, 2008; Mora-Sanguinetti et al., 2024; Setyadi et al., 2025; Triguero et al., 2013). Importantly, the longitudinal nature of our analysis demonstrates that the positive association between regulation and EI persists across both expansionary and contractionary phases, extending earlier cross-sectional findings. These results provide robust support for the *Dynamic Regulation Hypothesis* (H1): regulation positively influences firms’ eco-innovation in boom, crisis, and recovery.

While regulation strongly influences both types of EI, its effect is not evenly distributed. Regulatory factors exert a particularly pivotal role in environmental EI: the estimated marginal effects for high and moderate regulatory relevance are two to three times larger than those observed for efficiency EI. These differences are consistent across all phases of the business cycle, highlighting a structural distinction in how regulation drives environmental versus efficiency EI. Our results align

with the findings of Demirel & Kesidou (2011) and Horbach et al. (2012) for other European economies. Furthermore, our data show additional evidence that these differences remain robust across both prosperous and challenging times.

Financial support mechanisms exhibit more heterogeneous and temporally sensitive effects than regulation. EU-level R&D funding has a strong positive influence on environmental EI during crises (0.10302***), with the effect remaining significant, though weaker, in the recovery phase (0.05608*). Regional subsidies also show positive effects on environmental EI during challenging periods, albeit smaller in magnitude. By contrast, national subsidies do not demonstrate significant effects in any phase, suggesting that generic R&D support does not consistently stimulate green innovation in Spanish manufacturing. These results align with earlier European studies reporting the limited effectiveness of non-targeted subsidies for EI (Jové-Llopis & Segarra-Blasco, 2018; Triguero et al., 2013), but extend this evidence by highlighting their countercyclical relevance—their impact becomes most visible precisely when environmental innovators face resource constraints and heightened financial uncertainty.

The observed heterogeneity can be explained by the nature of the support programs. EU funding programs typically incorporate environmental objectives, yielding stronger effects, whereas regional subsidies are less mission-specific and sometimes show weaker or negative associations with efficiency EI. Public-private R&D contracts, which are more targeted and accountability-driven, consistently demonstrate positive effects on environmental EI (0.05712** in crisis; 0.09742+ in recovery). These results suggest that directionality and formal oversight enhance the effectiveness of policy instruments in steering firms toward environmental outcomes.

A complementary mechanism may involve legitimacy effects during periods of constrained credit availability. Participation in publicly supported programs can signal credibility to lenders, improving access to external finance—a dynamic observed in Chinese manufacturing (Sun et al., 2022). Taken together, these findings suggest that financial and contractual public interventions play a countercyclical role, sustaining EI during adverse macroeconomic conditions. This is particularly relevant in moderate innovator economies such as Spain, where internal financing is limited, banks are risk-averse, venture capital is scarce, and early-stage funding is constrained (see Context Setting). Thus, the *Countercyclical Support Hypothesis* (H2) is supported: regulation positively influences environmental innovators in boom, crisis and recovery, while financial support mechanisms become particularly influential during challenging times, with public R&D funding providing countercyclical reinforcement.

In sum, regulation consistently drives both efficiency and environmental EI, with a stronger effect on environmental EI. Subsidies and other R&D funding sources support environmental EI during challenging times but have limited impact on efficiency EI, providing support for the *Regulatory Dominance Hypothesis* (H3): Efficiency EI is primarily driven by regulation and is not significantly influenced by other policy instruments across the business cycle.

Overall, Spain exemplifies a policy-mix innovation model, where regulation acts as a long-term structural driver, while other policy tools operate more cyclically, particularly during periods of economic stress. Notably, internal R&D-related factors show limited statistical significance except during the crisis, reinforcing the idea that regulation provides consistent guidance when internal capabilities are weak—a pattern typical in moderate innovator countries.

5.2. Knowledge Base and Firms' External Sources of Information

Persistence. Both environmental and efficiency EI are more likely to emerge in firms with prior experience in EI, and this effect persists even during economic downturns, enhancing resilience through sustained innovation activity. Persistence increases the likelihood of efficiency EI by 24%–28% across the entire period and raises the probability of environmental EI by 11%–17%. These results align with earlier studies (Arranz et al., 2021; García-Sánchez & Rama, 2024; Horbach, 2008; Jové-Llopis & Segarra-Blasco, 2018) and extend them by demonstrating that prior experience remains an effective driver of EI even under adverse conditions. Accordingly, the *Persistence Hypothesis* (H4)—

firms with prior EI experience are more likely to engage in EI across boom, crisis, and recovery—is supported.

