// NO.25-026 | 05/2025

DISCUSSION PAPER

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The Effects of Public Procurement Requirements and Voluntary Standards on Environmental Product Innovation

Leibniz Association

ZEW

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This version: May 2025

Abstract

Public procurement requirements and voluntary standards are increasingly used to foster environmental product innovations. However, quantitative evidence on their individual and joint effects is absent, and their conceptualization remains at an early stage. This paper makes two contributions. First, it introduces the distinction between rigid threshold and flexible benchmark uses of voluntary standards in public tenders, theorizing their opposing effects on environmental product innovations. Second, using data from 5,127 firms in the 2021 German Innovation Survey and applying linear probability models, it provides the first quantitative analysis of their individual and joint effects across varying degrees of environmental significance. Results show that public procurement requirements and voluntary standards individually increase the probability of firms introducing environmental product innovations with high environmental significance. However, their interaction reveals a negative effect – discomplementarity – likely driven by rigid standard use, which offsets the effectiveness of procurement requirements. For environmental product innovations with low environmental significance, only voluntary standards exhibit a positive effect. These findings suggest that voluntary standards might limit the capacity of public procurement to foster more radical or disruptive environmental product innovations, while supporting more incremental innovations when used independently.

Keywords: Public procurement - Voluntary standards - Environmental innovation

JEL code: O31 - O38 - Q55 - Q58

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Acknowledgements: We thank Christian Rammer for his comments on the analysis of environmental innovations and their drivers with the German Innovation Survey. This work was supported in part by Horizon Europe project 'DemoTrans' (grant number 101059288).

1. Introduction

Public procurement – the acquisition of goods and services by public authorities – constitutes a significant share of global economic activity, accounting for approximately 15 to 20 percent of global gross domestic product (European Council, 2022). Among emerging policy instruments, green public procurement, which integrates environmental performance considerations into purchasing decisions, has been widely promoted as a mechanism to support environmental objectives (Aldenius & Khan, 2017; Bratt et al., 2013). While increasingly cited as instrumental for achieving the United Nations' Sustainable Development Goals (General Secretariat, 2022), the implementation and effectiveness of green tenders remain subject to ongoing debate (e.g.; Chiapinelli et al., 2025a; Deschamps, 2025; Krieger & Zipperer, 2022; Orsatti et al., 2020).

Public authorities typically implement green public procurement by incorporating environmental requirements alongside price considerations in tendering processes. These requirements are intended to incentivize bidders to offer products with reduced environmental harmfulness, thereby increasing their chances of securing contracts (European Commission, 2008a; Krieger & Zipperer, 2022; De Giacomo et al., 2019). Although quantitative evidence on green public procurement remains limited, available studies suggest that it can be an effective policy for promoting firms' introduction of environmental product innovations – defined as products with decreased environmental harmfulness (e.g.; Caravella & Crespi, 2020; Krieger & Zipperer, 2022; Stojčić, 2021) – and that it accounts for a none negligible share of public tenders and their value (Rosell, 2021; Yu et al., 2020). [1]

However, the effectiveness of green public procurement in reducing environmental harm critically depends on how environmental requirements are designed and implemented (Cheng et al., 2018). A key mechanism for structuring these requirements is the use of voluntary standards, through which procurers can request firms to certify compliance (Rainville, 2017). In general, standards aim to define the characteristics of products and processes to meet agreed-upon benchmarks (Blind et al., 2022), while voluntary standards document attributes that go beyond regulatory minimum requirements (Breyer, 1982). Voluntary standards can be

[1] Across the European Economic Area, Rosell (2021) found that 7.2 percent of public contracts contain green characteristics as award criteria. Yu et al. (2020) found that 9.4 percent of award notices included environmental criteria, with green procurement contracts accounting for 21.8 percent of total procurement value.

integrated into tenders in various ways, including performance specifications, and compatibility requirements.

Despite longstanding guidance on the use of voluntary standards to enhance the effectiveness and efficiency of green public procurement (European Commission, 2004), empirical evidence on their joined use remains scarce. At the European level, documenting the prevalence of standards in green tenders is complicated by language diversity (Rosell, 2021). Also, Krieger and Zipperer (2022) found that only 11.9 percent of tenders containing environmental criteria explicitly referenced environmental standards, and that most environmental criteria were formulated too broadly to reliably identify the application of any standard for the case of Germany.

Thus, despite increasing recognition of both standards and public procurement as important demand-side policies for environmental innovation, their combined use remains scarcely understood. To date, quantitative analyses systematically investigating the interplay between green public procurement and voluntary standards are lacking, as shown in the literature reviews by Chiapinelli et al. (2025b) and Blind et al. (2023) on public procurement and standards, respectively. Chiapinelli et al. (2025b) identify green public procurement as theoretically and empirically under-researched as an innovation policy. Blind et al. (2023) refer to public procurement and its potential relevance for standard adoption only briefly, while noting potential risks of their combination for innovation. Even at the conceptual level, linkages between the two have only begun to be addressed (Rainville, 2017), leaving substantial gaps in the understanding of how they interact to influence firms' environmental innovations.

First, we contribute by conceptually distinguishing between a *rigid threshold* and a *flexible benchmark* use of voluntary standards within green public procurement, and by analyzing their respective effects on the introduction of environmental product innovations with varying degrees of environmental performance. In the rigid threshold use, standards are applied as specifications that must be met, without rewarding performance beyond the requirement. This limits incentives for environmental product innovation, in particular with larger performance increases. In the flexible benchmark use, standards serve as reference points that can be exceeded, with higher environmental performance increasing the likelihood of contract award, thus creating incentives for large increases in the performance of environmental product innovations. With this, we conceptualize the risk highlighted by Blind et al. (2023), extend Rainville's (2017) framework by introducing an innovation-hampering use of voluntary standards, and position rigid standards as a mechanism that limits innovation – similar to public procurement focused on existing products (Edquist & Zabala-Iturriagagoitia, 2020) or solely on price (Krieger et al., 2024).

Second, we contribute by empirically examining the individual and joint effects of tender requirements and voluntary standards on the introduction of environmental product innovations with varying degrees of environmental performance. In doing so, we i) test our conceptual hypotheses and ii) extend prior quantitative research about the effects of green public procurement on environmental innovation by considering a previously unexplored policy combination (Caravella & Crespi, 2020; Chiapinelli et al., 2025a; Krieger & Zipperer, 2022; Stojčić, 2021). However, it is important to note, we are not able to distinguish between a rigid threshold and a flexible benchmark use of voluntary standards. Instead, our analysis captures the individual and joint net effects of voluntary standards, after the opposing influences of the two uses have offset each other.[2]

The analysis relies on the answers of 5,127 firms in the 2021 German Innovation Survey, whereas we examining the net-effects using linear probability models and entropy balancing technics to account for omitted variable bias.[3] We find public procurement requirements and voluntary standards individually positively affect the probability of a firm's introduction of environmental product with a high environmental significance. However, when examined jointly, we find a negative interaction (discomplementarity) between both. Thus, the rigid use of voluntary standards seems to empirically dominate, and the innovation fostering effects of using voluntary standards as flexible benchmarks remains invisible in our data.

The same pattern does not hold for environmental product innovations with low environmental significance. We identify no statistically significant interaction for this type of environmental product innovation. Moreover, while the positive individual effect of voluntary

[2] A limitation of our analysis are our measures for public procurement and voluntary standards at the level of the firm. It is not possible to quantitatively identify the use of voluntary standards in public procurement tenders. We discuss the reasons for this limitation and its implications for our analysis in Appendix C.

[3] While our design does not allow for causal identification in a strict sense, the direction of potential biases – together with alignment between our findings, theory, and prior evidence – supports a causally plausible interpretation of the estimated net-effects.

standards persists, the effects of public procurement requirements become statistically insignificant.

This heterogeneity highlights the importance of distinguishing between the individual and joint effects of public procurement requirements and voluntary standards, as well as between different levels of environmental performance when investigating environmental innovation policy effects. The results suggest that voluntary standards are particularly effective in supporting environmental product innovations with lower environmental significance and are therefore likely better suited to fostering more incremental forms of environmental product innovation. Public procurement requirements, in contrast, are only effective in promoting environmental product innovations with higher environmental significance – those more likely to reflect radical or disruptive environmental product innovation, with the potential to render previous product versions obsolete within a single leap or sequentially (Johnstone & Kivimaa, 2018).

However, the discomplementarity observed between public procurement requirements and voluntary standards in the case of environmental product innovations with high environmental significance suggests that their combined use – particularly when voluntary standards are applied in a rigid manner – limits high environmental performance increases. For procurers and policymakers, this highlights the need to assess how voluntary standards are integrated into public tenders, especially when targeting more radical and disruptive environmental product innovations. For firms, the results highlight the need to track how voluntary standards are specified in tenders. This is particularly important when developing environmental product innovations with high performance increases, as rigid standards may limit firms' ability to participate in a public tender, whereas well-designed procurement requirements can increase the chances of being selected as a supplier and receiving valuable early demand for a new product.

2. Conceptual framework

2.1. Environmental product innovation

We conceptualize environmental product innovation by adapting Rainville's (2017) innovation trajectory framework in Figure 1. In contrast to Rainville, we focus on the stages of the innovation life cycle following the initial commercialization of a product, and extend the framework by explicitly linking product iteration generations to both innovation life cycle maturity and changes in environmental and functional performance.[4]

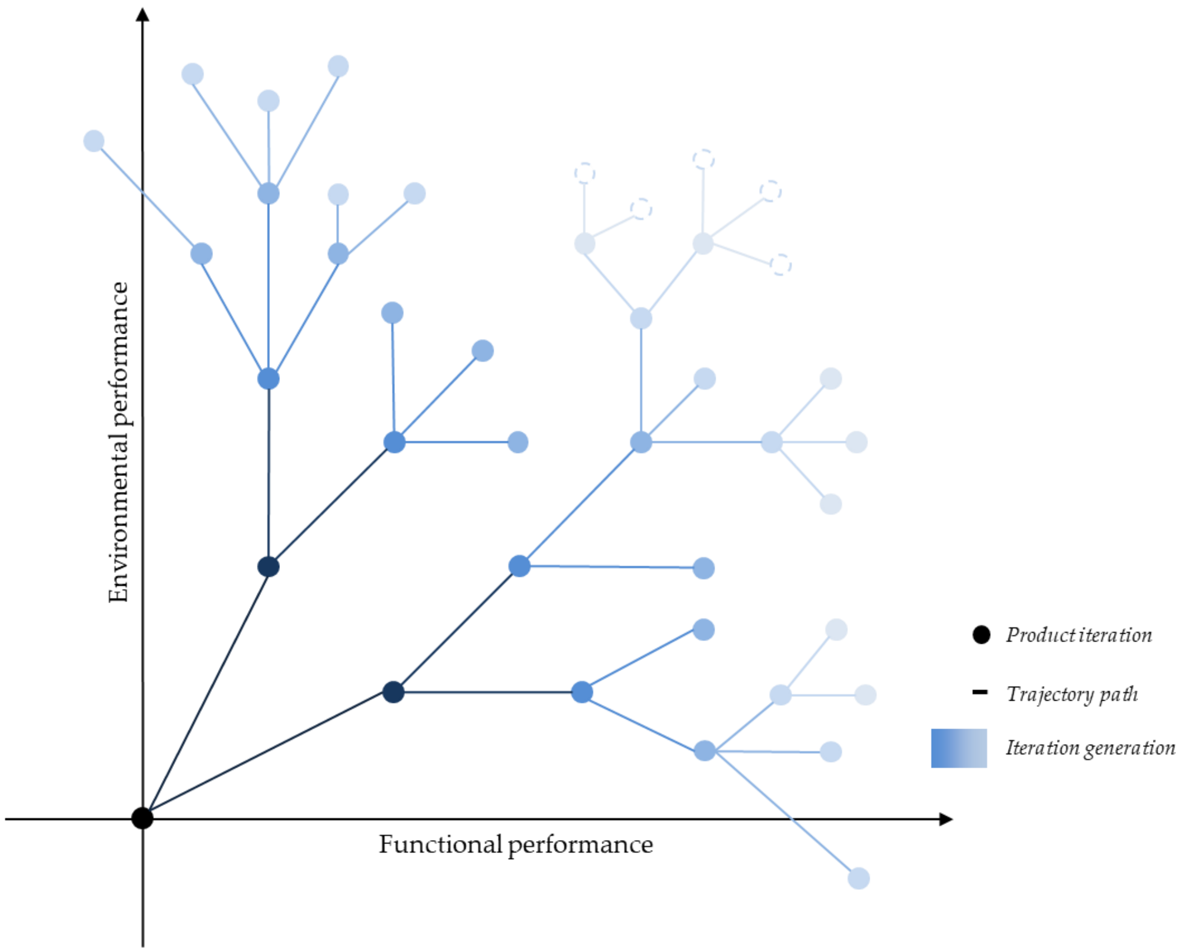

Figure 1: Environmental product innovation trajectory

Note: Each node represents a product iteration implemented by at least one firm. The color shading reflects the generational stage of each iteration, with lighter hues indicating greater maturity along the innovation life cycle. The trajectory paths connecting nodes visualize performance changes between iterations. Environmental product innovations, as a subcategory of product innovation, are characterized by improvements in the vertical dimension (environmental performance), whereas product innovation can generally reflect changes in functional (horizontal axis) and environmental (vertical axis) performance. Firms may costly enter or exit the different branches of the innovation trajectory at various stages.

In the figure, each node represents a product iteration implemented by at least one firm, positioned within a two-dimensional space defined by the iteration's functional performance (horizontal axis) and environmental performance (vertical axis). The color shading reflects the generational stage of each iteration, with lighter hues indicating greater maturity along the innovation life cycle.

[4] We assume that environmental product innovations have the same innovation life-cycle stages as innovations in general, encompassing both radical and incremental forms (Hellström, 2007; Rashid et al., 2014)

The origin node – positioned at the intersection of both axes – marks the initial commercialization of a product (Rainville, 2017), corresponding to a new-to-the-market product innovation.[5] This is defined as the first introduction of a product with new or significantly improved characteristics not previously available in the market. Subsequent nodes represent further developments of the product along the trajectory, each exhibiting performance changes relative to its predecessor. These follow-on product iterations correspond to new-to-the-firm innovations, where firms adapt an iteration of the original product innovation to their own operations.

The branches connecting nodes visualize performance changes between iterations: the longer the branch, the greater the deviation in performance. As product trajectories evolve, the magnitude of change tends to diminish, and convergence in both performance dimensions. More explicitly related to innovation life cycle maturity, nodes in later product iteration generations – reflecting a more mature stage – have lower increases in performances than nodes in earlier product iteration generations – reflecting a less mature stage (Frenken & Leydesdorff, 2000; Rainville, 2017; Foster, 1986). However, large performance increases become less likely, but remain possible. As a result, the branch length reflects a measure of innovation radicalness, while product iterations with extreme performance increases, which render all or most previous product iteration obsolete can be interpreted as a radical (environmental) product innovation. A more detailed discussion on the differences between incremental, radical, and disruptive (environmental) product innovations within this conceptualization is provided within Appendix A.2.

Firms may enter or exit the different branches of the innovation trajectory at various stages, and do not necessarily progress through an individual trajectory path sequentially. However, significant entry, exit, and switching costs might occur for the firm (Dosi, 1982; Teece, 1986).

Environmental product innovations, as a subcategory of product innovation, are characterized by improvements in the vertical dimension (environmental performance), whereas product innovation can generally reflect changes in functional (horizontal axis) and environmental (vertical axis) performance. Moreover, increases in environmental performance can be the

[5] For a more detailed discussion of new-to-the-world, new-to-the-market, and new-to-the-firm (environmental) product innovations, consult Appendix A.1.

primary objective of the product iteration, or a by-product increasing the functional performance (Horbach et al., 2012).

In sum, we define environmental product innovations as product iterations introduced by firms that improve environmental performance – such as reductions in emissions, energy consumption, or resource use – relative to previous versions of the product. This trajectory-based conceptualization enables a structured analysis of the influences that public procurement requirements and voluntary standards exert on the introduction of environmental product innovations at earlier and later stages of their innovation life cycle, which are characterized by higher and lower environmental performance increases, respectively.

2.2. Public procurement requirements and environmental product innovation

According to the European Commission Communication entitled "Public Procurement For A Better Environment," green public procurement aims at procuring products with reduced environmental harmfulness throughout their lifecycle compared to products with the same primary function that would otherwise be procured. Moreover, it is supposed to foster the uptake of environmental innovations within a market (European Commission., 2008b). In most cases, green public procurement is implemented as additional environmental product requirements during the award process of public authorities (Rainville, 2017, Testa et al., 2012). These additional requirements include aspects regarding environmental characteristics, such as a product's energy usage, or its recyclability (Krieger & Zipperer, 2022; De Giacomo et al., 2019). Firms performing better regarding the named requirements in their offer have a higher chance of winning the tender. Thus, tenders with environmental requirements reward firms for committing to the introduction of environmental product innovations by raising their chance of winning the contract.

In the early stages of the innovation lifecycle, public procurement can play a significant role in fostering the implementation of new products with high environmental performance increases compared to their predecessors with the same functionality. The selection requirements used in public tenders can codify environmental functionalities desired by procuring authorities, which are - in case of more demanding requirements – not or barely met by existing solutions. As a result, suppliers with products in the early stages of their life-cycle can meet these criteria, thereby encouraging innovation aimed at performance maximization (Utterback & Abernathy, 1975). Public procurement can, therefore, drive early-stage innovation by i) signaling new market opportunities (Edler & Georghiou, 2007; Utterback & Abernathy, 1975) and ii) securing an initial market size, which allows firms to realize economies of scale and quickly amortize their investments in innovation (Krieger & Zipperer, 2022; Edler & Georghiou, 2007).

As innovations mature, their potential for performance increases diminishes. However, public procurement likely remains an important driver of environmental product innovation in the later stages of their lifecycle with lower environmental performance increases compared to their predecessors. The mechanism of rewarding the commitment to environmental product innovations is not changed. Moreover, previous work demonstrates, if it includes award requirements, public procurement can drive firms to make incremental improvements (Czarnitzki et al., 2020). Thus, public procurement can encourage firms to compete on the basis of environmental performance, thereby driving steady advancements in product quality and environmental benefits during later stages of innovation maturity, too.

However, the effect of public procurement requirements on the introduction of environmental product innovations may be smaller at later stages of the innovation life cycle compared to earlier stages. This is because late-stage innovations typically face lower demand uncertainty (e.g., García-Quevedo et al., 2017; Guiso & Parigi, 1999; Tyagi, 2006) and require fewer additional investments for implementation (e.g., Banerjee & Siebert, 2017; Bos et al, 2013). As a result, they are less affected by the types of market failures – such as demand risk and financing constraints – that public procurement is particularly effective at addressing (Edler & Georghiou, 2007).

