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Unraveling the impacts of green knowledge spillovers on SMEs' green innovation, economic performance, and exporting: evidence from Germany

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Green innovation is critical for the green transition, yet little is known about green knowledge spillovers across industries. Based on the knowledge-spillovers literature and using empirical evidence from German manufacturing small- and medium-sized enterprises (SMEs) during 2009–2019, this analysis reveals that SMEs benefit from horizontal green knowledge spillovers to boost green innovation and from backward spillovers to enhance productivity and profitability. SMEs can leverage these green innovations to expand into international markets through exporting. These effects vary across industries and sub-national locations.

JEL Classification: L10, L20, O12, O33, Q56, R11

1. Introduction

Green innovation refers to products, services, or processes that limit the harm, impact, and deterioration of the environment while optimizing the use of resources (Schiederig *et al*., 2012). Encouraging the development and utilization of green innovation is a cornerstone of sustainable development strategies (Perruchas *et al*., 2020). The growing disparity in opportunities to develop green innovation and the potential to impede sustainable development are pressing concerns for both academics and policymakers (Mealy and Teytelboym, 2020). Green innovation can enhance firm performance, particularly by offsetting the costs associated with stringent environmental standards (Porter and van der Linde, 1995). It can improve process efficiency through the use of recycled inputs, better utilization of by-products, and the conversion of waste into more valuable forms (Bryson *et al*., 2024). Additionally, green innovation can increase revenue by differentiating products, selling pollution control technologies, and reducing raw material and energy costs (Ambec and Lanoie, 2008). Firms require green innovation to meet market and regulatory demands or expectations, and to enter new markets (Martínez-Ros and Merino, 2023).

The existing literature predominantly focuses on the creation of green innovation (Becchetti *et al*., 2022), the impacts of green innovation on firms' economic performance (Leoncini *et al*., 2019; Kesidou *et al*., 2024), green entrepreneurship (Colombelli and Quatraro, 2019), and environmental benefits along value chains (Costantini *et al*., 2017). There is a limited understanding of the external economic impacts of green innovation on other firms' innovation and economic development, with a few exceptions in the form of case studies (Hansen and Hansen, 2020). Research on green knowledge spillovers between green innovation creators and recipients often assumes that both parties possess patents (Dechezleprêtre *et al*., 2014), overlooking the significant potential of spillovers that benefit firms without patents.

This article investigates how green innovation can generate knowledge spillovers that indirectly affect other small- and medium-sized enterprises (SMEs) in terms of innovation, economic performance, and opportunities to expand internationally through exports. It examines whether these knowledge spillovers occur horizontally or via backward and forward linkages. The empirical work is based on a sample of 8552 German manufacturing SMEs during 2009–2019. Germany, a green transition pioneer, is one of the world's leading countries for per capita green patents, with a competitive advantage in wind and solar photovoltaic technologies (Pegels and Lütkenhorst, 2014). SMEs face technological and demand uncertainties associated with green innovation production, as well as limitations in their internal technological capabilities and financial resources to develop green innovation in-house (Cecere *et al*., 2020). These factors could impede SMEs from switching to greener production (Kannan *et al*., 2022). Against this backdrop, the critical question is how SMEs can utilize green knowledge spillovers to enhance performance in the green transition.

This article follows the mainstream definition of green innovation based on patents that have International Patent Classification codes listed in the World Intellectual Property Organization Green Inventory, or their Cooperative Patent Classification codes listed as "Greenly Sound Technologies" according to Organisation for Economic Co-operation and Development (OECD) OECD (2016) (Perruchas *et al*., 2020; Moreno and Ocampo-Corrales, 2022). Green innovation knowledge spillovers are generated following the seminal work of Javorcik (2004), which has been widely applied (Hansen and Hansen, 2020; Wu *et al*., 2023). The method uses coefficients from Input–Output Tables to capture vertical knowledge spillovers through inter-industry intermediate product transactions as well as horizontal knowledge spillovers via the presence of knowledge producers in the same industry as the focal firm. We find that SMEs benefit from horizontal green knowledge spillovers in green innovation production. Green knowledge spillovers from green innovation producers in upstream industries enhance SMEs' productivity and profitability in downstream industries via backward linkages. Green innovation increases SMEs' likelihood and intensity of exporting.