Persistent engagement in efficiency EI (PersistEcoEffic) positively influences environmental EI, with sustained material and energy savings increasing the probability of environmental EI by approximately 3%–6%. This finding is consistent with Costa-Campi et al. (2015), who report that persistent efficiency innovators also adopt environmentally oriented innovations. By contrast, persistent environmental EI is negatively associated with efficiency EI during both boom and crisis periods and shows no significant effect during recovery. This asymmetric relationship likely reflects Spain's high energy dependency, which strengthens incentives for resource-saving innovations that simultaneously generate environmental benefits, whereas environmentally driven initiatives do not consistently produce efficiency gains. Notably, these patterns remain stable across all phases of the business cycle.

Similarly, firms that engage consistently in both process and product innovations—green and non-green—are more likely to pursue environmental EI over time, whereas firms focusing exclusively on product innovation (*product*) exhibit a 9%–10% lower likelihood. Joint product–process innovations may arise from operational learning rather than formal R&D, while internal R&D personnel and funding show significant explanatory power only during crises. This suggests that joint innovation reflects a form of eco-innovation that is less technologically complex than often assumed. The *Continuous Innovation Hypothesis* (H5)—firms engaged in continuous joint product and process innovation are more likely to eco-innovate across boom, crisis, and recover—is therefore supported. These results further indicate that capability building in Spanish manufacturing is slow and cumulative, with incremental learning and path dependency shaping EI adoption.

Knowledge base. Firms with a higher-than-average share of R&D personnel relative to their two-digit industry (*i_RDpers_pw*) are more likely to engage in efficiency EI during recovery, but this factor shows no significant effect on environmental EI or during other phases. Similarly, the ability to finance R&D with internal resources (*i_RDownfunds*) positively affects efficiency EI only during the crisis and is not linked to environmental EI. These patterns suggest that, under challenging conditions such as rising energy costs, firms with greater R&D capacity leverage this asset to implement energy-saving innovations.

Jové-Llopis and Segarra-Blasco (2021) report similar results for Spanish manufacturing during the crisis and early recovery, highlighting the role of internal R&D in sustaining EI. Consistent with this, our results show that R&D positively influences efficiency EI during the recovery, increasing probability by 3%. However, as stated, this effect is not stable across the business cycle and does not extend to environmental EI. Similarly, firms with above-average internal funds to finance R&D are about 2% more likely (at the 10% significance level) to undertake efficiency EI during the crisis. This effect is not observed in other phases of the business cycle or in environmental EI. Our findings provide one of the few evidences that R&D-related factors may act as drivers of efficiency EI especially during challenging times. Yet, the reasons for this relationship are not fully clear, and we can only suggest tentative explanations. It is plausible that some firms responded to the shifting macroeconomic environment by intensifying their R&D efforts, as suggested by the theory of dynamic capabilities (Teece & Pisano, 1998). At the same time, we cannot rule out the possibility that firms already endowed with R&D-related capabilities and internal funding at the outset of the period were better positioned to pursue efficiency EI even during the crisis. Overall, our results indicate that in times of economic strain—particularly those marked by rising energy prices—firms with stronger R&D capacity were able to leverage this asset to implement energy-saving innovations.

In the case of environmental EI, the results similarly indicate that, beyond the experiential knowledge that proved sufficient during expansion, additional and exceptional factors became necessary for firms to sustain innovation once the crisis unfolded. The variety of cooperation (*CoopVariety*)—reflecting the diversity and openness of firms' collaborative networks—increased the likelihood of engaging in environmental EI during the crisis. Although the estimated marginal effects are modest, the relationship remains statistically significant. Notably, this effect was not observed in

other phases of the business cycle and did not extend to efficiency EI. Our findings are consistent with those of Jové-Llopis and Segarra-Blasco (2018), who likewise report that the breadth of external knowledge sources accessed by firms positively influences environmental innovation during the critical period examined in their study.