This conceptual framework informs the following empirically testable hypotheses:

H1a: Public procurement requirements increase the probability of a firm to introduce early-stage environmental product innovations characterized by high environmental performance increases.

H1b: Public procurement requirements increase the probability of a firm to introduce late-stage environmental product innovations characterized by low environmental performance increases.

H1c: The increases in introduction probabilities due to public procurement requirements are larger for H1a than H1b.

2.3. Voluntary standards and environmental product innovation

Standards shape the characteristics of products, and processes to fulfill agreed-upon criteria (Blind et al., 2023), whereas voluntary standards document the properties of firms' products, and processes beyond any mandatory standards set by governments (Breyer, 1982). Following Swann (2000), three economic functions of standards can be distinguished. First, standards reduce the variety of technologies, which allows firms to exploit economies of scale in mass production. Second, standardized interfaces of two or more components generate compatibility, which is the base for networks and network products (David and Greenstein, 1990). Third, standards help to define and certify minimum levels of quality related to health, environmental, or safety aspects of products and processes. Consequently, they reduce market failures caused by information asymmetries between customers and suppliers with regard to product and process quality.

Voluntary standards have the potential to increase and decrease environmental product innovation at an early stage of their life-cycle with large potential for performance increases (Blind et al., 2022; Blind & Mangelsdorf, 2016). Participation in the development of standards enhances firms' efficiency in research and development by providing clearer benchmarks, thereby reducing uncertainties associated with early-stage innovation (Zhang et al. 2020). Moreover, the participation facilitates collaborative innovation by fostering interactions with competitors, suppliers, and customers within standardization committees which enhances knowledge exchange and collective problem-solving (Wen et al., 2020; Blind et al., 2022). Finally, firms can gain a time advantage by shaping standards to align with their technological preferences and strategic interests, which accelerates the development and performance of early-stage innovation (Blind et al., 2022). However, on the negative side, the use of standards within firms might cause lock-in effects in late-stage environmental product innovation trajectories that restrict the development of market novelties introducing a new innovation trajectory.[6] These lock-in effects are even stronger in the context of compatibility standards, where they might hinder the transition into more radical innovations. Second, quality standards can be defined in such a challenging way by dominant market players that they

[6] For a detailed discussion on the link between market novelties and product innovation trajectories consult Appendix A1.

restrict the market access by competitors, thereby reducing competitive pressure, and hence environmental product innovation (e.g., Foucart & Li, 2021).

Voluntary standards foster environmental product innovations during the late stages of their lifecycle. Standards ensure consistency and reliability across products, which is important for their widespread adoption. By codifying best practices and establishing clear criteria for environmental performance, standardization promotes interoperability and reduces market fragmentation, making it easier for firms to introduce incremental innovations that align with established norms (Mangiarotti & Riillo, 2014). As a result, standards in the late lifecycle ensure that products continue to evolve and improve within established performance thresholds, contributing to steady, incremental advancements in environmental product innovation (Foucart & Li, 2021).

As the theoretical effects of voluntary standards on early-stage environmental product innovation are ambivalent at the level of our empirical analysis – potentially fostering innovation through coordination or hindering it through lock-in – we do not formulate a directional hypothesis for early-stage innovations. Instead, our conceptualization only informs a testable hypothesis for late-stage innovations:

H2: Voluntary standards increase the probability of a firm to introduce late-stage environmental product innovations characterized by low environmental performance increases.

2.4. Voluntary standards, green public procurement, and environmental product innovation

The combination of voluntary standards and public procurement requirements aims to promote environmental product innovation. However, voluntary standards are non-mandatory specifications developed through industry consensus to define environmental or functional performance benchmarks (Blind et al., 2023). While not legally binding, they can become effectively mandatory when referenced in public procurement requirements. This gives rise to two applications of voluntary standards as public procurement requirements: i) flexible benchmark use and ii) rigid threshold use.

Flexible benchmark use occurs when voluntary standards are referenced in award requirements in such a way that exceeding the benchmark is rewarded. This application fosters innovation by allowing suppliers to differentiate themselves through superior environmental performance. It aligns with the mechanisms described in Section 2.2 and supports the introduction of both early- and late-stage environmental product innovations accordingly, while providing particularly clear benchmarks.

Rigid threshold use, in contrast, treats voluntary standards as fixed specifications that firms are expected to match – neither falling too short nor exceeding them too much. In this case, suppliers must align their product with the standard to qualify, but receive no additional benefit for offering higher environmental performance. This approach discourages improvements beyond the standard and limits offers to largely established products, thereby limiting the scope for environmental performance improvements.

This mechanism mirrors the lock-in effects of price-based (Krieger et al. 2024) and off-the-shelf procurement (Edquist & Zabala-Iturriagagoitia, 2020), where requirements specify predefined products and selection is based solely on price. Thus, like these procurement types, rigid standard-based requirements discourage environmental product innovations, particularly those at early-stages of their innovation life cycle and characterized by high environmental performance increases.

In sum, the framework demonstrates that the effect of voluntary standards on environmental product innovation in the context of public procurement is contingent on their mode of application. When applied as flexible benchmarks within award requirements, voluntary standards can complement green public procurement by providing orientation and incentivizing performance differentiation. In contrast, their use as rigid thresholds within eligibility requirements may constrain the solution space and conflict with innovation objectives – particularly for early-stage environmental product innovations with high performance potential. Given this conceptual ambiguity, we focus on the theoretically directional relationship that can be evaluated within our empirical setting:

H3: The rigid threshold use of standards discourages the introduction of environmental product innovation at early-stages of their innovation life-cycle characterized by high environmental performance increases, stronger than the introduction of environmental product innovation at late-stages of their innovation life-cycle characterized by low environmental performance increases.

Rainville (2017) provides detailed descriptions and practical examples of how a wide range of voluntary standards can be integrated into public procurement from the perspective of public procurers. The conceptual framework used in our analysis enables the differentiation between incremental, disruptive, and radical environmental product innovations, as well as innovations that are new-to-the-firm, new-to-the-market, and new-to-the-world, as illustrated in Appendices A1 and A2. While this differentiation enriches the theoretical foundation, it does not alter our core hypotheses. However, due to data limitations – specifically, the lack of information on the introduction of these distinct types of environmental product innovations – we are unable to empirically test this extended framework. Therefore, we refrain from presenting the extension in the main text and leave its further development to future research.

3. Empirical framework

3.1. Database

We use the German Innovation Survey for our analysis. The survey is the German contribution to the European Community Innovation Surveys and is conducted annually by ZEW Mannheim on behalf of the German Federal Ministry of Education and Research. It is designed as a representative sample of firms in the German manufacturing and service industries with five or more employees and focuses on collecting information about various aspects of firms' innovation activities. Peters and Rammer. (2023) provide an extensive description of the German Innovation Survey. In addition to detailed information about firm-level innovations, the survey includes data on firm performance, such as revenues, exports, and employee numbers. Most importantly for our analysis, the survey includes different focus topics each year, which cover additional questions (Krieger & Zipperer, 2022; Blind et al., 2022). These focus topics are not repeated annually but at longer intervals. In the 2021 survey, environmental innovations were a focus topic, including questions on the importance of public procurement criteria and voluntary standards for the introduction of environmental innovations (Rammer & Schubert, 2022).[7]

[7] This is the only instance in which the importance of *public procurement criteria* has been surveyed in the German Innovation Survey. The microdata from the European Community Innovation Surveys is not yet available. Access to the German data was obtained through the ZEW Mannheim.

3.2. Variable construction

Environmental product innovation - The 2021 German Innovation Survey asked firms about their implementation of environmental product innovations and the significance of the environmental benefits achieved during their use:

During the three years 2018 to 2020, did your enterprise introduce innovations with any of the following environmental benefits, and, if yes, was their contribution to environmental protection rather significant or insignificant?

Environmental benefits obtained during the use of your products/services:

	Yes, Significant	Yes, Insignificant	No
Reduced energy use or CO_2 footprint	☐	☐	☐
Reduced air, water, soil, or noise pollution	☐	☐	☐
Facilitated recycling of product after use	☐	☐	☐
Extended product life	☐	☐	☐

Figure 2: Environmental product innovation survey questions

We use this information to generate dichotomous variables for the introduction of eco-innovations with a heterogeneous environmental significance:

Significant environmental product innovation are defined as equal to one if a firm answered "Yes, significant contribution" within one of its four environmental externality classes. Otherwise, it is zero.

Insignificant environmental product innovation are defined as equal to one if a firm answered "Yes, insignificant contribution" within one of its four environmental externality classes. Otherwise, it is zero.

This definition aligns with our conceptual framework by distinguishing between environmental product innovations that yield higher (more radical) and lower (less radical) improvements in environmental performance. Similar to our framework, it allows for environmental performance improvements to be either the primary objective of the product innovation or an unintended benefit resulting from enhancements in the product's functional performance. However, unlike our framework, it adopts the perspective of the firm rather than that of a product innovation trajectory. As such, while this definition serves as a useful proxy for identifying environmental product innovations as described, it introduces potential measurement errors – particularly in cases where a firm exits, enters, or switches between innovation trajectory branches. In these scenarios, a significant increase in environmental performance may occur, for instance, due to the firm temporarily exiting the innovation trajectory, skipping several product iteration generations, and re-entering at a later stage. Consequently, a high performance increase could reflect either i) a smaller number of long innovation branches – consistent with our framework's definition of significant environmental product innovation – or ii) a larger number of short branches – which would not align with our conceptual framework. We elaborate in Appendix D, why this definition of environmental product innovation represents the best available proxy for our analysis.

Public procurement – In addition, the survey asked about potential factors for introducing environmental innovations, the need to meet requirements in public procurement contracts being one of them:

During 2018 to 2020, how important were the following factors in driving your enterprise's decisions to introduce innovations with environmental benefits?				
	High	Medium	Low	Not Relevant
Need to meet requirements for public procurement contracts	☐	☐	☐	☐

Figure 3: Public procurement survey question

We use this information and generate a dichotomous variable equal to one if a firm answered at least "Medium" and zero otherwise.

Voluntary standards **-** Similarly, the survey asked about the importance of voluntary industry standards and commitments as factor for introducing environmental innovations:

During 2018 to 2020, how important were the following factors in driving your enterprise's decisions to introduce innovations with environmental benefits?				
	High	Medium	Low	Not Relevant
Voluntary actions or standards for environmental good practice within your sector	☐	☐	☐	☐

Figure 4: Voluntary standards survey question

Again, we utilize this and generate a dichotomous variable equal to one if a firm answered at least "Medium" and zero otherwise.

We aim to examine the interaction of public procurement requirements and voluntary standards using the two described variables. Measuring both i) the existence of requirements and ii) the inclusion of voluntary standards at the level of public procurement tenders would be optimal. However, at this point, no database allows for such an analysis in a larger quantitative manner. As we elaborate in detail in Appendix D, the two described variables represent the best available proxy for our analysis – and are more likely to result in an underestimation of our effects.

Control variables – Previous research identified various factors explaining the introduction of innovations in general and the introduction of environmental innovations in particular (e.g., Blind et al., 2022; Krieger & Zipperer, 2022; Stojčić, 2021; Caravelle & Crespi, 2020; Czarnitzki et al., 2020). We, therefore, create various control variables:

Innovation inputs - We consider the current innovation efforts of individual firms by including innovation intensity measured as innovation expenditures over revenues and by creating dichotomous variables for the occasional and continuous performance of internal R&D activities during the last three years. Firms devoting more resources to innovation activities are more likely to introduce new or significantly improved products and processes. Moreover, they are most potentially more likely to win public procurement tenders with additional award criteria and to face standards related to the characteristics of their innovative products, services, and production processes.

Firm structure – Larger and older firms are associated with lower resource constraints. Therefore, they are less constrained concerning investing in innovation and allocating resources to engage in public procurement tenders. Thus, we control for firm size measured by a firm's number of employees as full-time equivalent and a firm's age in years. The ownership structure of firms is linked to their governance structures and their access to resources. Both are related to the innovation activities of firms, their success in public procurement tenders, and their ability to adhere to voluntary standards and commitments. Hence, we extract a dichotomous company-group membership variable that differentiate between firms being part of a company group or not. Lastly, to consider learning from exporting possibilities, we add another dichotomous variable for having export revenues or not.

Public policy – Public policies are related to innovation, public procurement, and standards. Firms receiving public funding for their innovation activities are, for instance, on average more skilled considering the application process of competitive tenders, implementing voluntary standards, and innovating. Hence, we add dichotomous public-policy variables. First, we create a dichotomous variable equal to one if public subsidies were a factor for introducing eco-innovations of at least medium importance. Second, we generate another dichotomous variable equal to one if existing environmental regulations or existing environmental taxes were a factor for introducing eco-innovations of at least medium importance.

During 2018 to 2020, how important were the following factors in driving your enterprise's decisions to introduce innovations with environmental benefits?				
	High	Medium	Low	Not Relevant
Existing environmental regulations	☐	☐	☐	☐
Existing environmental taxes, charges or fees	☐	☐	☐	☐
Government grants, subsidies, etc., for environmental innovations	☐	☐	☐	☐

Figure 5: Public policies as environmental innovation driver survey questions

Market structure – Environmental product innovation, public procurement requirement, and voluntary standard dynamics naturally differ between industries. Therefore, industry fixed effects based on the NACE Rev. 2 classification cover differences across industries (Czarnitzki et al., 2020). In addition, German state fixed effects account for regional structural differences. Finally, we create four controls on a firm's competition environment. We create a control for i) the substitutability of a firm's products, ii) the level of price competition, iii) the intensity of competition through market entries, and iv) the magnitude of international competition. Each variable is based on statements on a firm's competitive situation in the German Innovation Survey:

Please indicate to what extent the following characteristics describe the competitive situation of your enterprise during 2018 to 2020.				
	Applies Fully	Applies Somewhat	Applies Very Little	Does Not Apply
Products/services from competitors are easily substituted for those of your enterprise	☐	☐	☐	☐
Major threat to market position because of entry of new competitors	☐	☐	☐	☐
Strong competition from abroad	☐	☐	☐	☐
Price increases lead to immediate loss of clients	☐	☐	☐	☐

Figure 6: Competition environment survey questions

We define a variable as zero if a firm answered with "not at all," or "very little," and as one otherwise.

3.3. Descriptive statistics

The sample consists of 5.127 firms. Descriptive statistics for the generated variables are demonstrated in Table 1. The share of firms introducing significant environmental product innovations corresponds to 17.0 percent, and the share of firms introducing insignificant environmental product innovations to 36.0 percent. Thus, our descriptive statistics are in line with former analyses using the information on environmental innovations from the German Innovation Survey (e.g; Krieger & Zipperer, 2022). *Voluntary standards and commitments* were a factor for introducing environmental product innovations for 25.0 percent of firms and *requirements of public procurement tenders* for 12.0 percent. Both factors were simultaneously important for 8.0 percent of our sample.

There are no peculiar values for the means, standard deviations, maxima, or minima of the control variables. We present a correlation matrix of the presented variables in Table B.1 in Appendix B. The share of firms *considering public procurement tenders as an important factor for environmental innovations* is significantly higher than the share of firms *winning economically significant public procurement tenders with environmental criteria in the award phase* identified in the Tenders Electronic Database between 0.5 and 1.5 percent by Krieger and Zipperer (2022). Thus, environmental criteria within the technical specification of procurement tenders (i.e., rather than award criteria), or within smaller tenders seem to be important for firms, too (Kesidou & Demirel, 2012).

Table 1: Descriptive sample statistics

Variable	Mean	Standard deviation	Maximum	Minimum
Significant environmental product innovation (0/1)	0.17	0.38	1.00	0.00
Insignificant environmental product innovation (0/1)	0.36	0.48	1.00	0.00
Voluntary standards (0/1)	0.25	0.43	1.00	0.00
Public procurement criteria (0/1)	0.12	0.33	1.00	0.00
Voluntary standards# public procurement criteria (0/1)	0.08	0.27	1.00	0.00
Innovation expenditures/revenues	0.04	0.15	4.89	0.00
Continuous internal R&D (0/1)	0.26	0.44	1.00	0.00
Occasional internal R&D (0/1)	0.11	0.31	1.00	0.00
Employees as FTE	170.00	2,001.80	102,348.00	0.50
Age in years	32.82	30.66	531.50	0.50
Company group (0/1)	0.32	0.47	1.00	0.00
Exporter (0/1)	0.40	0.49	1.00	0.00
Regulation or taxes (0/1)	0.36	0.48	1.00	0.00
Public funding (0/1)	0.15	0.36	1.00	0.00
Substitutable products (0/1)	0.52	0.50	1.00	0.00
Market entry competition (0/1)	0.41	0.49	1.00	0.00
Foreign competition (0/1)	0.33	0.47	1.00	0.00
High price competition (0/1)	0.43	0.50	1.00	0.00

Note: Number of observations is equal to 5,127.

We compare the shares of firms introducing significant and insignificant environmental product innovation for the group of firms i) considering public procurement requirements as important, ii) considering voluntary standards and commitments as important, iii) considering both factors as important, and iv) considering both factors as not important. The comparison is shown in Table 2. Firms considering both factors as not important are the least likely to introduce environmental product innovations, whereas firms considering both factors as important are the most likely to introduce them. Firms considering only one of the two factors as important lie in between the two groups, although firms considering voluntary standards and commitments as important have a slightly higher probability to innovate. Thus, investigating solely the descriptive statistics of our sample suggests a net *complementarity* of voluntary standards and public procurement requirements. However, they do not take any form of *endogeneity*, in particular omitted variables, self-selection, and reverse causality, into account.

Table 2: Descriptive comparisons according to voluntary standards and public procurement requirements

Comparison groups	Share of firms introducing		Observations
	Significant environmental product innovation (0/1)	Insignificant environmental product innovation (0/1)	
Voluntary standards# public procurement criteria (0/1)	40.7	62.8	418
Voluntary standards (0/1)	37.6	59.6	1,261
Public procurement criteria (0/1)	37.1	55.8	634
None (0/1)	0.09	28.1	3,650

3.4. Empirical model

Model specification – We relate the importance of requirements in public procurement tenders and the importance of voluntary standards with the probability to introduce environmental product innovations. Thus, we adapt the baseline model by Czarnitzki et al. (2020). Czarnitzki et al. (2020) examine an innovation equation, which tries to explain *the role of innovative public procurement as a driver of product innovations with different levels of novelty*. In contrast, we focus our analysis on public procurement requirements, voluntary standards, and their interaction as a driver of *environmental product innovations with different levels of environmental significance*. More precisely, we estimate the following baseline models:

$$Y_i = \alpha_0 + \alpha_1 PP_i + \alpha_2 ST_i + \delta \boldsymbol{X_i} + \boldsymbol{\gamma_i} + \boldsymbol{\theta_i} + \epsilon_i^{\alpha} \tag{1}$$

$$Y_i = \beta_0 + \beta_1 PP_i + \beta_2 ST_i + \beta_3 PP_i * ST_i + \tau \boldsymbol{X_i} + \boldsymbol{\gamma_i} + \boldsymbol{\theta_i} + \epsilon_i^{\beta}. \tag{2}$$

Y_i represents our dependent variable. It is defined as our dichotomous environmental product innovation variables. PP_i, and STA_i represent the importance of public procurement criteria and voluntary standards. Therefore, α_1 and α_2 demonstrate the individual relationships of public procurement criteria and voluntary standards with environmental product innovations, while abstracting from potential complementarities and discomplementarities between them in Model (1). As a result, this model analyzes the net relations between the two and environmental product innovations. In contrast, Model (2) incorporates the interaction term $PP_i * ST_i$. As a result, β_1 and β_2 represent the individual relationships of public procurement criteria and voluntary standards with environmental product innovations during the absence of one another, and β_3 demonstrates the complementarities (positive coefficient) or discomplementarities (negative coefficient) between both factors. In both models, $\boldsymbol{X_i}$ is a vector of control variables, $\boldsymbol{\theta_i}$ corresponds to a vector of state fixed effects, and $\boldsymbol{\gamma_i}$ to a vector of industry fixed effects. α_0 and β_0 are the constant terms, and ϵ_i^{α} and ϵ_i^{β} the error terms in their respective model.

Estimation method – All estimations employ Ordinary Least Squares (OLS), representing a Linear Probability Model (LPM). Although dichotomous dependent variable models such as Probit and Logit prevent out-of-bounds predictions, the OLS estimator offers better handling of heteroscedasticity. Additionally, OLS results are largely indistinguishable from the average marginal effects obtained through Probit and Logit estimations (Angrist & Pischke, 2008). Standard errors are robust to heteroscedasticity in all estimations.

Boundary conditions – We conduct subsample estimations based on firm size, age, industry, as well as general innovation output and input to identify potential boundary conditions and provide more nuanced guidance for policymakers.

Robustness tests – We combine our main estimations with entropy balancing (Hainmueller, 2012). Entropy balancing stochastically assigns weights to the observations of the control group, such that the moments of the group's control variables are the same as those in the treatment group.[8] Using this weighting as a step prior to our main estimations controls for confounding variables outside of the estimation equation and ensures the comparability of the treatment and control group.[9] Additionally, we explore variations in the definition of our independent variables to test the robustness of our results. The robustness tests are presented in Appendix C. In sum, our results remain robust.

Empirical limitations – Finally, we provide a detailed discussion of potential endogeneity concerns, asserting that the likelihood of our main findings being influenced by omitted variables, self-selection, or reverse causality is low. Furthermore, we highlight the implications of our firm-level measures for public procurement criteria and voluntary standards, noting that these measures are likely to result in an underestimation of the investigated relations. For conciseness, the discussion is covered in Appendix D.

4. Results

4.1. Baseline results

Table 3 presents our baseline results. Columns (1) and (2) focus on significant environmental product innovations as the dependent variable, whereas Columns (3) and (4) concentrate on insignificant environmental product innovations. Moreover, Columns (1) and (3) estimate Model (1), abstracting from an interaction between voluntary standards and public procurement criteria, while Columns (2) and (4) present estimates of Model (2), which includes the interaction.

[8] We define our treatment groups separately as $PP_i * ST_i = 1$, $PP_i = 1$, and $ST_i = 1$, and the corresponding control groups as $PP_i * ST_i = 0$, $PP_i = 0$, and $ST_i = 0$. Consequently, i) we estimate three distinct sets of weights, one for each treatment group, and ii) run three separate regressions, each for one of the treatment groups. In each regression, the three variables $PP_i * ST_i$, PP_i, and ST_i are treated as fully flexible dichotomous variables and included directly in all weighted regressions. It is not possible to use them within the estimation of weights as i) PP_i and ST_i are never zero for $PP_i * ST_i = 1$, ii) $PP_i * ST_i$ is never one for $ST_i = 0$, and iii) $PP_i * ST_i$ is never one for $SP = 0$.

[9] Entropy balancing, therefore, constitutes an alternative to a variety of widely used data preprocessing methods, such as Mahalanobis distance or propensity score matching, whereas it outperforms them in finite samples with regard to bias reduction and efficiency (Hainmueller, 2012).

Column (1) shows positive and statistically significant relations of voluntary standards and public procurement criteria with highly significant environmental product innovations, indicating a net positive relationship. In Column (2), these relations remain positive and significant when each factor is considered in the absence of the other. Additionally, Column (2) reveals a statistically significant negative interaction term, indicating that while both voluntary standards and public procurement criteria individually relate positively to environmental product innovations, their combined presence weakens the overall relationship, suggesting discomplementarities between them. These discomplementarities appear to primarily constrain the positive relationship between public procurement criteria and significant environmental product innovations. Specifically, the estimate for public procurement criteria in Model (1) is only 46 percent of its value in Model (2), whereas the estimate for voluntary standards retains 88 percent of its strength. This suggests that the weakening effect from the interaction is largely driven by the diminished relation between public procurement criteria and significant environmental product innovations.

Columns (3) and (4) focus on environmental product innovations with low significance as the dependent variable. Column (3) estimates Model (1), showing a positive and statistically significant relation of voluntary standards with insignificance environmental product innovations, while public procurement criteria show no significant relation. Column (4) estimates Model (2), where voluntary standards maintain a positive and significant relation with insignificance environmental product innovations, while public procurement criteria remain statistically insignificant. Additionally, Column (4) reveals a non-significant interaction term, indicating that the combination of voluntary standards and public procurement criteria does not generate an additional effect beyond their individual contributions for insignificance environmental product innovations.

There are no irregularities in the magnitude, statistical significance, or signs of our control variables.

Table 3: Voluntary standards, public procurement criteria, and environmental product innovation

Dependent variable:	Significant environmental product innovation (0/1)		Insignificant environmental product innovation (0/1)	
Estimation model:	Model 1	Model 2	Model 1	Model 2
Column #:	(1)	(2)	(3)	(4)
Voluntary standards (0/1)	0.14*** (0.02)	0.16*** (0.02)	0.15*** (0.02)	0.15*** (0.02)
Public procurement criteria (0/1)	0.06*** (0.02)	0.13*** (0.03)	0.03 (0.02)	0.04 (0.03)
Voluntary standards# pub. proc. criteria (0/1)		-0.11*** (0.04)		-0.02 (0.04)
Innovation expenditures/ revenues	0.07* (0.04)	0.07* (0.04)	0.07 (0.05)	0.07 (0.05)
Continuous internal R&D (0/1)	0.15*** (0.02)	0.15*** (0.02)	0.16*** (0.02)	0.16*** (0.02)
Occasional internal R&D (0/1)	0.09*** (0.02)	0.09*** (0.02)	0.14*** (0.02)	0.14*** (0.02)
Ln(employees as FTE)	0.00 (0.00)	0.00 (0.00)	0.03*** (0.00)	0.03*** (0.00)
ln(age in years)	-0.02*** (0.01)	-0.02*** (0.01)	0.01 (0.01)	0.01 (0.01)
Company group (0/1)	-0.01 (0.01)	-0.01 (0.01)	-0.01 (0.01)	-0.01 (0.01)
Export revenues (0/1)	0.03** (0.01)	0.03** (0.01)	0.00 (0.02)	0.00 (0.02)
Regulation or taxes (0/1)	0.09*** (0.01)	0.09*** (0.01)	0.17*** (0.02)	0.17*** (0.02)
Public funding (0/1)	0.09*** (0.02)	0.09*** (0.02)	-0.01 (0.02)	-0.01 (0.02)
Substitutable products (0/1)	-0.01 (0.01)	-0.01 (0.01)	0.02 (0.01)	0.02 (0.01)
Market entry competition (0/1)	-0.01 (0.01)	-0.01 (0.01)	0.01 (0.01)	0.01 (0.01)
Foreign competition (0/1)	-0.00 (0.01)	-0.00 (0.01)	0.02 (0.02)	0.02 (0.02)
High price competition (0/1)	0.01 (0.01)	0.01 (0.01)	-0.01 (0.01)	-0.01 (0.01)
R-squared	0.19	0.19	0.16	0.16
Observations	5,127	5,127	5,127	5,127

Note: Estimates are based on pooled OLS. Heteroscedasticity robust standard errors in parentheses. Industry and state fixed effects are included. * p<0.1 ** p<0.05 *** p<0.01

4.2. Boundary conditions

We conduct subsample analyses across firms' size, age, industry, as well as general innovation input and output to uncover potential boundary conditions. In the following, we present the estimates using Model 2, which takes the interaction between public procurement criteria and voluntary standards into account. The estimates using Model 1, which abstracts from this interaction, are presented in Appendix E. In sum, using Model 1 slightly reduced the statistical significance, and magnitude of our estimates for public procurement criteria and voluntary standards, whereas all results remain qualitatively robust. Moreover, the discomplementarities between voluntary standards and public procurement criteria seems to robustly limit the positive relation of public procurement criteria with significant environmental product innovations in particular. The estimates of the interaction term mirror the magnitude and statistical significance of the public procurement criteria estimates, and the statistically significance and magnitude of public procurement criteria are reduced more strongly than the statistical significance and magnitude of voluntary standards using Model (1).

Firm size – Firm size is measured by the number of employees in full-time equivalents, and the sample is divided into quartiles. Figures 1.A–1.F present the results. For significant environmental product innovations, voluntary standards are statistically significant across all size categories (Figure 1.A). Public procurement criteria (Figure 1.B) and its interaction with voluntary standards (Figure 1.C) lose statistical significance in smaller firms but hold statistical significance for larger ones. For insignificant environmental product innovations, voluntary standards are statistically significant across all size categories, with the largest coefficient in smaller firms (Figure 1.D). Public procurement criteria (Figure 1.E) and its interaction term with voluntary standards (Figure 1.F) are not statistically significant.

Estimates for *significant environmental product innovation* by *employee number*

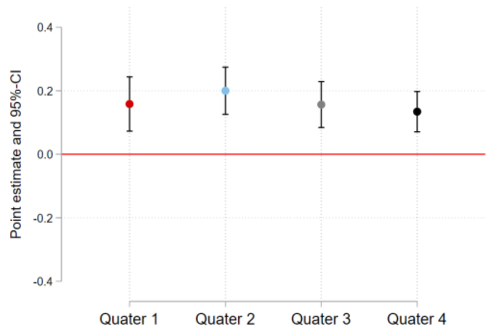

Figure 1.A: Voluntary standards

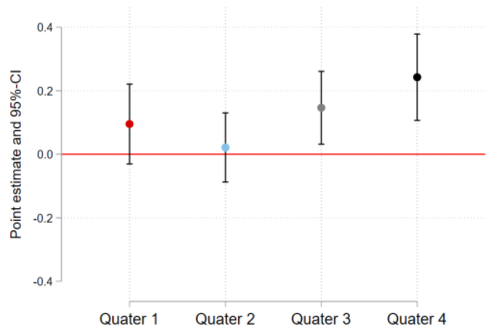

Figure 1.B: Public procurement criteria

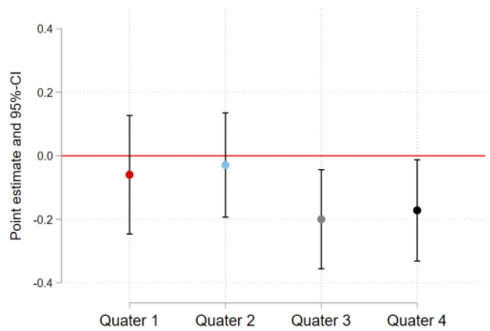

Figure 1.C: Interaction

Estimates for *insignificant environmental product innovation* by *employee number*

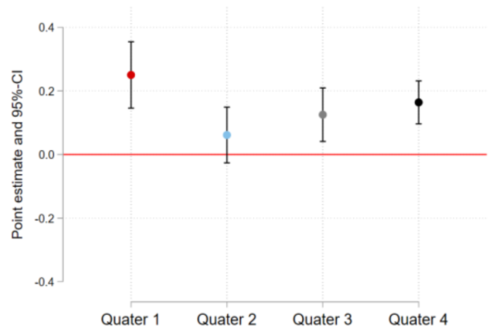

Figure 1.D: Voluntary standards

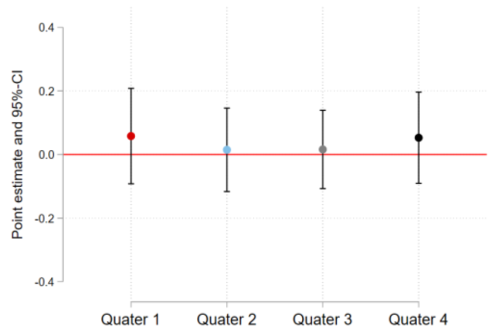

Figure 1.E: Public procurement criteria

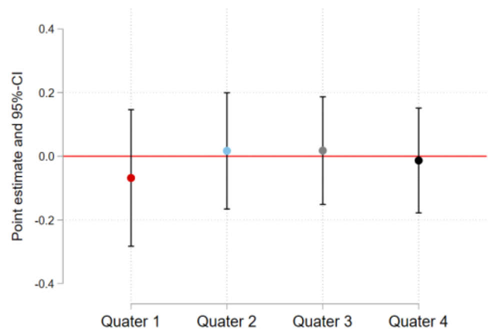

Figure 1.F: Interaction

Figure 1: Subsamples estimations by firms' employee number

Note: Fig. 1.A. to Fig. 1.F. present point estimates and confidence intervals for estimating Model 2 for the subsamples Quarter 1 to 4 using significant (1.A. to 1.C) and insignificant (1.D. to 1.F) environmental product innovations as dependent variable. Quarter 1 to 4 represent our equally quartered sample according to firms' employee number ordered from a lower to a higher number.

Firm age – In the same vein, we split and analyze our sample by firm age in years, as depicted in Figure 2. For significant environmental product innovations, voluntary standards are statistically significant across all subsamples, though their magnitude decreases slightly with age (Figure 2.A). Following the previous pattern for size, public procurement criteria (Figure 2.B), and its interaction with voluntary standards (Figure 2.C), seem to increase with age – even though its statistical significance is reduced to the ten-percent level for several subsamples. For insignificant environmental product innovations, voluntary standards consistently show statistical significance across all subsamples, whereas public procurement criteria and their interaction with voluntary standards do not reach significance in any subsample.

Estimates for *significant environmental product innovation* by *age in years*

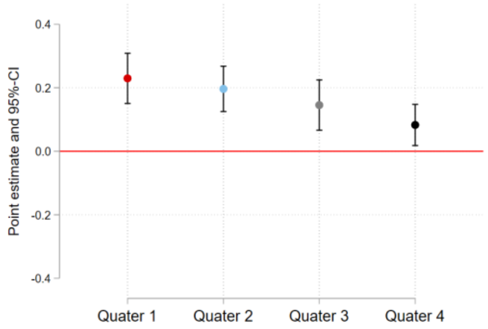

Figure 2.A: Voluntary standards

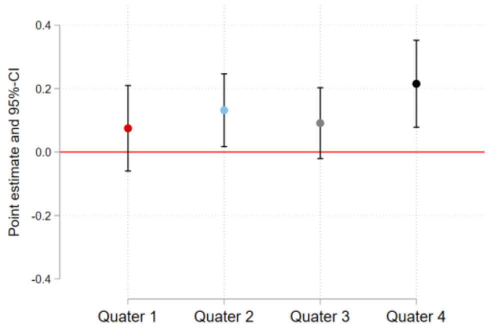

Figure 2.B: Public procurement criteria

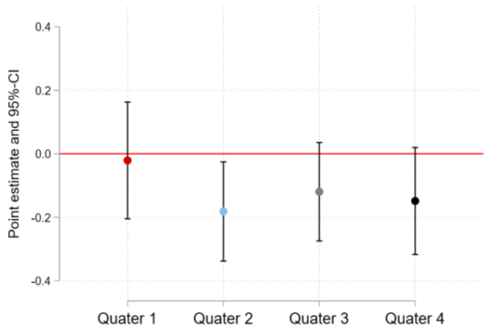

Figure 2.C: Interaction

Estimates for *insignificant environmental product innovation* by *age in years*

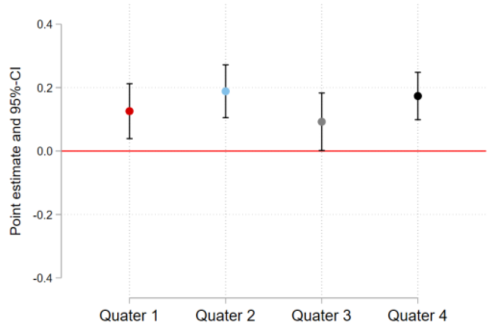

Figure 2.D: Voluntary standards

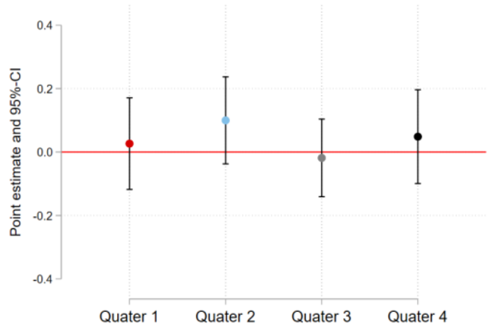

Figure 2.E: Public procurement criteria

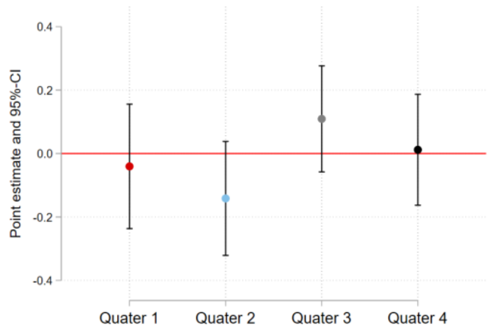

Figure 2.F: Interaction

Figure 2: Subsamples estimations by firms' age in years

Note: Fig. 2.A. to Fig. 2.F. present point estimates and confidence intervals for estimating Model 2 for the subsamples Quarter 1 to 4 using significant (2.A. to 2.C) and insignificant (2.D. to 2.F) environmental product innovations as dependent variable. Quarter 1 to 4 represent our equally quartered sample according to firms' age in years ordered from a younger to an older age.