Firms with above-average gross investment in tangible assets per 1,000 employees (*i_invest_pw*) are 2%–3% more likely to pursue environmental EI during the crisis and subsequent recovery. This likely reflects enhanced access to external finance during Spain's credit crunch and greater capacity to integrate green technologies at lower marginal costs. Together, these findings support the *Knowledge Integration Hypothesis* (H6): access to diversified external knowledge and internal R&D-related capabilities positively influences EI during challenging times, but not necessarily during expansions.

External knowledge. Spillovers from professional associations consistently increase both efficiency and environmental EI by 5%–6% over the entire period. This aligns with evidence from the food and beverage sector (Galliano & Nadel, 2015; García-Sánchez & Rama, 2024), although this important source of spillovers remains underexplored in the broader EI literature. Our results corroborate the evidence reported by Qi et al. (2021) in the context of Chinese firms, suggesting that imitative pressure from peer organizations constitutes a central mechanism driving environmental EI. This process is reinforced by the role of professional associations, which function as repositories of social capital (Granovetter, 2005). From the perspective of institutional theory, these dynamics can be understood as a form of isomorphic behaviour.

Supplier spillovers similarly enhance green innovation throughout the period, with stronger effects on efficiency EI (increases probability of 4% to 7%). In particular, investments in machinery (*i_Machine_Effort*) increase the probability of efficiency EI by 3%–4% and appear linked to the transfer and adaptation of technological knowledge from suppliers. This is consistent with Costa-Campi et al. (2015).

Synthesis. Some knowledge factors exert persistent effects—such as prior experience, joint product–process innovations, and supplier/associational spillovers—while others become relevant primarily during crises, including internal R&D capabilities and the diversity of external networks. Our results indicate that learning-by-doing and the assimilation of external knowledge constitute alternative pathways to building absorptive capacity (Cohen & Levinthal, 1990; Zahra & George, 2002) and that these mechanisms tend to be more stable across the business cycle than formal R&D investment. Nevertheless, during challenging periods, R&D resources and access to diverse knowledge sources acquire importance, enhancing firms' engagement in EI. These findings provide empirical support for H6 and illustrate how Spanish manufacturing firms navigate systemic constraints to sustain EI under adverse economic conditions.

5.3. Size, Ownership, and Market

Larger firms consistently exhibit a higher likelihood of engaging in environmental innovation across boom, crisis, and recovery periods, consistent with the literature emphasizing economies of scale in R&D and innovation capacity (see Literature Review). Size-related advantages—such as superior access to financial, technological, and managerial resources—appear to facilitate the integration of environmental objectives into firms' innovation strategies. Foreign ownership (*multinational*) further increases the probability of environmental EI by 3%–7% during the boom and 3%–5% during the crisis, likely reflecting better access to international financing during the 2008 downturn. Most foreign subsidiaries are classified as medium-large or large firms. These findings provide empirical support for the *Baseline Size Effect Hypothesis* (H7): larger firms are more likely to engage in eco-innovation in boom, crisis, and recovery.

By contrast, smaller firms display a more cyclical pattern. Their likelihood of eco-innovating rises significantly during periods of economic expansion, when liquidity constraints are relaxed and demand prospects improve. The coefficient for micro-enterprises (≤ 10 employees) is not statistically significant across the business cycle, suggesting that their ecological behaviour is largely comparable

to small firms (11–49 employees), which serve as the reference category. During the boom and recovery, small firms’ EI levels are similar to medium-sized firms, whose coefficients are generally non-significant or only marginally significant at the 10% level.

However, during downturns, small firms struggle to maintain EI, while medium and medium-large firms are approximately 3% and 4%–5% more likely than small firms to engage in EI. These results highlight that the effect of firm size on EI is contingent rather than stable, providing support for the *Cyclical Sensitivity of Smaller Firms Hypothesis* (H8): small firms’ likelihood of eco-innovating increases during expansions but diminishes in challenging times. The relative decline of small firms under adverse conditions underscores their vulnerability to financial and operational shocks. Effective EI during crises requires enhanced capabilities—including formal R&D, access to internal and external finance, and the ability to leverage diverse technological knowledge—that smaller firms often lack. This finding nuances conventional views of small firms as structurally constrained in EI, showing instead that their eco-innovation capacity is opportunity-driven, emerging when expansionary conditions align resources, reduce uncertainty, and provide strategic incentives. By adopting this dynamic perspective, apparent “mixed results” in cross-sectional studies can be interpreted as temporal variations rather than contradictions.