Firm size and age – Because firm size and firm age are highly correlated, we repeat the analyses by considering both simultaneously. We classify firms into four groups: young and small (YS), young and large (YL), old and small (OS), and old and large (OL), based on the medians of the previous variables. For significant environmental product innovations, voluntary standards exhibit statistical significance in all four groups, with higher magnitudes in younger firms (YS, YL) than in older firms (OS, OL) (Figure 3.A). Public procurement criteria (Figure 3.B) and its interaction with voluntary standards (Figure 3.C) are significant only in the two larger-firm subsamples (YL, OL). For insignificant environmental product innovations, voluntary standards are significant across all groups. Public procurement criteria (Figure 3.E) and its interaction with voluntary standards (Figure 3.F) are not significant.

Estimates for *significant environmental product innovation* by *employee number* and *age in years*

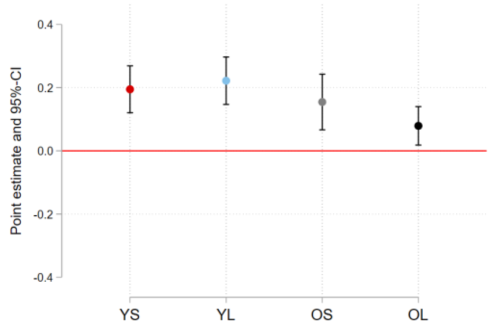

Figure 3.A: Voluntary standards

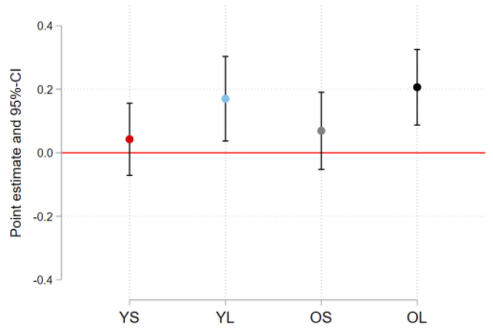

Figure 3.B: Public procurement criteria

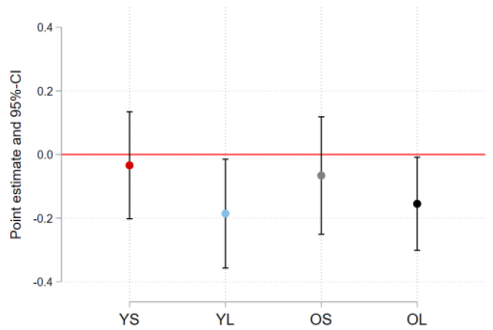

Figure 3.C: Interaction

Estimates for *insignificant environmental product innovation* by *employee number* and *age in years*

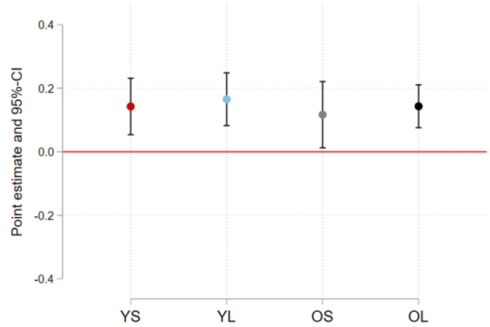

Figure 3.D: Voluntary standards

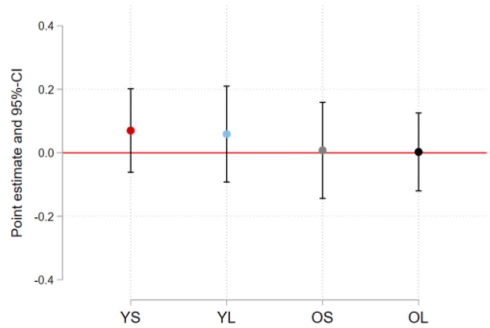

Figure 3.E: Public procurement criteria

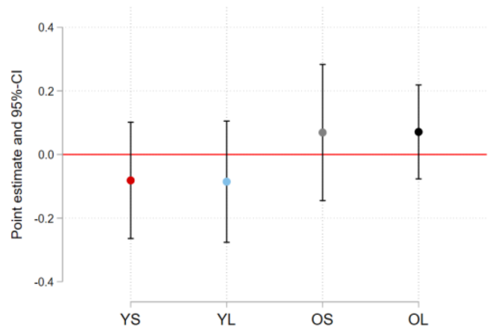

Figure 3.F: Interaction

Figure 3: Subsamples estimations by firms' employee number and age in years

Note: Fig. 3.A. to Fig. 3.F. present point estimates and confidence intervals for estimating Model 2 for the subsamples YS, YL, OS, and OL using significant (3.A. to 3.C) and insignificant (3.D. to 3.F) environmental product innovations as dependent variable. The sample is quartered according to the median age in years, and median number of employees in our sample. YS covers firms in the younger and smaller median, YL firms in the younger and larger median, OS firms in the older and smaller median, and OL firms in the older and larger median.

Industry – Figure 4 presents subsample estimations by industry affiliation: high-tech manufacturing (HT), medium-high-tech manufacturing (MHT), medium-low-tech manufacturing (MLT), low-tech manufacturing (LT), knowledge-intensive services (KIS), and all remaining industries (Others). Because the number of subsamples increases, the statistical power of individual estimations decreases, yielding fewer significant estimates. Still, some informative patterns can be observed. No consistent pattern emerges for voluntary standards in either significant environmental product innovations (Figure 4.A) or insignificant environmental product innovations (Figure 4.D). Similarly, public procurement criteria (Figure 4.E) and its interaction with voluntary standards (Figure 4.F) do not display a clear pattern for insignificant environmental product innovations. However, for significant environmental product innovations, public procurement criteria (Figure 4.B) and its interaction with voluntary standards (Figure 4.C) appear particularly relevant for technology-intensive manufacturing industries.

Estimates for *significant environmental product innovation* by *industry*

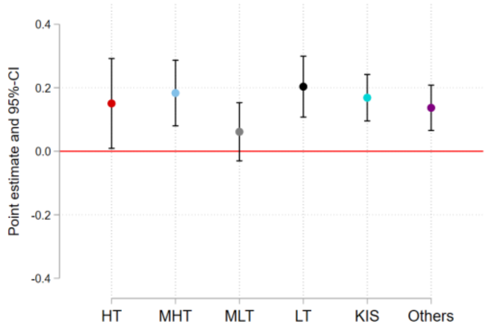

Figure 4.A: Voluntary standards

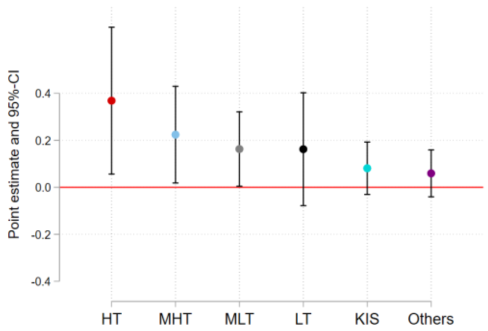

Figure 4.B: Public procurement criteria

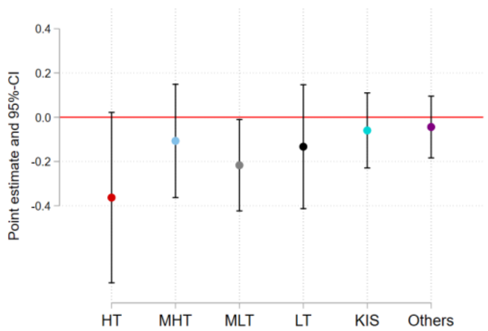

Figure 4.C: Interaction

Estimates for *insignificant environmental product innovation* by *industry*

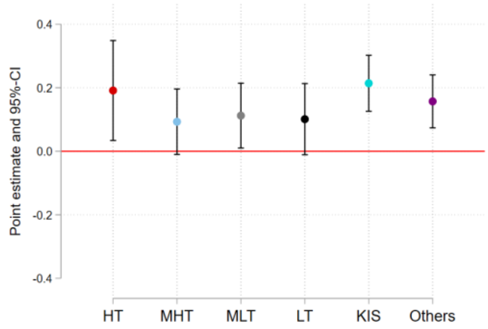

Figure 4.D: Voluntary standards

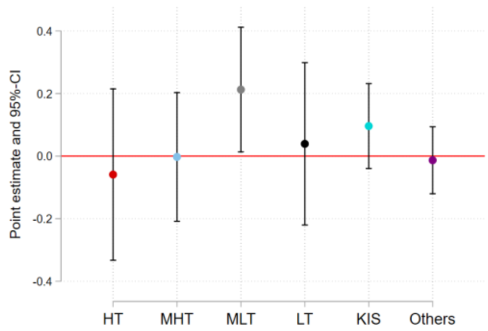

Figure 4.E: Public procurement criteria

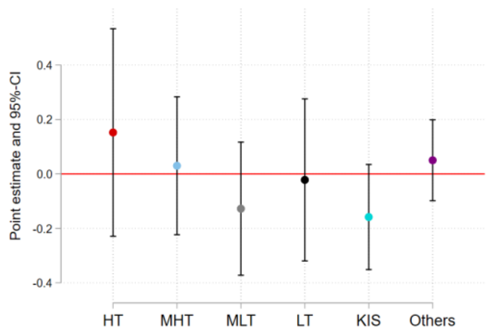

Figure 4.F: Interaction

Figure 4: Subsamples estimations by firms' industry

Note: Fig. 4.A. to Fig. 4.F. present point estimates and confidence intervals for estimating Model 2 for the subsamples HT, MHT, MLT, LT, KIS, and Others using significant (4.A. to 4.C) and insignificant (4.D. to 4.F) environmental product innovations as dependent variable. HT represents firms in high-tech manufacturing, MHT firms in medium-high-tech manufacturing, MLT firms in medium-low-tech manufacturing, LT firms in low-tech manufacturing, KIS firms in knowledge intensive high-tech, market, and financial services, and Others firms in all remaining industries. The industry classification follows the definition of knowledge-intensive services, and high-tech manufacturing from Eurostat (2024).

Innovation output – We split the sample by the novelty of firms' product innovations in terms of primary functionality, as depicted in Figure 5. No Nov. represents firms without product innovations; Product Nov. covers firms with product innovations; Market Nov. includes those with product innovations new to their market; and World Nov. indicates innovations new to the world. Figures 5.A–5.C show that, for significant environmental product innovations, the magnitude and statistical significance of all estimates increase with greater product innovation novelty. For insignificant environmental product innovations, the relevance of voluntary standards declines as novelty rises and becomes statistically insignificant for firms with market and world novelties (Figure 5.D). In the same subsamples, public procurement criteria (Figure 5.E) and its interaction with voluntary standards (Figure 5.F) do not achieve any significance.

These subsample results correspond to an additional test in which we explicitly assume that the novelty of general product innovations serves as a proxy for the maturity of environmental product innovations, distinguishing between late (firm novelties), intermediate (market novelties), and early (world novelties) life-cycle stages. The findings verify our theoretical reasoning, showing that previously identified discomplementarities between public procurement criteria and voluntary standards are stronger for environmental product innovations at earlier life-cycle stages. Thus, our results substantiate the notion that rigid standards embedded in public procurement tenders can disproportionately hinder more early-stage forms of environmental product innovation through lock-in effects.

Estimates for *significant environmental product innovation* by *product innovation novelty*

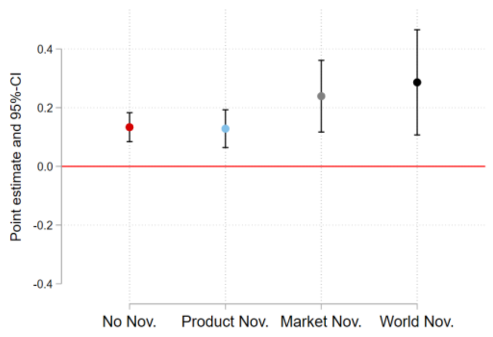

Figure 5.A: Voluntary standards

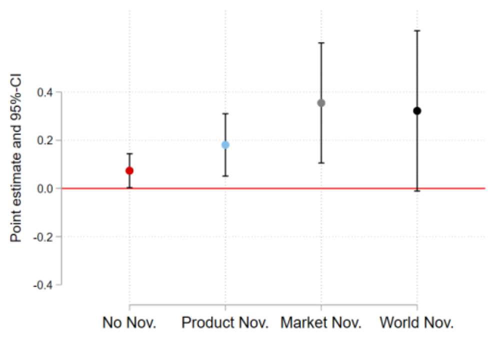

Figure 5.B: Public procurement criteria

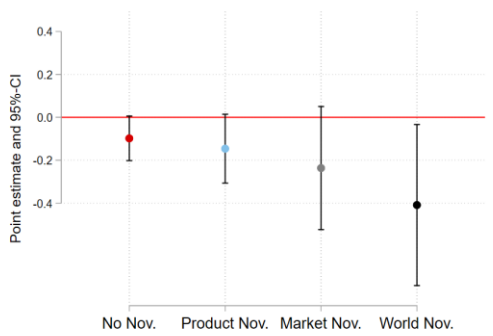

Figure 5.C: Interaction

Estimates for *insignificant environmental product innovation* by *product innovation novelty*

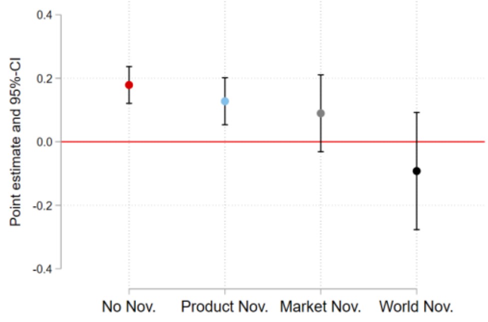

Figure 5.D: Voluntary standards

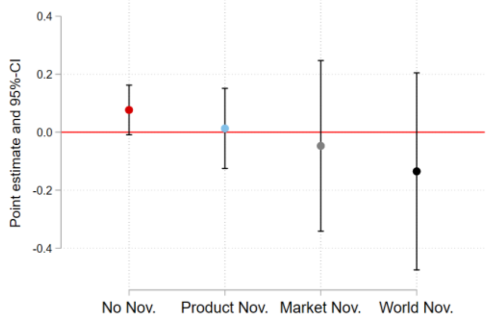

Figure 5.E: Public procurement criteria

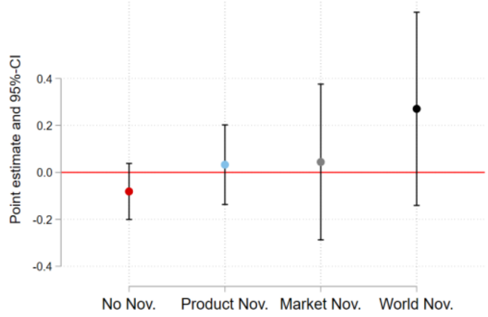

Figure 5.F: Interaction

Figure 5: Subsamples estimations by firms' product innovation novelty

Note: Fig. 5.A. to Fig. 5.F. present point estimates and confidence intervals for estimating Model 2 for the subsamples No Nov., Product Nov., Market Nov., and World Nov. using significant (5.A. to 5.C) and insignificant (5.D. to 5.F) environmental product innovations as dependent variable. No Nov. represents firms without general product innovations, Product Nov. firms with general product innovations, Market Nov. firms with general product innovations new to their market, and World Nov. firms with general product innovations new to the world.

Innovation input – Moreover, we split the sample by firms' innovation intensity. No Input includes those with zero innovation intensity. Remaining firms – those with positive innovation intensity – are divided into quartiles (Q1 Input, Q2 Input, Q3 Input, Q4 Input) from lower to higher intensity. For significant environmental product innovations, voluntary standards gain magnitude and statistical significance as innovation intensity increases (Figure 6.A). Public procurement criteria (Figure 6.B) follow an inverse U-shape, while their interaction with voluntary standards (Figure 6.C) follows a U-shape. For insignificant environmental product innovations, voluntary standards consistently show significance, though without a clear pattern (Figure 6.D). Public procurement criteria and their interaction with voluntary standards do not reach significance in any of these subsamples.

Estimates for *significant environmental product innovation* by *innovation intensity*

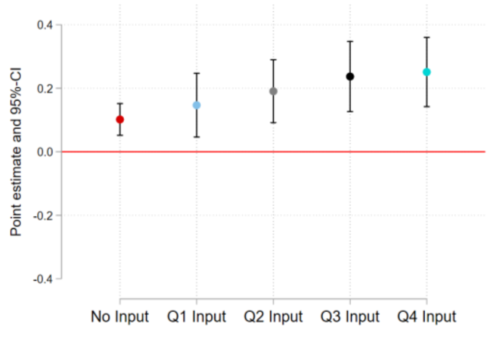

Figure 6.A: Voluntary standards

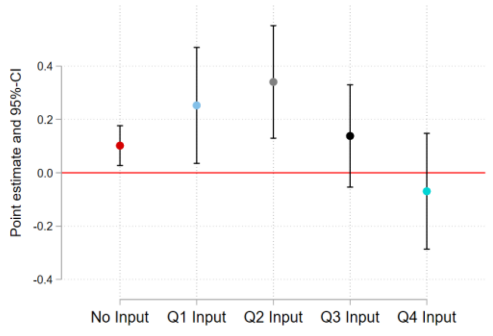

Figure 6.B: Public procurement criteria

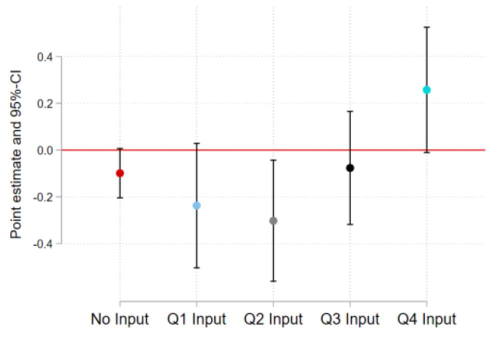

Figure 6.C: Interaction

Estimates for *insignificant environmental product innovation* by *innovation intensity*

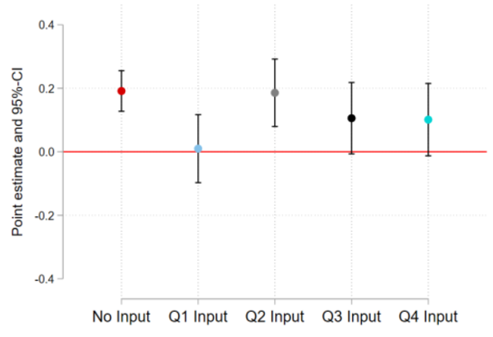

Figure 6.D: Voluntary standards

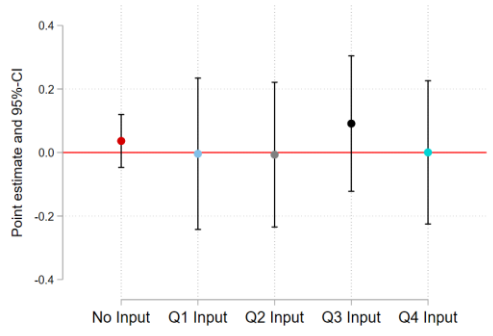

Figure 6.E: Public procurement criteria

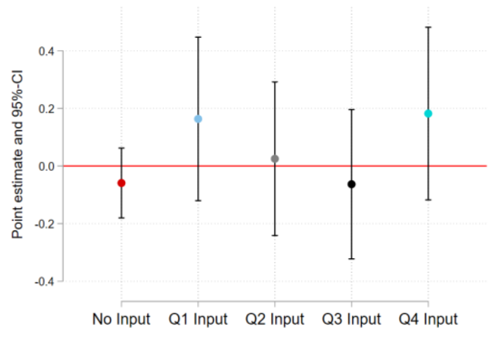

Figure 6.F: Interaction

Figure 6: Subsamples estimations by firms' innovation input intensity

Note: Fig. 6.A. to Fig. 6.F. present point estimates and confidence intervals for estimating Model 2 for the subsamples No Input, Q1 Input, Q2 Input, Q3 Input, and Q4 Input using significant (6.A. to 6.C) and insignificant (6.D. to 6.F) environmental product innovations as dependent variable. No Input represents the firms in our sample with an innovation intensity of zero. The remaining firms in our sample with a positive innovation intensity are equally quartered into Q1 Input, Q2 Input, Q3 Input, and Q4 Input from a lower to a higher intensity. Innovation intensity is measured as firms' innovation expenditures over their revenues.

5. Discussion

We extend the understanding of how public procurement requirements and voluntary standards individually and jointly influence environmental product innovations with varying degrees of environmental significance.

Hypotheses testing – First, consistent with *Hypotheses 1a* and in line with previous research (Krieger & Zipperer, 2022), public procurement requirements positively influence the probability of firms introducing environmental product innovations with high environmental significance, whereas *Hypotheses 1b* – the positive influence on environmental product innovations with low environmental significance – is not supported due the absence of any statistically significant effects. Thus, the market demand created by public procurement requirements seems to support earlier life-cycle environmental product innovations with high environmental significance rather than the diffusion of those at later stages. However, *Hypotheses 1c* – the stronger effect of public procurement requirements on environmental product innovations with high environmental significance – is confirmed as a result.

Second, consistent with *Hypothesis 2*, voluntary standards positively affect the introduction of environmental product innovations with low environmental significance, indicating their supportive role in later stages of the environmental product innovation life cycle by encouraging firms' adherence to established norms in more mature markets (Foucart & Li, 2021). In addition, voluntary standards seem to foster the introduction of environmental product innovations with high environmental significance, too.

Third, in line with Hypothesis 3, we uncover a negative interaction (discomplementarity) when public procurement criteria and voluntary standards are simultaneously important to a firm, limiting the positive impact of public procurement criteria on significant environmental product innovations. Moreover, we do not find an influence on environmental product innovations with a low environmental significance. Thus, the negative effects resulting from the rigid use of voluntary standards seem to surpass the potentially positive effects of their use as flexible benchmarks for environmental product innovations with a high environmental significance.

Effect boundaries – In addition, subsample analyses across firm size, age, industry, and innovation input and output further clarify boundary conditions of our main analysis:

Voluntary standards positively influence significant environmental product innovations across all firm sizes and age groups. Notably, these effects are more pronounced in younger and smaller firms, emphasizing their potential to drive innovation in less established firms. Conversely, public procurement criteria and their interaction with voluntary standards primarily affect larger and older firms. Their significance grows with firm size and age, although statistical relevance tends to diminish for younger firms.

Industry-specific analyses highlight that public procurement requirements and their interaction are particularly effective in stimulating significant environmental product innovations within technology-intensive manufacturing sectors. In contrast, voluntary standards lack a consistent industry-specific pattern, suggesting a broader applicability. Furthermore, examining firms by product innovation novelty reveals that voluntary standards, public procurement criteria, and their interaction become increasingly influential as novelty rises. Finally, firms with higher innovation intensity experience greater benefits from voluntary standards, whereas public procurement criteria and their interaction exhibit nonlinear patterns across different levels of innovation intensity, underlining the complex interplay between innovation inputs and policy instruments.

Mechanism discussion – Voluntary standards promote environmental product innovation across varying degrees of environmental significance. Distinct from public procurement requirements, they positively affect innovations characterized by lower environmental significance. This may be attributed to the role of voluntary standards in facilitating incremental innovation by guiding firms toward conformity with established norms, particularly within mature market contexts (Foucart & Li, 2021). In contrast, the demand generated by public procurement requirements appears better positioned to support the commercialization of environmental product innovations with substantial environmental performance gains, particularly in the early stages of the innovation life cycle, consistent with the mechanism outlined in Hypothesis 1c.

In addition, the positive effects of voluntary standards on environmental product innovations with high environmental performance increases seem to excel. However, the mechanisms behind this net-effect remain multifaceted. Previous research suggests several explanations, including the reduction of uncertainties associated with early-stage innovations through the provision of common terminologies, performance benchmarks, and testing methodologies (Zhang et al., 2020; Rainville, 2017), which help firms align their development efforts with future regulatory or market expectations. Moreover, participation in standardization processes facilitates early access to emerging norms and fosters knowledge exchange among stakeholders within standardization committees (Blind et al., 2022). This collaborative environment not only enhances the efficiency of R&D but also allows firms to shape standards in ways that align with their technological trajectories, potentially accelerating the time-to-market of environmental product innovations with significant environmental benefits. Finally, in early innovation life-cycle stages characterized by openness to design variety and performance maximization (Utterback & Abernathy, 1975), such anticipatory coordination via standards can reduce coordination failures and support the market entrance of novel environmental solutions.

Moreover, to align our conceptual framework on the complementary and discomplementary relations between public procurement requirements and the (rigid/flexible) use of voluntary standards within them with our empirical analysis, we kept the description of our mechanisms broad, abstaining from a detailed account of mechanisms that are difficult to observe empirically. However, within the concept of using (rigid/flexible) voluntary standards in public tenders, there are more detailed mechanisms that could be driving the discomplementary effects we identify.[10]

First, the inclusion of voluntary standards in tenders may constrain variety too early, steering firms toward solutions with smaller performance increases, which are more likely to conform to existing standards (Tsipouri et al., 2010). This inhibits the implementation of more radical environmental product innovations that significantly improve environmental performance

[10] There is a potential alternative mechanism: firms might need to navigate competing pressures between compliance with procurement requirements, adherence to voluntary standards, and the pursuit of novel solutions. This friction is particularly acute for firms with fewer resources introducing new-to-market products, as they may lack the capacity to meet multiple demands simultaneously. As a result, they may opt to submit safer, more standardized bids rather than riskier, more innovative solutions that could otherwise offer significant environmental benefits (Dosi, 1982; Blind et al., 2022). However, the discomplementarities empirically appear less pronounced for smaller firms—those typically facing greater resource constraints. Thus, it seems unlikely that our results are primarily driven by multiple competing pressures.

(Foucart & Li, 2021; Rainville, 2017). In pre-paradigmatic phases of innovation – characterized by performance experimentation (Utterback & Abernathy, 1975) – rigid standards may lock firms into trajectories with low potential to improve environmental performance; reducing long-term innovation potential.

Second, there is the potential for temporal misalignment as source of discomplementarity. Standardization processes typically operate on longer timescales than i) procurement processes, or ii) product innovation development. This might create lags in which innovation fostering standards not yet exist to be included in a tender, while existing standards reflect mature solutions with a high risk of being too rigid (Swann, 2000; Rainville, 2017).

Procurer implications – These findings offer relevant implications for public contracting authorities, particularly with regard to the design and integration of voluntary standards within green public procurement. A simplistic reading of our results might suggest that voluntary standards are ineffective for fostering environmental product innovations with low environmental performance increases, and even counterproductive for innovations with higher environmental significance. However, such a view would misrepresent the underlying mechanisms.

Instead, our analysis underscores a more differentiated interpretation. Voluntary standards possess the potential to foster environmental product innovation across the lifecycle – provided they are selected and applied strategically. This conclusion directly builds on our conceptual distinction between rigid threshold and flexible benchmark uses of standards in public tenders. When standards are used as rigid eligibility criteria, they risk excluding novel solutions and prematurely narrowing the solution space – particularly in early innovation life-cycle stages marked by design variety and experimentation (Utterback & Abernathy, 1975). Conversely, when applied as flexible benchmarks, standards can act as directional signals for innovation, enabling firms to exceed baseline requirements and compete on environmental performance.

To avoid unintended discomplementarities and better align green public procurement with innovation policy objectives, we recommend that public buyers apply Rainville's (2017) lifecycle-oriented procurement framework. This framework emphasizes the alignment of procurement instruments and standard types with the maturity of the targeted environmental innovation. Practically, this involves three steps:

Assess innovation maturity – Determine whether the targeted solution is early- or late-stage. Patent landscape analyses based on functional specifications, combined with early market engagement, can serve as practical tools.

Select suitable procurement instruments – Match instruments such as pre-commercial procurement, public procurement of innovation, or conventional green public procurement with the maturity and novelty of the targeted product.

Integrate standards appropriately – In early stages, avoid over-specification and rigid certification-based standards. Instead, use performance-based criteria that incentivize but do not constrain innovative responses.

More broadly, this interpretation reframes voluntary standards not as fixed requirements, but as potential policy levers that – when appropriately chosen and flexibly implemented – can guide technological change in line with environmental objectives. Our findings, combined with Rainville's (2017) framework, point to the importance of adjusting the mode of standard use to the innovation life-cycle stage and maintaining institutional flexibility. Failure to do so risks discouraging high-impact environmental innovations by locking firms into established trajectories and limiting their ability to propose novel solutions.

Policymaker implications – Moreover, the results of our analysis support existing calls to more carefully account for the diversity of environmental product innovations when evaluating policy effectiveness, both empirically (Caravella & Crespi, 2020) and theoretically (Rainville, 2017). In the context of public procurement requirements and voluntary standards, our findings suggest that improved coordination, sequencing, and institutional guidance may help to strengthen their complementary potential and mitigate risks of discomplementarity (Rainville, 2017; Dosi, 1982; Edquist & Zabala-Iturriagagoitia, 2012).

First, policymakers may consider offering clearer guidance on how to *sequence* policies across the innovation lifecycle. In early stages, green public procurement could be prioritized as a lead market intervention (Edler & Georghiou, 2007), relying on performance-based specifications while avoiding adherence to existing standards. At this point, voluntary standards may be applied with caution – serving, for example, as benchmarks rather than as strict eligibility criteria (Blind et al., 2023; Swann, 2000). In later stages, voluntary standards appear more suitable for codifying environmental expectations, enabling comparability, and supporting broader diffusion (Foucart & Li, 2021; Mangiarotti & Riillo, 2014).

Second, the *combination* of policies may need to be applied selectively, depending on the intended innovation outcome. Our results suggest that the simultaneous use of public procurement requirements and voluntary standards can lead to discomplementarities, particularly in the case of environmental product innovations with high environmental significance. In such settings, the rigid application of certification-based standards may unintentionally constrain innovation by reinforcing trajectories associated with lower performance potential (Krieger et al., 2024; Edquist & Zabala-Iturriagagoitia, 2020). Accordingly, the combined application of both policies may be more appropriate in later innovation stages, where the focus shifts toward supporting more incremental forms of innovation (Czarnitzki et al., 2020).

Third, public contracting authorities may benefit from institutional support, particularly in identifying the life-cycle stage of the targeted products. In addition to individual training, this could include access to shared analytical tools, the establishment of early market consultation procedures (Rainville, 2021), and the development of inter-agency collaboration platforms that link procurement practitioners with relevant stakeholders. Furthermore, contracting authorities may profit from guidance on drafting tenders that are based on functional specifications aligned with user needs (Edquist & Zabala-Iturriagagoitia, 2012; Mazzucato, 2018), as well as on assessing whether voluntary standards are likely to enable or constrain innovation in a given procurement context (Blind et al., 2023).

Finally, public procurement requirements are *not a neutral process*. Rather, they constitute a mechanism through which multiple public objectives – innovation, sustainability, and competitiveness – interact. As such, their design likely necessitates prioritization. Attempting to address several objectives simultaneously, without carefully aligning procurement requirements with the targeted innovation stage and environmental ambition, risks undermining all. By integrating public procurement requirements and voluntary standards in a manner that reflects the maturity of the innovation lifecycle and the expected environmental impact, policymakers can increase the likelihood that both policies operate as complementary, rather than conflicting, components of an effective innovation and environment policy mix.

Firm implications – For firms engaged in environmental product innovation, the results point to the relevance of aligning innovation strategies with the policy instruments most suited to each stage of the innovation life cycle. In particular, firms developing innovations with high environmental significance may benefit from engaging with public procurement opportunities at an early stage, as these can provide critical demand-side support for initial market entry. At the same time, firms should remain attentive to the potential constraints associated with the use of voluntary standards in tenders during this phase, particularly where such standards are applied rigidly. If introduced too early or without adequate flexibility, these standards may restrict design options and limit the scope for more radical forms of innovation.

Incremental, disruptive, and radical innovation – Finally, the previous discussion corresponds with our conceptual distinction between incremental, radical, and disruptive environmental product innovations, as outlined in Appendices A1 and A2.

Incremental environmental product innovations – defined as product iterations with relatively modest environmental performance increases – appear largely unaffected by public procurement requirements, as well as by the discomplementarities identified between them and voluntary standards. This aligns with their emergence in later phases of innovation trajectories, where large performance increases are less likely, and the risks of rigid voluntary standards excluding innovative product iterations are lower.

In contrast*, radical and disruptive environmental product innovations* – both characterized by substantial environmental performance improvements and the potential to render preceding product iterations obsolete – are, on the one hand, likely more vulnerable to the constraints imposed by rigid voluntary standards. In such cases, the interaction between procurement requirements and voluntary standards may prematurely narrow the product space, thereby discouraging the development of individual product iterations with substantial performance increases (radical innovation), or the evolution of innovation trajectories with transformative potential (disruptive innovation). On the other hand, our results indicate that public procurement requirements – when applied without rigid standardization – can offer important demand-side support for such innovations.

6. Conclusion

This paper provides the first quantitative evidence on how public procurement requirements and voluntary standards – individually and jointly – affect firms' introduction of environmental product innovations, distinguishing between innovations with high and low environmental significance. The findings offer a more nuanced understanding of how demand-side policies influence environmental innovation outcomes across different stages of the product innovation life cycle.

First, public procurement requirements increase the likelihood that firms introduce environmentally significant product innovations. This underscores the important role of procurement in enabling early-stage innovations that deliver substantial improvements in environmental performance and are characterized by higher levels of radicalness and disruptiveness.

Second, voluntary standards promote the introduction of environmental product innovations across both ends of the environmental significance spectrum. They thus support i) more incremental innovations at later stages of the innovation life cycle and ii) more radical and disruptive innovations at earlier stages, depending on how they are applied.

Third, and most notably, we find that the combined importance of public procurement requirements and voluntary standards reduces the likelihood that firms introduce environmentally significant product innovations. This discomplementarity is consistent with a lock-in mechanism: when voluntary standards are implemented rigidly within tenders – as fixed eligibility thresholds rather than as flexible benchmarks – they narrow the solution space and thereby diminish the effectiveness of procurement requirements in stimulating more radical and disruptive innovations at earlier life-cycle stages.

These results carry several implications. For public buyers, they highlight the importance of aligning the procurement process with the maturity of the targeted product. Functional and performance-based approaches may be more appropriate for early-stage solutions, whereas rigid standardization should be avoided. For policymakers, our findings support calls for a more nuanced use of policy mixes, including improved coordination and sequencing of procurement and standardization efforts. For firms, particularly those developing early-stage innovations, it is essential to assess how voluntary standards are applied in public tenders – a rigid use might exclude their innovative products, while a more flexible use might reward them.

These findings should be interpreted in light of several limitations:

First, the indirect method used to assess the life-cycle stage of environmental product innovations introduces uncertainty. We rely on the environmental significance of product innovations reported by firms as a proxy, which may not fully capture their underlying maturity. Future research could address this limitation by developing or using datasets that more precisely trace the life-cycle stages of environmental product innovations.

Second, we are unable to observe the specific types of voluntary standards referenced in tenders, nor how they are integrated into procurement processes. This limits our ability to empirically distinguish between rigid and flexible uses. Further work is needed to develop monitoring instruments that capture not only whether voluntary standards are important to a firm, but also how they are implemented and function within a public tender.

Third, although we control for a wide range of firm-level and contextual variables, concerns about endogeneity remain. Future studies could draw on longitudinal data or employ instrumental variable techniques to better isolate causal effects.

Fourth, our analysis focuses on the interaction between public procurement and voluntary standards, but other policy instruments – such as subsidies, tax incentives, or environmental regulations (Stojčić, 2021) – may also interact with or moderate their effects. Exploring these additional combinations would offer a more complete understanding of how policy mixes shape environmental product innovation.

Fifth, the relationship between public procurement, voluntary standards, and environmental product innovation might vary across national contexts. Institutional differences in regulatory priorities, market structures, and administrative capacities may influence how standards are applied and procurement processes are designed. For instance, more economically developed countries prioritize sustainability in their public tenders more often (Rosell, 2021) and are likely to have more mature institutional frameworks, greater administrative capacity, and stronger enforcement mechanisms that enhance the effectiveness of both procurement and standard-setting in promoting environmental product innovation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT4o and ChatGPT4.5 in order to improve the writing of the paper. Also, it was used to unify the format of the references. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Appendix A – Extension of conceptual framework

A.1. New-to-the-world, -market, and -firm (environmental) product innovation

This product innovation trajectory framework can be extended to further distinguish between new-to-the-market and new-to-the-world (environmental) product innovations, as defined by the European Community Innovation Survey. A new-to-the-market innovation refers to a product introduced for the first time within a firm's operational market. In contrast, a new-to-the-world innovation is introduced globally, regardless of market context.