Consistent with the characteristics of the Spanish NIS, EI is structurally uneven and strongly linked to firm size and foreign ownership, particularly during crises.

Two market-oriented factors—market expansion and product quality—emerge as stable drivers of EI. Pursuit of new or expanded markets (*h_objectMarket*) raises the probability of efficiency EI by 5%–7% and environmental EI by 2%–3% throughout the business cycle, supporting the *Market Expansion Hypothesis* (H9: Firms pursuing market expansion or entry into new markets are more likely to eco-innovate across boom, crisis, and recovery). Similarly, prioritizing quality (*h_object_qualit*) exerts a stronger influence, increasing the likelihood of efficiency EI by 6%–11% and environmental EI by 3%–5% across all phases, providing support for the *Quality Hypothesis* (H10: Firms emphasizing product quality are more likely to eco-innovate across boom, crisis, and recovery). Our results are consistent with previous studies (Demirel & Kesidou, 2011; Horbach, 2008; Ren & Mia, 2025). However, our longitudinal approach additionally reveals that these market factors remain relevant in both favourable and adverse economic conditions. These results indicate that strategic market objectives foster sustained EI, reflecting a proactive, opportunity-driven approach to competitiveness. A possible interpretation is that, given the limitations of the Spanish NIS and firms’ knowledge bases, Spanish manufacturers may rely, at least in part, on market expansion and quality management as substitutes for scientific innovation capacity. The widespread adoption of quality certifications (ISO 9001/14001) and branding strategies (Molero, 2020) likely compensates for relatively limited R&D capabilities, enabling firms to sustain EI despite structural constraints.

Table 4 provides a synthesis of the findings, classifying drivers as either stable—positive and significant across boom, crisis, and recovery—or cyclical, significant only during challenging periods (crisis and recovery). The table further distinguishes whether each driver primarily affects efficiency EI, environmental EI, or both.

Table 4. Stable and cyclical drivers of Eco innovation, (2004–2016).

Stable drivers (whole period)	Type of EI	Cyclical drivers emerging in challenging times ¹	Type of EI
Regulation	Both	Subsidies	Environmental EI
Persistence in EI	Both	R&D contracts	Environmental EI
Continuous joint product-process innovation	Both	R&D personnel	Efficiency EI

Supplier spillovers	Both	R&D own funding	Efficiency EI
Professional associations spill	Both	Cooperation variety	Environmental EI
Market factors ²	Both	Above-average gross investment	Environmental EI

Source: Authors’ own elaboration based on PITEC data. Notes: ¹ Refers to crisis and recovery periods.

² Market expansion goals and product quality goals.

5.4. Towards a Tentative Framework of Eco-Innovation Drivers

All of our hypotheses are supported (Table 5), providing a coherent pattern of empirical relationships that can inform a preliminary conceptual understanding of EI drivers in Spanish manufacturing.

Table 5. Hypotheses Tested in the Study and Results of the Econometric Analysis.

Number	Name	Hypotheses	Results
H1	<i>Dynamic Regulation Hypothesis</i>	Regulation positively influences firms’ eco-innovation in boom, crisis and recovery	Supported
H2	<i>Complementary Institutional Hypothesis</i>	Regulation positively influences environmental innovators in boom, crisis and recovery, while financial support mechanisms become particularly influential during challenging times, with public R&D funding providing countercyclical reinforcement.	Supported
H3	<i>Regulatory Dominance Hypothesis.</i>	Efficiency EI is primarily driven by regulatory frameworks and is not significantly influenced by other policy instruments across the business cycle	Supported
H4	<i>Persistence Hypothesis</i>	Firms with prior EI experience are more likely to engage in eco-innovation across boom, crisis and recovery	Supported
H5	<i>Continuous Innovation Hypothesis</i>	Firms engaged in continuous joint product and process innovation are more likely to eco innovate across boom, crisis and recovery.	Supported
H6	<i>Knowledge Integration Hypothesis</i>	Access to diversified external knowledge and internal R&D-related factors positively influences EI during challenging times, but not necessarily during expansive phases.	Supported
H7	<i>Baseline Size Effect Hypothesis</i>	Larger firms are more likely to engage in eco-innovation EI in boom, crisis and recovery	Supported
H8	<i>Cyclical Sensitivity of Smaller Firms Hypothesis</i>	The likelihood of eco-innovation among smaller firms increases during periods of economic expansion but diminishes during challenging times	Supported
H9	<i>Market Expansion Hypothesis</i>	Firms pursuing market expansion or entry into new markets are more likely to eco-innovate across boom, crisis, and recovery.	Supported