In this adaptation, the origin node – the first product iteration at the intersection of functional and environmental performance – represents a new-to-the-world (environmental) product innovation, marking its initial implementation across all markets. Subsequent nodes represent follow-on iterations that may qualify as new-to-the-market innovations, depending on whether they are novel within the adopting firm's specific market. As a result, this classification is context-dependent; however, as product iterations diffuse across operational markets, the likelihood that a given iteration qualifies as new-to-the-market declines with each successive generation.

Figure A1 illustrates how market-specific innovation trajectories can emerge from different points within the broader product space. The world market trajectory begins at the origin node, representing the global first implementation of the product. Firm A's market (red) and firm B's market (orange) reflect market-specific trajectories that originate from product iterations four generations removed from the original world-market novelty, each continuing along different branches. The origin node of each market trajectory marks the first adoption of a specific product iteration – derived from the global trajectory – within the respective market of firm A or firm B.[11]

The figure thus demonstrates the decentralized nature of market novelty. Markets may enter the product innovation space at different generation stages and from different branches, depending on when and where specific iterations are introduced. Each node, therefore, has the potential to serve as the starting point of a new market-specific trajectory. Consequently, identifying whether a product iteration constitutes a market novelty requires an

[11] Moreover, it is possible that an individual market trajectory does not necessarily just span an individual branching from its original market novelty as illustrated in "Market of firm A,", but that product iteration from other branches, than the original market novelty, can enter a market too, as illustrated in "Market of firm B.".

understanding of both its absolute position within the global product innovation trajectory and its relative novelty within the specific market of the adopting firm.

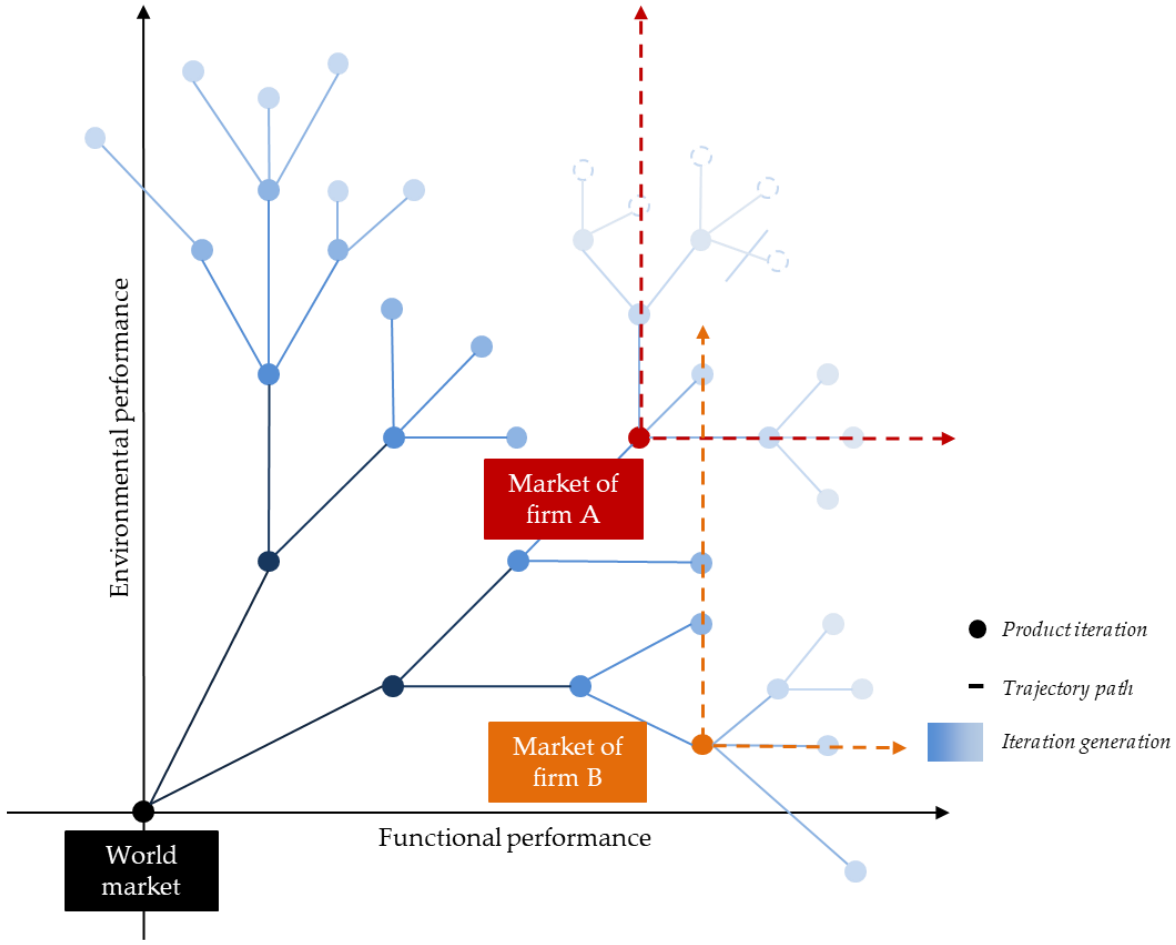

Figure A1: Environmental product innovation trajectory with different markets

Note: Each node represents a product iteration implemented by at least one firm. The color shading reflects the generational stage of each iteration, with lighter hues indicating greater maturity along the innovation life cycle. The trajectory paths connecting nodes visualize performance changes between iterations. Environmental product innovations, as a subcategory of product innovation, are characterized by improvements in the vertical dimension (environmental performance), whereas product innovation can generally reflect changes in functional (horizontal axis) and environmental (vertical axis) performance. Firms may costly enter or exit the different branches of the innovation trajectory at various stages. Market-specific innovation trajectories are highlighted by their additional vertical and horizontal axes in red and orange.

A.2. Incremental, radical and disruptive (environmental) product innovation

Finally, incremental, radical, and disruptive (environmental) product innovations can be illustrated within our conceptual derivation, too. Within this framework, incremental product innovations are represented by short branches between nodes – indicating smaller improvements in one or both performance dimensions – within later iteration generation. These refinements typically involve the optimization of solutions. As such, they rather reflect new-to-the-firm, than new-to-the-market or new-to-the-world market product innovation.

Disruptive environmental product innovations, in contrast, initiate new trajectories by entering niche markets. These innovations often underperform in terms of mainstream functional criteria at first but offer superior environmental performance potential (Figure A2, orange trajectory). Over time, through successive performance improvements in environmental and functional performance, they surpass the performance of the original innovation trajectory (Figure A2, blue trajectory) and challenge its viability; potentially transforming or displacing the trajectory (Christensen, 1997; Johnstone & Kivimaa, 2018).

Radical (environmental) product innovations differ in their mode of entry. Rather than emerging gradually from niche markets, they enter directly with a significant discontinuous performance improvement (Figure A3, orange trajectory). These innovations typically originate from innovation breakthroughs and represent a paradigm shift that has the potential to renders the previously dominant trajectory performance (Figure A3, blue trajectory) obsolete (Dosi, 1982; Tushman & Anderson, 1986; Garcia & Calantone, 2002). They do not need to be, but can be directly connected to a product iteration of the original trajectory.

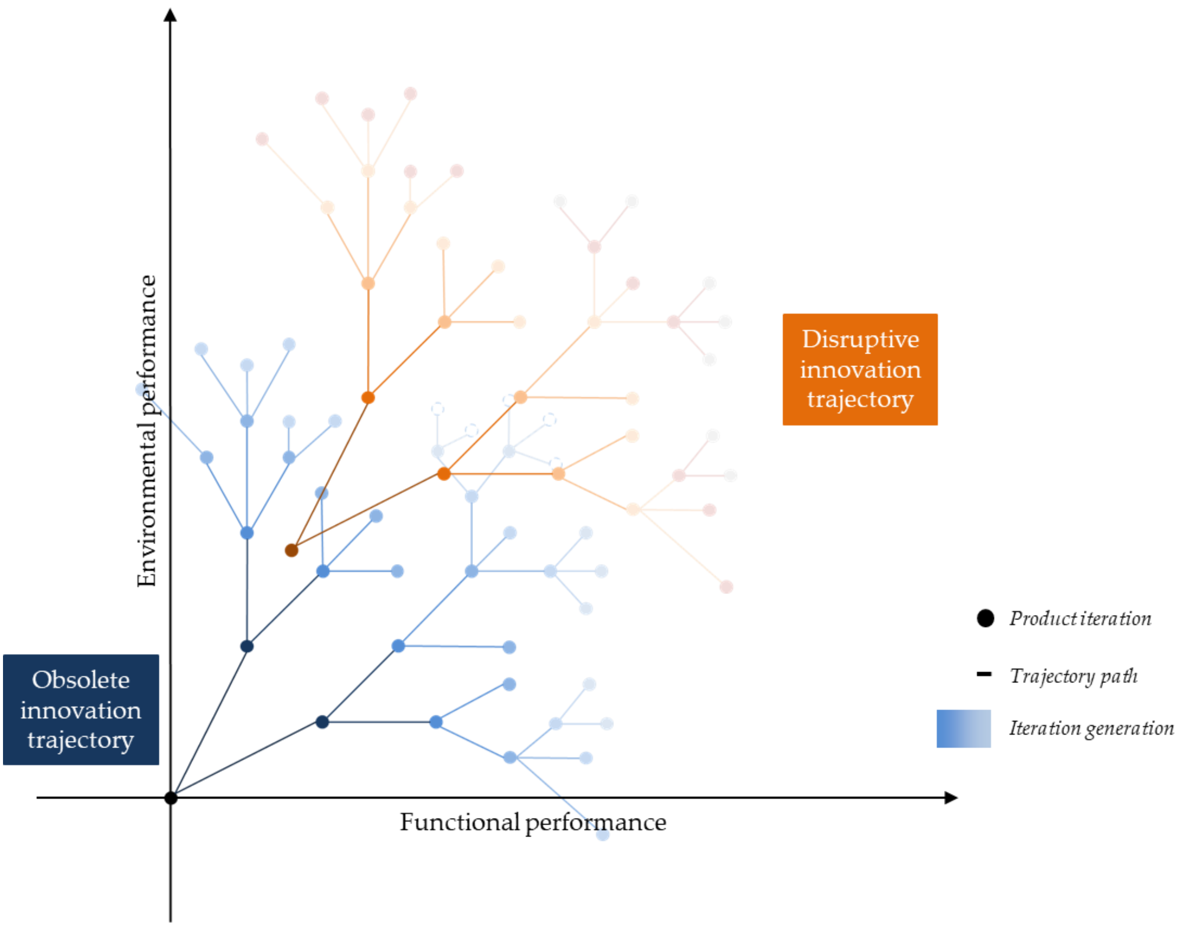

Figure A2: Environmental product innovation trajectory with different markets

Note: Each node represents a product iteration implemented by at least one firm. The color shading reflects the generational stage of each iteration, with lighter hues indicating greater maturity along the innovation life cycle. The trajectory paths connecting nodes visualize performance changes between iterations. Environmental product innovations, as a subcategory of product innovation, are characterized by improvements in the vertical dimension (environmental performance), whereas product innovation can generally reflect changes in functional (horizontal axis) and environmental (vertical axis) performance. Firms may costly enter or exit the different branches of the innovation trajectory at various stages. The additional disruptive innovation trajectory is highlighted in orange.

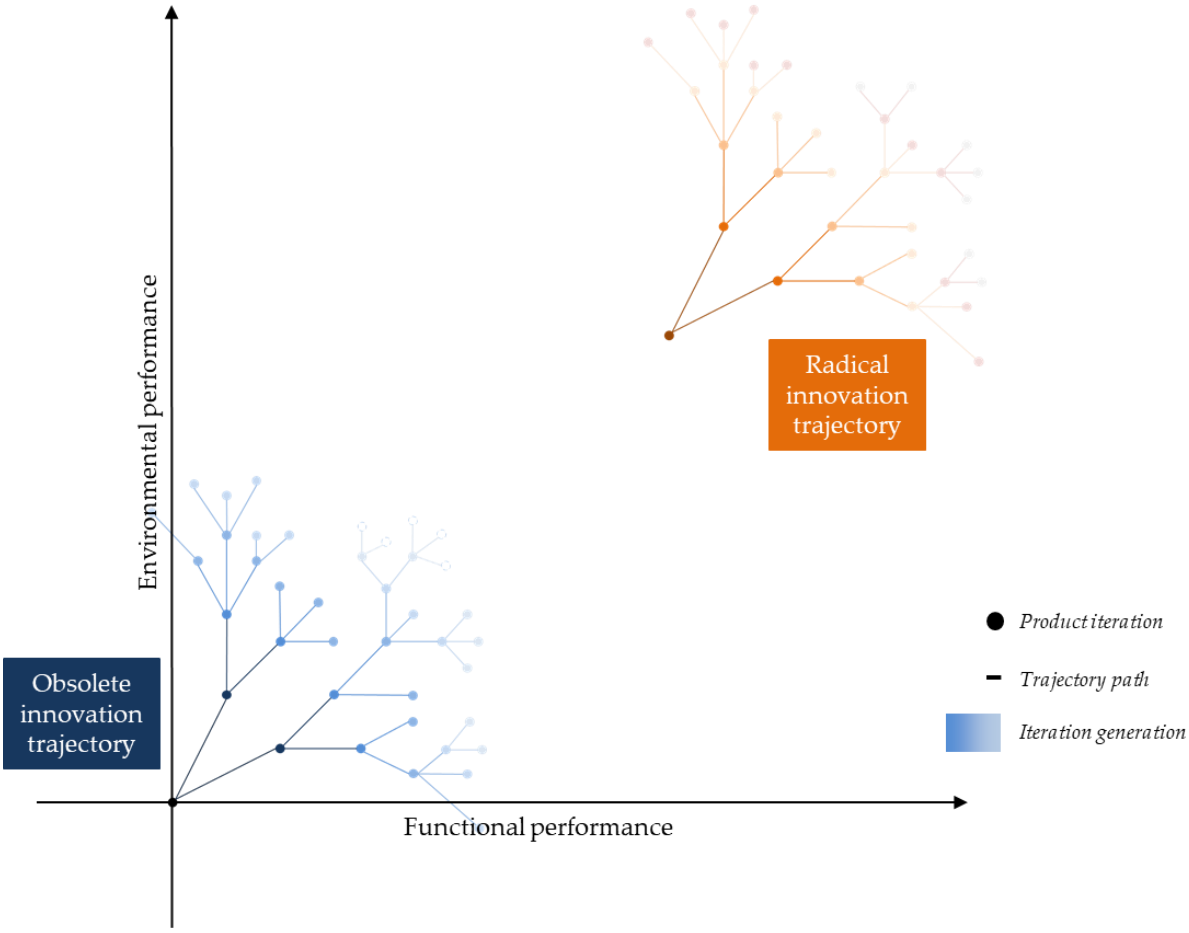

Figure A3: Environmental product innovation trajectory with different markets

Note: Each node represents a product iteration implemented by at least one firm. The color shading reflects the generational stage of each iteration, with lighter hues indicating greater maturity along the innovation life cycle. The trajectory paths connecting nodes visualize performance changes between iterations. Environmental product innovations, as a subcategory of product innovation, are characterized by improvements in the vertical dimension (environmental performance), whereas product innovation can generally reflect changes in functional (horizontal axis) and environmental (vertical axis) performance. Firms may costly enter or exit the different branches of the innovation trajectory at various stages. Market-specific innovation trajectories are highlighted by their additional vertical and horizontal axes in red and orange.

In summary, the extended innovation trajectory framework offers a nuanced understanding of environmental product innovation by integrating functional and environmental performance dimensions. It distinguishes between new-to-the-market and new-to-the-world innovations, emphasizing the context-dependent nature of novelty and the decentralized, multi-branch structure of market-specific adoption paths. Environmental product innovations are conceptualized as a subcategory of product innovations, with improvements along the environmental performance axis. The framework also accommodates different innovation types: incremental innovations refine existing trajectories through small improvements;

disruptive innovations enter from niche markets and gradually overtake dominant trajectories; and radical innovations emerge abruptly through breakthrough performance shifts, potentially rendering previous trajectories obsolete. Together, this approach captures the diverse paths through which (environmental) product innovations evolve after their commercialization, and reshape product markets over time.

Appendix B: Correlation matrix

Table B1: Correlation matrix

Variable name	ID	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
Significant environmental product innovation (0/1)	**A**	1																	
Insignificant environmental product innovation (0/1)	**B**	0.2	1.0																
Voluntary standards (0/1)	**C**	0.3	0.3	1.0															
Public procurement criteria (0/1)	**D**	0.2	0.2	0.4	1.0														
Vol. stand.#pub. pro. crit. (0/1)	**E**	0.2	0.2	0.5	0.8	1.0													
Innovation expenditures/revenues	**F**	0.1	0.1	0.0	0.0	0.0	1.0												
Continuous internal R&D (0/1)	**G**	0.2	0.2	0.2	0.0	0.1	0.3	1.0											
Occasional internal R&D (0/1)	**H**	0.1	0.1	0.1	0.0	0.0	0.0	-0.2	1.0										
Ln(employees as FTE)	**I**	0.2	0.2	0.2	0.1	0.1	-0.1	0.3	0.0	1.0									
ln(age in years)	**J**	0.0	0.1	0.1	0.0	0.0	-0.1	0.0	0.0	0.2	1.0								
Company group (0/1)	**K**	0.1	0.1	0.1	0.1	0.1	0.0	0.2	0.1	0.4	0.1	1.0							
Export revenues (0/1)	**L**	0.2	0.2	0.2	0.0	0.0	0.1	0.4	0.2	0.3	0.1	0.2	1.0						
Regulation or taxes (0/1)	**M**	0.3	0.3	0.5	0.4	0.3	0.0	0.2	0.1	0.3	0.1	0.2	0.2	1.0					
Public funding (0/1)	**N**	0.2	0.2	0.3	0.4	0.4	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.4	1.0				
Substitutable products (0/1)	**O**	0.0	0.1	0.1	0.0	0.0	-0.1	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.0	1.0			
Market entry competition (0/1)	**P**	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.4	1.0		
Foreign competition (0/1)	**Q**	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.0	0.2	0.1	0.1	0.3	0.1	0.1	0.2	0.3	1	
High price competition (0/1)	**R**	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.3	0.3	0.3	1

Appendix C: Robustness tests

As a first robustness test, we examine the validity of our results using an alternative definition of voluntary standards and public procurement criteria. More precisely, we re-estimate our baseline estimations, redefining voluntary standards and public procurement criteria as one if they have high importance and zero otherwise. Columns (1) and (2) in Tables C1 (for significant environmental product innovations) and C2 (for insignificant environmental product innovations) present the estimation results. In sum, our results remain robust. First, we find statistically significant positive net relations of highly important voluntary standards and public procurement criteria with significant environmental product innovations (Table C1, Column 1), whereas their joint high importance is negatively related to significant environmental product innovations (Table C1, Column 2). Second, we find that high importance of voluntary standards is positively net-related to insignificant environmental product innovations (Table C2, Column 1). Also, highly important public procurement criteria and their interaction with highly important voluntary standards remain statistically insignificant. Thus, compared to our baseline results in Table 3, the same estimates are statistically significant with the same sign.

To test for differences in the magnitude of our estimates, we run a seemingly unrelated regression (SUR) framework. This framework treats the regressions from Tables C1 and C2 and their counterparts from Table 3 as parts of a larger system, pooling their estimates and covariance matrices, which allows for a joint Wald test of differences in the relevant coefficients. Columns (3) and (4) in Tables C1 and C2 display the differences in the estimates compared to Table 3. For significant environmental product innovations, the magnitude of all estimates increased when focusing on voluntary standards and public procurement criteria with high importance. However, only the difference in the net relation of voluntary standards is statistically significant at the ten percent level (Table C1, Column 3). All other differences for significant environmental product innovations are statistically insignificant. For insignificant environmental product innovations, we find that the magnitude of all estimates decreased. Most notably, the positive relationship between standards and insignificant environmental product innovations weakened when concentrating on highly significant environmental product innovations. The same applies to the estimates for public procurement criteria, though they remain statistically insignificant different from zero in both Table 3 and

Table C2. In sum, the results for significant environmental product innovations appear to be more strongly driven by the high importance of voluntary standards and public procurement criteria, whereas the results for insignificant environmental product innovations seem to be influenced more by their medium importance.

Table C1: Voluntary standards and public procurement requirements with high importance and significant environmental product innovation

Dependent variable:	Significant environmental product innovation (0/1)			
Factor importance:	High importance			
Estimation model:	Model 1	Model 2	Model 1	Model 2
Difference estimation:			TB1 – T3	TB1 – T3
Column #:	(1)	(2)	(3)	(4)
Public procurement criteria (0/1)	0.10***	0.16***	D: 0.04	D: 0.03
	(0.04)	(0.05)	P: 0.22	P. 0.55
Voluntary standards (0/1)	0.18***	0.20***	D: 0.04*	D: 0.04
	(0.03)	(0.03)	P: 0.07	P: 0.07
Voluntary standards# pub. proc. Criteria (0/1)		-0.15*		D: −0.03
		(0.08)		P: 0.68
Innovation expenditures/ revenues	0.08*	0.07*		
	(0.04)	(0.04)		
Continuous internal R&D (0/1)	0.15***	0.15***		
	(0.02)	(0.02)		
Occasional internal R&D (0/1)	0.10***	0.10***		
	(0.02)	(0.02)		
Ln(employees as FTE)	0.00	0.00		
	(0.00)	(0.00)		
ln(age in years)	-0.02***	-0.02***		
	(0.01)	(0.01)		
Company group (0/1)	-0.01	-0.01		
	(0.01)	(0.01)		
Export revenues (0/1)	0.03**	0.03**		
	(0.01)	(0.01)		
Regulation or taxes (0/1)	0.12***	0.12***		
	(0.01)	(0.01)		
Public funding (0/1)	0.11***	0.11***		
	(0.02)	(0.02)		
Substitutable products (0/1)	-0.00	-0.00		
	(0.01)	(0.01)		
Market entry competition (0/1)	-0.01	-0.01		
	(0.01)	(0.01)		
Foreign competition (0/1)	0.00	0.00		
	(0.01)	(0.01)		
High price competition (0/1)	0.01	0.01		
	(0.01)	(0.01)		
R-squared	0.19	0.19	n.a.	n.a.
Observations	5,127	5,127	n.a.	n.a.

Note: Estimates in Columns (1) and (2) are based on pooled OLS. Heteroscedasticity-robust standard errors in parentheses. Industry and state fixed effects are included. Both columns classify only a high importance of voluntary standards and public procurement criteria as “1” for the dichotomous variables, rather than grouping high or medium importance together. The levels of p-values correspond to * p<0.1, ** p<0.05, *** p<0.01.
Columns (3) and (4) compare the derived coefficients for voluntary standards and public procurement criteria with our baseline results in Table 3 using a seemingly unrelated regression (SUR) framework. This approach treats the separate regressions as parts of a larger system and pools their estimates and covariance matrices, allowing a joint Wald test of the differences in the relevant coefficients. Columns (3) and (4) display the difference (D:) between Table B1 (TB1) and Table 3 (T3) as well as the significance level (P:) from that joint test.

Table C2: Voluntary standards and public procurement criteria with high importance and insignificant environmental product innovation

Dependent variable:	Insignificant environmental product innovation (0/1)			
Factor importance:	High importance			
Estimation model:	Model 1	Model 2	Model 1	Model 2
Difference estimation:			TB2 – T3	TB2 – T3
Column #:	(1)	(2)	(3)	(4)
Public procurement criteria (0/1)	-0.04 (0.04)	-0.05 (0.05)	D: –0.07** P: 0.03	D: –0.09* P. 0.05
Voluntary standards (0/1)	0.08*** (0.03)	0.08*** (0.03)	D: –0.07*** P: 0.01	D: –0.07*** P: 0.01
Voluntary standards# pub. proc. criteria (0/1)		0.03 (0.08)		D: 0.05 P: 0.54
Innovation expenditures/ revenues	0.07 (0.05)	0.07 (0.05)		
Continuous internal R&D (0/1)	0.17*** (0.02)	0.17*** (0.02)		
Occasional internal R&D (0/1)	0.14*** (0.02)	0.14*** (0.02)		
Ln(employees as FTE)	0.03*** (0.00)	0.03*** (0.00)		
ln(age in years)	0.01 (0.01)	0.01 (0.01)		
Company group (0/1)	-0.01 (0.02)	-0.01 (0.02)		
Export revenues (0/1)	0.00 (0.02)	0.00 (0.02)		
Regulation or taxes (0/1)	0.22*** (0.02)	0.22*** (0.02)		
Public funding (0/1)	0.03 (0.02)	0.03 (0.02)		
Substitutable products (0/1)	0.02 (0.01)	0.02 (0.01)		
Market entry competition (0/1)	0.01 (0.01)	0.01 (0.01)		
Foreign competition (0/1)	0.02 (0.02)	0.02 (0.02)		
High price competition (0/1)	-0.01 (0.01)	-0.01 (0.01)		
R-squared	0.15	0.15	n.a.	n.a.
Observations	5,127	5,127	n.a.	n.a.

Note: Estimates in Columns (1) and (2) are based on pooled OLS. Heteroscedasticity-robust standard errors in parentheses. Industry and state fixed effects are included. Both columns classify only a high importance of voluntary standards and public procurement criteria as "1" for the dichotomous variables, rather than grouping high or medium importance together. The levels of p-values correspond to * p<0.1, ** p<0.05, *** p<0.01.

Columns (3) and (4) compare the derived coefficients for voluntary standards and public procurement criteria with our baseline results in Table 3 using a seemingly unrelated regression (SUR) framework. This approach treats the separate regressions as parts of a larger system and pools their estimates and covariance matrices, allowing a joint Wald test of the differences in the relevant coefficients. Columns (3) and (4) display the difference (D:) between Table B1 (TB2) and Table 3 (T3) as well as the significance level (P:) from that joint test.

As a second robustness test, we use entropy balancing to control for potential confounding variables outside of the regression.[12] We define our treatment groups separately as $PP_i * ST_i = 1$, $PP_i = 1$, and $ST_i = 1$, and the corresponding control groups as $PP_i * ST_i = 0$, $PP_i = 0$, and $ST_i = 0$. Consequently, i) we estimate three distinct sets of weights, one for each treatment group, and ii) run separate weighted regressions for each treatment group. Each control group is balanced based on the mean, variance, and skewness of its weighting variables. In each regression, the three variables $PP_i * ST_i$, PP_i, and ST_i are treated as fully flexible dichotomous variables and included directly in all weighted regressions. It is not possible to use them within the weighting as i) PP_i and ST_i are never zero for $PP_i * ST_i = 1$, ii) $PP_i * ST_i$ is never one for $ST_i = 0$, and iii) $PP_i * ST_i$ is never one for $SP = 0$.

Table C3 presents the mean differences between control variables for firms considering voluntary standards as important ($ST_i = 1$) and firms not considering voluntary standards as important ($ST_i = 0$). Before the balancing, there are clear differences in means, whereas these virtually disappear after applying the estimated balancing weights. A similar pattern is observed for firms considering public procurement criteria as important ($PP_i = 1$) or as not important ($PP_i = 0$) in Table C4, as well as for firms considering voluntary standards and public procurement criteria jointly as important ($PP_i * ST_i = 1$) or not ($PP_i * ST_i = 0$) in Table C5. The success of the balancing is further confirmed by regressing each treatment variable on the balancing variables using a probit model. Before weighting the samples, the balancing variables show a high joint significance level of 0.00 in each case. After weighting, the variables become jointly insignificant, with a p-value of 1.00 in each case. Moreover, each variable used for weighting is statistically insignificant.

Table C6 demonstrates the robustness of our results. The estimates of public procurement criteria and voluntary standards, as well as the estimates of their interaction, are similar in magnitude and statistical significance compared to our previous results in Table 3 across all specifications.

[12] This follows the same ideas as the matching procedure of Stojčić (2021) investigating different policies and their effect on environmental innovations.

Table C3: Mean differences between balancing variables before and after entropy balancing: Balancing on voluntary standards (0/1)

Variable	$ST_i = 1$	$ST_i = 0$ *unweighted*	$ST_i = 0$ *weighted*	Differences *unweighted*	Differences *weighted*
Innovation expenditures/revenues	0.05	0.04	0.05	0.01	0.00
Continuous internal R&D (0/1)	0.39	0.21	0.39	0.18	0.00
Occasional internal R&D (0/1)	0.14	0.09	0.14	0.05	0.00
Ln(employees as FTE)	3.76	2.91	3.76	0.86	0.00
ln(age in years)	3.27	3.15	3.27	0.12	0.00
Company group (0/1)	0.44	0.28	0.44	0.15	0.00
Export revenues (0/1)	0.54	0.36	0.54	0.18	0.00
Regulation or taxes (0/1)	0.74	0.24	0.74	0.50	0.00
Public Funding (0/1)	0.36	0.08	0.36	0.28	0.00
Substitutable products (0/1)	0.57	0.50	0.57	0.07	0.00
Market entry competition (0/1)	0.46	0.39	0.46	0.07	0.00
Foreign competition (0/1)	0.44	0.30	0.44	0.14	0.00
High price competition (0/1)	0.51	0.41	0.51	0.10	0.00

Table C4: Mean differences between balancing variables before and after entropy balancing: Balancing on public procurement criteria (0/1)

Variable	$PP_i = 1$	$PP_i = 0$ *unweighted*	$PP_i = 0$ *weighted*	Differences *unweighted*	Differences *weighted*
Innovation expenditures/revenues	0.04	0.04	0.04	0.00	0.00
Continuous internal R&D (0/1)	0.30	0.25	0.30	0.06	0.00
Occasional internal R&D (0/1)	0.14	0.10	0.14	0.04	0.00
Ln(employees as FTE)	3.59	3.05	3.59	0.54	0.00
ln(age in years)	3.24	3.17	3.24	0.07	0.00
Company group (0/1)	0.41	0.31	0.41	0.10	0.00
Export revenues (0/1)	0.42	0.40	0.42	0.02	0.00
Regulation or taxes (0/1)	0.82	0.30	0.82	0.53	0.00
Public Funding (0/1)	0.48	0.10	0.49	0.38	0.00
Substitutable products (0/1)	0.55	0.51	0.55	0.04	0.00
Market entry competition (0/1)	0.47	0.40	0.47	0.07	0.00
Foreign competition (0/1)	0.40	0.32	0.40	0.07	0.00
High price competition (0/1)	0.53	0.42	0.53	0.12	0.00

Table C5: Mean differences between balancing variables before and after entropy balancing: Balancing on voluntary standards#public procurement criteria (0/1)

Variable	$PP_i * ST_i = 1$	$PP_i * ST_i = 0$ *unweighted*	$PP_i * ST_i = 0$ *weighted*	Differences *unweighted*	Differences *weighted*
Innovation expenditures/revenues	0.05	0.04	0.05	0.01	0.00
Continuous internal R&D (0/1)	0.33	0.25	0.33	0.08	0.00
Occasional internal R&D (0/1)	0.14	0.10	0.14	0.04	0.00
Ln(employees as FTE)	3.76	3.06	3.75	0.70	0.00
ln(age in years)	3.27	3.18	3.27	0.09	0.00
Company group (0/1)	0.43	0.31	0.43	0.12	0.00
Export revenues (0/1)	0.46	0.39	0.46	0.07	0.00
Regulation or taxes (0/1)	0.90	0.32	0.90	0.58	0.00
Public Funding (0/1)	0.58	0.11	0.58	0.47	0.00
Substitutable products (0/1)	0.55	0.51	0.55	0.04	0.00
Market entry competition (0/1)	0.48	0.40	0.48	0.08	0.00
Foreign competition (0/1)	0.43	0.32	0.43	0.10	0.00
High price competition (0/1)	0.53	0.42	0.53	0.10	0.00

Table C6: Voluntary standards and public procurement requirements with entropy balancing

	Dependent variable:	Significant Environmental product Innovation		Insignificant Environmental product Innovation	
	Estimation model:	Model 1	Model 2	Model 1	Model 2
	Column #:	(1)	(2)	(3)	(4)
(A)	Voluntary standards (0/1)	0.12***	0.15***	0.11***	0.11***
		(0.02)	(0.02)	(0.02)	(0.02)
(B)	Public procurement criteria (0/1)	0.06**	0.11***	0.04	-0.01
		(0.03)	(0.03)	(0.03)	(0.04)
(C)	Voluntary standards# pub. proc. Criteria (0/1)		-0.17***		-0.01
			(0.06)		(0.06)
	Observations	5,125	5,125	5,125	5,125

Note: Estimates are based on pooled OLS regressions with heteroscedasticity-robust standard errors in parentheses. Industry and state fixed effects are included. Lines (A), (B), and (C) represent separate regressions, each treating the displayed independent variable as the treatment. As a result, different observations are classified as treated and non-treated across regressions, with control group weights applied based on Hainmueller (2012). * p<0.1 ** p<0.05 *** p<0.01

Appendix D: Empirical limitations

Measurement

Environmental product innovation – As mentioned above, we cannot observe the introduced environmental product innovations from the perspective of a firm. In general, databases on the introduction of environmental innovations are rare (Ghisetti, 2017; Stojčić, 2021). Furthermore, at this point, there is no database combining our concept of environmental product innovations build on innovation trajectories, public procurement criteria, and voluntary standards. The analysis of green patents does not pose a viable option either. First, public procurement criteria and standards, do not focus on the development of technologies. They rather focus on the characteristics of products (Kristensen et al., 2021). Second, firms applying for green patents are rare (e.g., Krieger & Zipperer, 2022), and distinguishing green patents with respect to their novelty would result in even smaller numbers of firms being active in less or more novel green patenting. As a result, the required statistical power for the analysis of green patents as the dependent variable is, besides that they are not the ideal dependent variable in any case, not present. Consequently, in sum, we consider in-/significant environmental product innovations at the firm level as best available proxy for our concept of environmental product innovations with high or low environmental performance increases.

Public procurement requirements and voluntary standards – We aim to examine the interaction of public procurement requirements and voluntary standards and its relationship with environmental product innovations. Measuring both, i) the existence of criteria and ii) their inclusion of voluntary standards, at the level of public procurement tenders would be optimal. However, at this point, there is no database allowing for such an analysis in a larger quantitative manner, namely larger than an analysis broader than smaller regions, a selection of public authorities, or specific industries. The analysis of Krieger and Zipper (2022), for instance, indicates that the share of firms winning tenders registered in the Tenders Electronic Daily database is between 0.5 percent and 1.5 percent in Germany. Furthermore, of their identified tenders with environmental criteria, only 11.9 clearly contained environmental standards, and the majority of environmental criteria were too broad for an identification of standards. This limited occurrence and identifiability of standards in public procurement tenders prevents an analysis with the Tenders Electronic Daily database and similar datasets.

As a result, investigating the simultaneous importance of standards and public procurement criteria at the level of the firm poses the best viable option. First, it makes the reasonable assumption of public procurement criteria and voluntary standards at the tender level to be correlated with public procurement criteria and voluntary standards at the firm level. Second, as the discussed correlation between the tender and firm level is not perfect, our previous analysis rather underestimates than overestimates the identified relationships.

Endogeneity

The three main sources of endogeneity in our analysis are omitted variables, self-selection, and reverse causality. In total, we consider the risk of endogeneity driving our results as low. The reason for this is i) that previous literature suggests our controls to cover the most important confounding variables, and ii) that the bias resulting from self-selection or reverse causality would most potentially be positive, however, our coefficient of the interaction of voluntary standards and public procurement requirements is negative.

Omitted variables – We consider the risk of omitted variables affecting our i) procurement, ii) standard, and iii) environmental product innovation variables, as low. Czarnitzki et al. (2020) find that their results for innovative public procurement barely change between using control variables in a cross-sectional setup similar to ours, or using firm-level fixed effects taking time-constant unobservable differences between firms into account in a panel setup. Moreover, Krieger and Zipperer (2022) find no time-constant difference between firms winning large green public procurement tenders at some point and firms not winning green public procurement tenders at some point. Thus, the results of both papers suggest the absence of unobservable differences after taking similar control variables as ours into account. Furthermore, similar to Blind et al. (2022), we control for the most relevant potential confounders related to standards and firm innovation.

Self-selection – The descriptive statistics in Table 2 demonstrate that firms considering public procurement requirments and voluntary standards as important have the highest average probability to introduce any kind of our investigated environmental product innovations. Moreover, these statistics are in line with the reasonable assumption of more innovative firms considering more factors as important to their introduction of environmental product innovations.[13] Thus, we expect the self-selection bias of firms into considering both factors as important to be positive, in case we are not able to fully consider it within our control variables. As a result, it would rather reduce our found discomplementary between voluntary standards and public procurement requirements.