H10	<i>Quality Hypothesis</i>	Firms emphasizing product quality are more likely to eco-innovate across boom, crisis, and recovery.	Supported
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Based on the evidence, we propose a tentative framework in which EI emerges from the interaction of external guidance, accumulated capabilities, and adaptive resources. Regulation appears as the primary trigger, functioning as an external cognitive scaffold that consistently directs firms toward environmental objectives across macroeconomic conditions. Once activated, EI tends to follow a cumulative trajectory, sustained by prior innovation experience, learning-by-doing, supplier knowledge flows, and mimetic spillovers from professional associations. These mechanisms illustrate how experiential learning and embedded routines foster persistence in innovation activity over time. Similarly, strategic orientations toward product quality and market expansion consistently support EI, embedding environmental innovation within broader competitive and operational goals.

Importantly, our findings also highlight context-dependent contingencies. During periods of economic downturn, firms require additional internal capacities—such as funding for R&D, skilled human capital, and engagement in diverse collaborative networks—to maintain EI under tighter financial and market constraints.

From a theoretical perspective, the framework aligns with evolutionary arguments emphasizing path dependence, cumulative learning, and capability development, as well as institutional theory, in which regulatory pressures, public funding mechanisms, and mimetic influences exert complementary effects. These results suggest that the drivers of EI are both structural and dynamic, with stable mechanisms (e.g., regulation, persistence, cumulative experience) operating alongside cyclical factors that become salient during crises (e.g., internal R&D capacity, collaborative networks, financial resources).

We emphasize that this framework is tentative and context-specific, derived from Spanish manufacturing and moderate-innovator environments. It should be interpreted as a provisional conceptual synthesis that highlights mechanisms and interactions observed over the business cycle, rather than as a definitive or universally generalizable theory. Nonetheless, it offers a useful lens for understanding how firms integrate regulatory, organizational, and market factors to sustain eco-innovation over time, and it provides a foundation for future empirical and comparative research.

6. Conclusions

This study advances the debate on the drivers of eco-innovation (EI) by examining how regulation, institutional interventions, and firm-level innovation capabilities shape two distinct types of EI: efficiency EI (energy and material saving) and environmental EI (reducing environmental harm). While research on EI has expanded considerably, most studies rely on cross-sectional designs, leaving the temporal dynamics of EI and its determinants under varying macroeconomic conditions largely unexplored. By analysing panel data for Spanish manufacturing firms across three phases of the business cycle—economic expansion (2004–2007), the global financial crisis (2008–2013), and subsequent recovery (2014–2016)—this study addresses that gap.

Our findings demonstrate that regulation is the most consistent policy instrument fostering both efficiency and environmental EI across all phases. In contrast, subsidies and public–private collaboration exert more cyclical effects, particularly supporting environmental EI during economic downturns. Contrary to common expectations, firms do not resist environmental regulation in crises. Instead, regulation functions as an “external cognitive guide,” providing direction and incentives in a context where firms often exhibit weak endogenous innovation capabilities, typical of moderate innovator countries.

The longitudinal evidence further reveals the cumulative and path-dependent nature of EI. Persistence in EI and continuous joint product–process innovation positively influence both efficiency and environmental EI across economic cycles. Learning-by-doing, sustained innovation activities, knowledge flows from suppliers, and mimetic spillovers from professional associations collectively reinforce firms’ ability to maintain environmental innovation over time. Yet the crisis highlighted

important differentiating factors: firms with stronger human capital and the financial capacity to sustain R&D gained a clear advantage in efficiency EI, while firms embedded in more diverse collaborative networks were better positioned to maintain environmental EI. This indicates that experiential knowledge suffices during expansionary periods, but additional capabilities are critical to sustain EI in downturns.