Reverse causality – It is likely there is a circular relationship between introducing environmental product innovation and considering voluntary standards and public procurement criteria as important. However, as for self-selection, the bias resulting from reverse causality in our case can be expected to be positive. Firms become more environmentally innovative and as a result, they consider more factors important for their introduction of environmental product innovations, and inversely. A negative circular relationship indicating that becoming more environmentally innovative reduces the joint importance of the two factors seems less probable, in particular, while having a positive relationship with the factors' individual importance as in our case. Thus, we also expect the reverse causality bias between environmental product innovations and the importance of public procurement criteria and voluntary standards to be positive. Consequently, it would rather reduce our found discomplementarity, too.

[13] This assumption is in line with the findings of Stojčić (2021), who investigates a mixture of other public policies and their importance to implement environmental innovations.

Appendix E: Subsample estimations using Model 1

Estimates for *significant environmental product innovation* by *employee number*

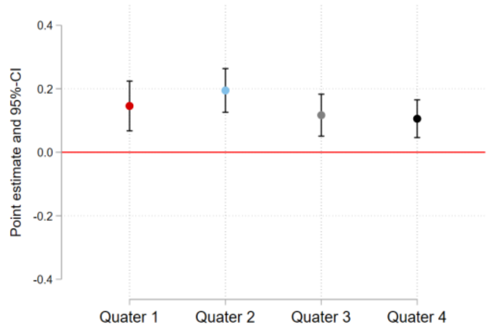

Figure E1.A: Voluntary standards

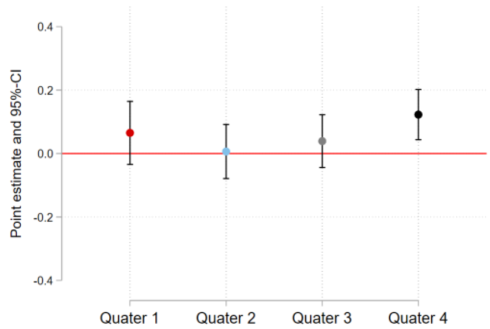

Figure E1.B: Public procurement criteria

Estimates for *insignificant environmental product innovation* by *employee number*

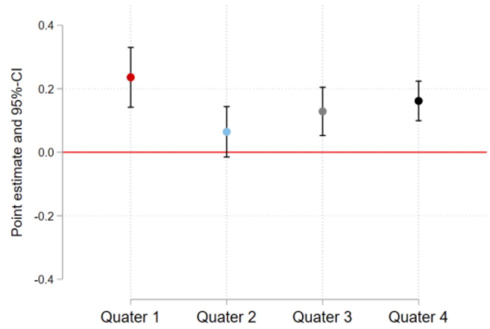

Figure E1.C: Voluntary standards

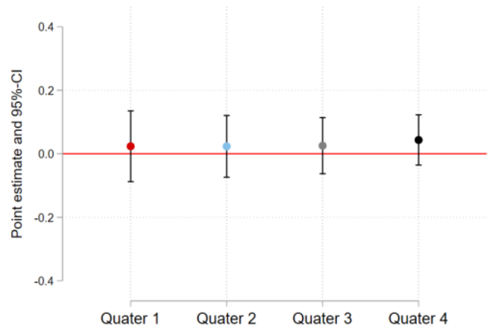

Figure E1.D: Public procurement criteria

Figure E1: Subsamples estimations by firms' employee number without interaction

Note: Fig. E1.A. to Fig. E1.D. present point estimates and confidence intervals for estimating Model 1 for the subsamples Quarter 1 to 4 using significant (E1.A. to E1.B) and insignificant (E1.C. to E1.D) environmental product innovations as dependent variable. Quarter 1 to 4 represent our equally quartered sample according to firms' employee number ordered from a lower to a higher number.

Estimates for *significant environmental product innovation* by *age in years*

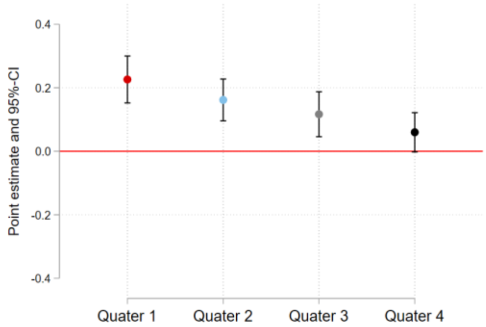

Figure E2.A: Voluntary standards

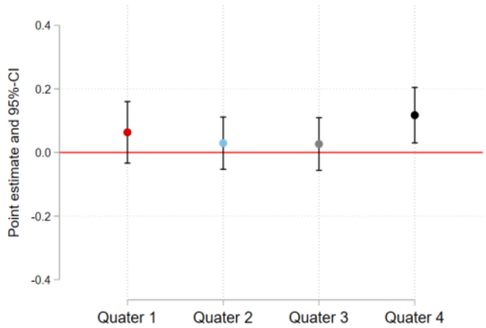

Figure E2.B: Public procurement criteria

Estimates for *insignificant environmental product innovation* by *age in years*

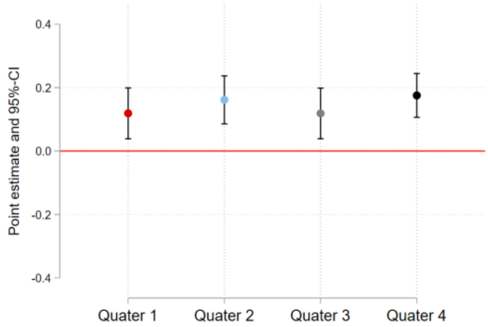

Figure E2.C: Voluntary standards

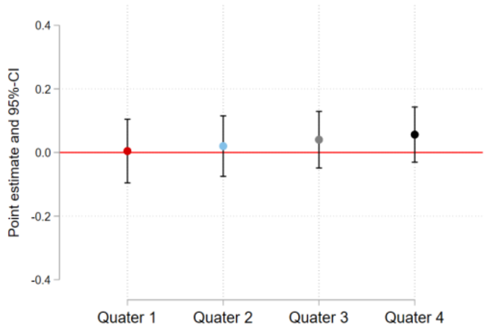

Figure E2.D: Public procurement criteria

Figure E2: Subsamples estimations by firms' age in years without interaction

Note: Fig. E2.A. to Fig. E2.D. present point estimates and confidence intervals for estimating Model 1 for the subsamples Quarter 1 to 4 using significant (E2.A. to E2.B) and insignificant (E2.C. to E2.D) innovations as dependent variable. Quarter 1 to 4 represent our equally quartered sample according to firms' age in years ordered from a younger to an older age.

Estimates for *significant environmental product innovation* by *employee number* and *firm age in years*

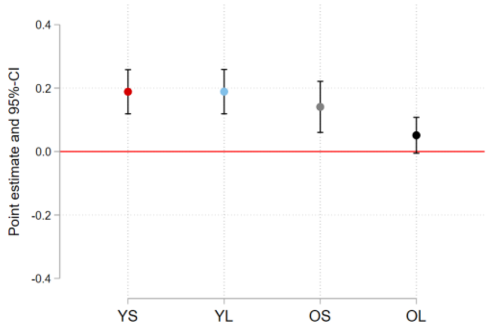

Figure E3.A: Voluntary standards

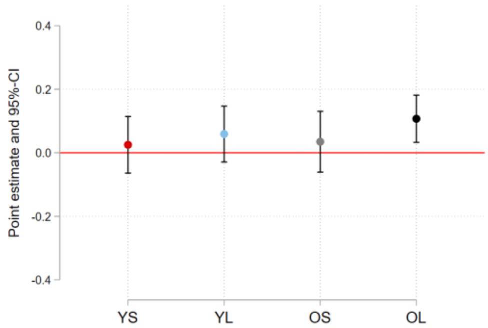

Figure E3.B: Public procurement criteria

Estimates for *insignificant environmental product innovation* by *employee number* and *firm age in years*

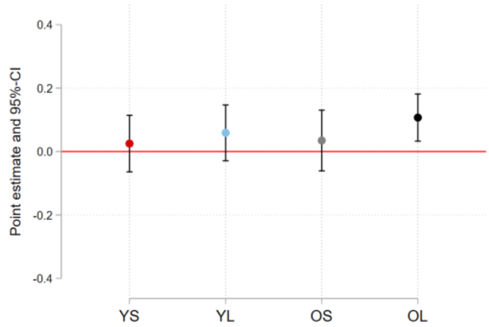

Figure E3.C: Voluntary standards

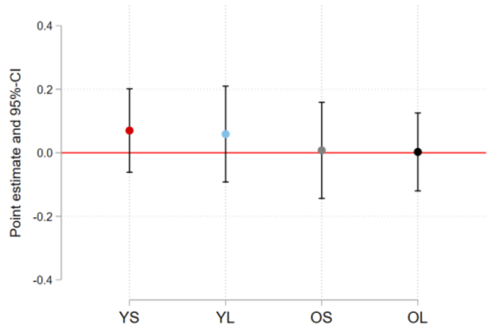

Figure E3.D: Public procurement criteria

Figure E3: Subsamples estimations by firms' employee number and age in years

Note: Fig. E3.A. to Fig.ED3.D. present point estimates and confidence intervals for estimating Model 1 for the subsamples YS, YL, OS, and OL using significant (E3.A. to E3.B) and insignificant (E3.C. to E3.D) environmental product innovations as dependent variable. The sample is quartered according to the median age in years, and median number of employees in our sample. YS covers firms in the younger and smaller median, YL firms in the younger and larger median, OS firms in the older and smaller median, and OL firms in the older and larger median.

Estimates for *significant environmental product innovation* by *industry*

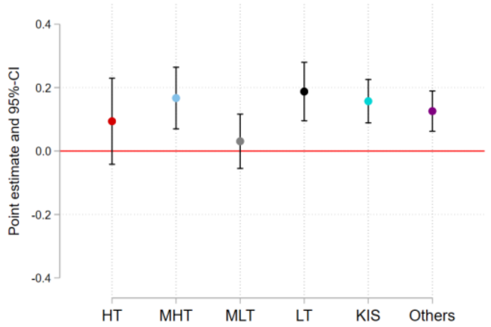

Figure E4.A: Voluntary standards

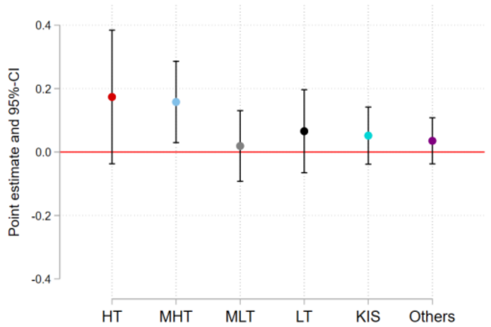

Figure E4.B: Public procurement criteria

Estimates for *insignificant environmental product innovation* by *industry*

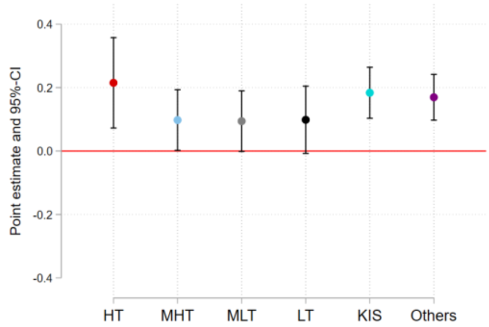

Figure E4.C: Voluntary standards

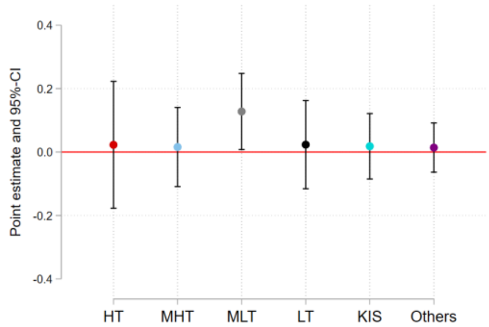

Figure E4.D: Public procurement criteria

Figure E4: Subsamples estimations by firms' industry without interaction

Note: Fig. E4.A. to Fig. E4.D. present point estimates and confidence intervals for estimating Model 1 for the subsamples HT, MHT, MLT, LT, KIS, and Others using significant (E4.A. to E4.B) and insignificant (E4.C. to E4.D) environmental product innovations as dependent variable. HT represents firms in high-tech manufacturing, MHT firms in medium-high-tech manufacturing, MLT firms in medium-low-tech manufacturing, LT firms in low-tech manufacturing, KIS firms in knowledge intensive high-tech, market, and financial services, and Others firms in all remaining industries. The industry classification follows the definition of knowledge-intensive services, and high-tech manufacturing from Eurostat (2024).

Estimates for *significant environmental product innovation* by *product innovation novelty*

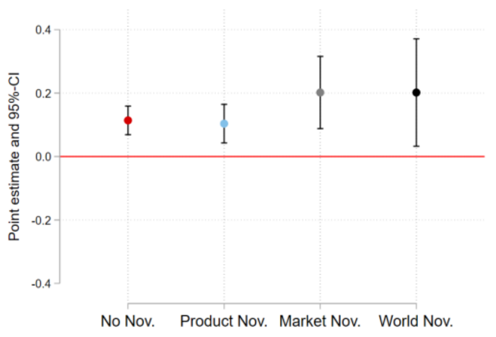

Figure E5.A: Voluntary standards

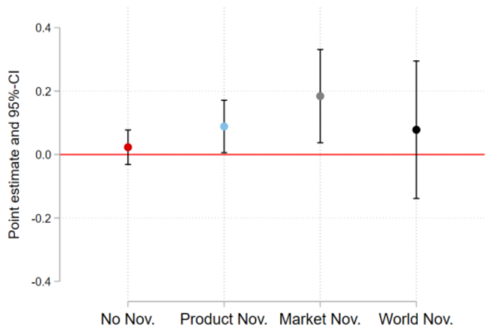

Figure E5.B: Public procurement criteria

Estimates for *insignificant environmental product innovation* by *product innovation novelty*

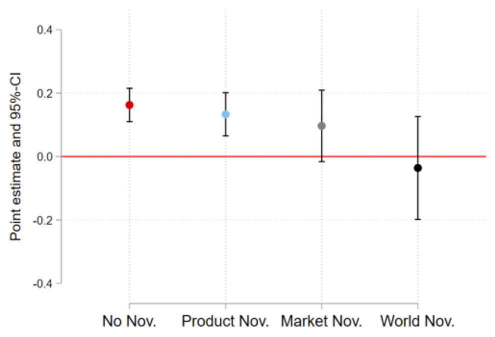

Figure E5.C: Voluntary standards

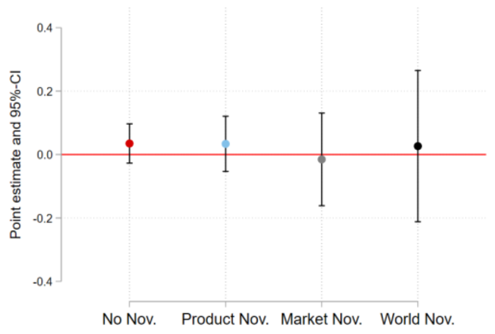

Figure E5.D: Public procurement criteria

Figure E5: Subsamples estimations by firms' product innovation novelty without interaction

Note: Fig. E5.A. to Fig. E5.D. present point estimates and confidence intervals for estimating Model 1 for the subsamples No Nov., Product Nov., Market Nov., and World Nov. using significant (E5.A. to E5.B) and insignificant (E5.C. to E5.D) environmental product innovations as dependent variable. No Nov. represents firms without general product innovations, Product Nov. firms with general product innovations, Market Now. firms with general product innovations new to their market, and World Nov. firms with general product innovations new to the world.

Estimates for *significant environmental product innovation* by *innovation intensity*

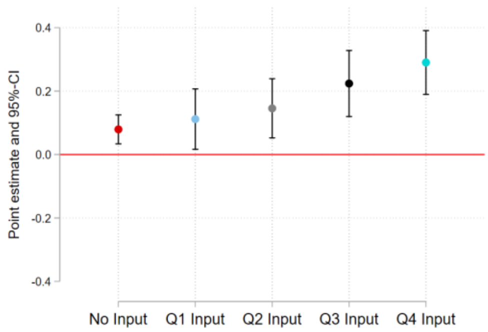

Figure E6.A: Voluntary standards

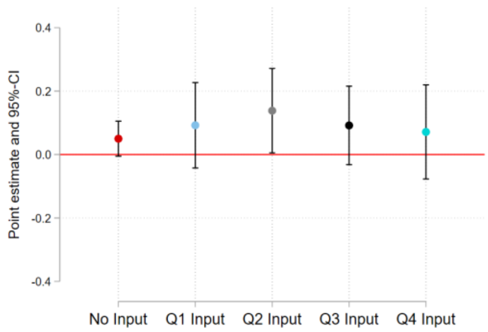

Figure E6.B: Public procurement criteria

Estimates for *insignificant environmental product innovation* by *innovation intensity*

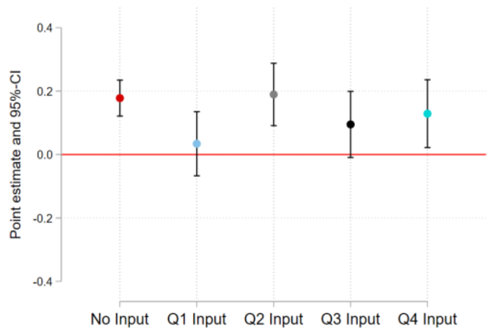

Figure E6.C: Voluntary standards

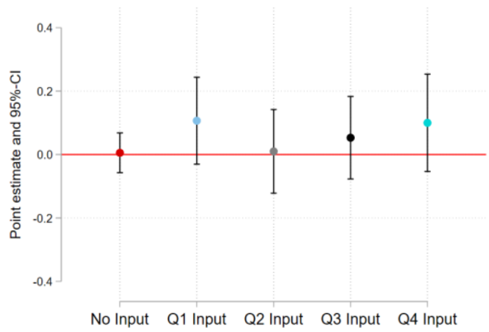

Figure E6.D: Public procurement criteria

Figure D6: Subsamples estimations by firms' innovation input intensity without interaction

Note: Fig. E6.A. to Fig. E6.D. present point estimates and confidence intervals for estimating Model 1 for the subsamples No Input, Q1 Input, Q2 Input, Q3 Input, and Q4 Input. using significant (E6.A. to E6.B) and insignificant (E6.C. to E6.D) environmental product innovations as dependent variable. No Input represents the firms in our sample with an innovation intensity of zero. The remaining firms in our sample with a positive innovation intensity are equally quartered into Q1 Input, Q2 Input, Q3 Input, and Q4 Input from a lower to a higher intensity. Innovation intensity is measured as firms' innovation expenditures over their revenues.

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