Market-oriented strategies—particularly those focused on product quality and market expansion—emerge as stable, long-term drivers, anchoring environmental objectives within broader competitiveness strategies. Differences between large and small firms persist across the business cycle: large firms consistently lead in green innovation due to greater resources and reputational incentives, while smaller firms’ engagement is more cyclical and sensitive to macroeconomic conditions. Targeted policy support can therefore help smaller firms maintain EI during downturns.

In synthesis, EI is activated by a combination of institutional pressure, accumulated capabilities, and resource-based resilience, with the relative importance of each factor shifting across the business cycle. Stable drivers—such as regulatory frameworks, prior innovation experience, market expansion, product quality, and spillovers—highlight the value of long-term policy strategies to sustain green innovation. Meanwhile, drivers critical during economic downturns—including internal R&D funding, above-average R&D personnel, and participation in diverse collaborative networks—underscore the need for countercyclical support measures, such as targeted R&D grants or facilitation of collaborative innovation platforms.

For managers, the results suggest that embedding environmental goals within broader competitiveness strategies enhances resilience and continuity in innovation. Continuous investment in R&D, skilled human capital, and collaborative networks strengthens long-term environmental performance. From an academic perspective, the longitudinal evidence enriches understanding of how regulation, firm capabilities, and learning processes shape green innovation over time, and it encourages further research on firm heterogeneity and the cyclical dynamics of EI.

This study is not without limitations. Information on environmental technologies relies on firms’ self-reported perceptions of the importance of green innovation. While restricting the sample to firms classified as innovators increases the likelihood of capturing actual eco-innovative efforts, complete accuracy cannot be guaranteed. Moreover, CIS-type datasets—including PITEC—do not provide detailed information on R&D specifically devoted to EI, necessitating reliance on broader R&D indicators, general innovation metrics, and non-targeted support schemes. These constraints point to promising avenues for future research. Nonetheless, despite these limitations, this study offers rare longitudinal evidence on how the drivers of eco-innovation evolve under both favourable and adverse economic conditions.

Conflicts of Interest: The authors report no conflicts of interest.

Appendix A

Table A1. Description of variables and descriptive statistics.

Name of variable	Type	Description	Descriptive statistics
Dependent variables			
EcoEffic_innov	dummy	Innovative firm with efficiency-oriented innovation targets (high or medium relevance)	1 = yes (34.55%) 0 = no N = 64,891; n = 6,736
EcoEnviron_innov	dummy	Innovative firm with environmental-innovation targets (high or medium relevance)	1 = yes (47.28%) 0 = no N = 52,202; n = 6,273

Independent variables			
Intitutional intervention			
Regulation (high/moderate/non-relevant)-regul	Categorical	How important or relevant does firm consider eco-regulation when innovating (highly / moderately / low /non-relevant)	1 = high: 28.84% 2 = moderate: 24.96% 3 = low: 15.47% (base category) 4 = non-relevant: 30.72% N = 52,021; n = 6,273
RD_EU_funding	dummy	Received R&D EU funding	1 = yes (1.78%) 0 = no N = 52,021; n = 6,273
RD_GovSubs_funding	dummy	Received R&D subsidy funding from the Spanish central government	1 = yes (24.24%) 0 = no N = 64,891; n = 6,736
RD_RegSubs_funding	dummy	Received R&D subsidy funding from regional/local government	1 = yes (25.29%) 0 = no N = 64,891; n = 6,736
RD_GovContr_funding	dummy	Received R&D funding through contracts from the Spanish central government	1 = yes (17.38%) 0 = no N = 64,891; n = 6,736
RD_RegContrfunding	dummy	Received R&D funding through contracts from regional/local government	1 = yes (17.69%) 0 = no N = 64,891; n = 6,736
Firm Size	categorical	Firms size according with its number of employees: micro (<10), small (10-49), medium (50-249), medium-large (250-999) or large (>=1,000).	1 = micro: 8.61% 2 = small: 40.87% (base category) 3 = medium: 35.74% 4 = medium-large: 12.61% 5 = large: 2.17% N = 64,891; n = 6,736
Crisis and persistence variables			
Crisis	categorical	Business cycle phase based on the Spanish GDP path	0 = boom (2004–2007): 36.20% 1 = crisis (2008–2013): 47.17% 2 = recovery (2014–2016): 16.63% N = 64,891; n = 6,736
PersistEcoEffic	dummy	Persistence in efficiency oriented eco-innovation	1 = yes (23.16%) 0 = no N = 59,703; n = 6,592
PersistEcoEnviron	dummy	Persistence in environmental impact reduction eco-innovation	1 = yes (14.3%) 0 = no N = 47,889; n = 6,122
Cooperation/Spillovers			

CoopVariety	Count	variety of cooperation partners (min.: 0, max.: 6)	0: 67.11% 1: 13.06% 2: 7.81% 3: 5.32% 4: 3.28% 5: 2.01% 6: 1.42% N = 52,025; n = 6,274
Coopcontsuppl	dummy	Continuous cooperation with suppliers	1 = yes (9.66%) 0 = no N = 47,772; n = 6,122
Coopcontcli	dummy	Continuous cooperation with clients	1 = yes (7.3%) 0 = no N = 47,726; n = 6,122
Spill_suppl	dummy	Spillovers from suppliers have high/medium relevance for innovation	1 = yes 0 = no N = ; n =
Spill_compet	dummy	Spillovers from competitors have high/medium relevance for innovation	1 = yes 0 = no N = ; n =
Spill_profassoc	dummy	Spillovers from professional associations have high/medium relevance for innovation	1 = yes 0 = no N = ; n =
Market			
h_objectmarket	dummy	'high' priority of market penetration or market share increase through innovation	1 = yes (51.8%) 0 = no N = 64,891; n = 6,736
h_incumb_dom	dummy	'high' relevance of market dominated by incumbent firms as a barrier to innovation	1 = yes (19.29%) 0 = no N = 64,891; n = 6,736
h_objectrange	dummy	'high' priority on expanding product range through innovation	1 = yes (47.06%) 0 = no N = 64,891; n = 6,736
h_objectqualit	dummy	'high' priority of increasing product quality through innovation	1 = yes (47.13%) 0 = no N = 52,022; n = 6,273
h_DemandUncertain	dummy	'high' relevance of uncertain demand for innovative products as a barrier to innovation	1 = yes (23.46%) 0 = no N = 64,891; n = 6,736

h_prev_innov	dummy	high relevance of prior innovations in the market as a barrier to innovation	1 = yes (4.37%) 0 = no N = 64,891; n = 6,736
Mktbreadth	categorical	market breadth (local-regional / national / UE / Rest World)	1 = local/regional: 4.40% 2 = national: 15.13% (base category) 3 = EU: 15.57% 4 = other international (outside EU): 64.89% N = 64,891; n = 6,736
Investment and innovation			
i_invest_pw	dummy	Gross investment in tangible assets per 1,000 workers above industry average.	1 = yes (19.03%) 0 = no N = 64,890; n = 6,736
i_RDDownfunds	dummy	Percentage of own funds financing R&D above industry average	1 = yes (44.79%) 0 = no N = 64,890; n = 6,736
i_RD_Effort	dummy	Effort in R&D activities (internal + external) above industry average	1 = yes (38.25%) 0 = no N = 64,891; n = 6,736
i_Machine_Effort	Dummy	Effort in acquisition of machinery, equipment and software above industry average	1 = yes (12.43%) 0 = no N = 64,877; n = 6,736
i_KnowAcqEffort	Dummy	Effort in external knowledge acquisition (patents) above industry average	1 = yes (1.79%) 0 = no N = 64,877; n = 6,736
i_TrainingEffort	Dummy	Effort in workforce training above industry average	1 = yes (9.61%) 0 = no N = 59,689; n = 6,592
i_RDpers_pw	Dummy	Number of R&D employees per 1,000 employees above industry average	1 = yes (41.12%) 0 = no N = 64,890; n = 6,736
Innovclass	categorical	innovation class: product innovation, process innovation or both	1 = Product: 23.56% 2 = Process: 21.56% 3 = Both: 54.87% (base category) N = 46,507; n = 6,098
novelty	Dummy	introduced products new-to-the-market	1 = yes (56.26%) 0 = no N = 36,676; n = 5,510
noveltent	Dummy	introduced products new-to-the-enterprise	1 = yes (78.22%) 0 = no N = 36,675; n = 5,510

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