This article makes three key contributions. First, our granular analysis enhances the understanding of green knowledge spillovers, even for firms not engaged in in-house green innovation production. Prior studies have primarily focused on the economic benefits of green technologies for their producers (Colombelli *et al*., 2020; Martínez-Ros and Merino, 2023). Despite the high novelty and broad applicability of green innovation across various industries (Barbieri *et al*., 2020), its substantial potential to generate knowledge spillovers has been largely overlooked (e.g., Dechezleprêtre *et al*., 2014; Colombelli and Quatraro, 2019). This study addresses this gap by examining the broader impacts of green knowledge spillovers on SME performance. Understanding these benefits is critical to highlight the need for focused research and additional policy support to advance the green transition (Becchetti *et al*., 2022).

Second, our analysis considers different channels of green knowledge spillovers. This approach allows us to explicitly investigate various aspects of firms' developmental needs. We argue that the mechanisms of knowledge spillovers vary by the nature of the knowledge, which determines knowledge compatibility across industries, and whether the knowledge sets focus on the factor market or product market of the focal firms' operations (Un and Asakawa, 2015). Consequently, green knowledge spillovers via intra- and inter-industry channels could have distinct effects on firms' green innovation and economic performance.

Third, our analysis provides a comprehensive understanding of how SMEs can leverage green knowledge spillovers to autonomously develop capacity in green innovation, enhance economic performance, and facilitate international expansion through exporting. Existing studies have predominantly focused on top-down and bottom-up approaches in green technological catch-up, often using case studies of large firms (Lema *et al*., 2020; Zhou *et al*., 2020; Becchetti *et al*., 2022; Lema *et al*., 2024). They emphasize the significance of accumulated technological capacity, the ability to conduct mergers and acquisitions, build international connections, or establish overseas research centers for technological advancement (Dai *et al*., 2020; Hansen and Hansen, 2020).

However, these strategies are often challenging for SMEs to implement. Our article addresses this gap by highlighting the necessity to complement existing research with an examination of how SMEs can autonomously identify and utilize green knowledge spillovers to drive innovation and economic performance in the green transition, supported by large-scale microlevel evidence.

The rest of this article is structured as follows. Section 2 explains the theoretical framework underpinning this research. Section 3 reviews the literature and develops the hypotheses. Section 4 describes the datasets and empirical models. Section 5 reports the findings, followed by an analysis of heterogeneous effects across industries and sub-national locations. Section 6 discusses the results, and Section 7 concludes.

2. Theoretical framework

Regional economies consist of interconnected organizations sharing knowledge, machinery, and methods. Knowledge flows both tacitly and explicitly between companies through continuous interactive and collective learning. This learning arises from various spillovers, including information and knowledge facilitated by customers, trade associations, suppliers, consultants, and employees changing employers (Bryson and Daniels, 2006). The knowledge-spillovers theory posits that knowledge is non-rival and can spill over to others, creating economic value in diverse applications (Arrow, 1962). Complex and tacit knowledge is best transmitted through face-to-face interactions and repeated communication (Von Hippel, 1994). Therefore, local proximity to knowledge producers is critical for firms to benefit from knowledge spillovers (Audretsch and Feldman, 1996; Billing *et al*., 2024). The Marshall–Arrow–Romer theories suggest that firms can benefit from spillovers through co-location with knowledge-producing firms. Co-location enables firms to share specialized suppliers, access a wider range of differentiated intermediate inputs, and tap into a large pool of skilled workers, efficiently matching labor with firms requiring specific skills (Marshall, 1920; Glaeser and Resseger, 2010). Furthermore, firms can imitate and compete with external knowledge producers, internalizing knowledge related to new production inputs and market preferences (Duranton and Puga, 2004).

Knowledge spillovers are important for firms' innovation and economic performance through interactions with competitors, customers, suppliers, and labor turnover (Roper *et al*., 2017). Empirical evidence confirms the positive effects of knowledge spillovers on innovation and economic performance (Audretsch and Belitski, 2020; Hansen and Hansen, 2020).

Green innovation generates knowledge spillovers along value chains and improves environmental performance in vertically related industries (Gilli *et al*., 2014; Costantini *et al*., 2017; Ghisetti and Quatraro, 2017). However, the impact of green knowledge spillovers on innovation and economic performance remains unclear. This article proposes that green knowledge spillovers are particularly important for SMEs for three reasons.

First, green technologies are characterized by high technological uncertainty, which requires innovators to acquire new knowledge beyond their existing realms (De Marchi, 2012). Consequently, green technology production relies more on external knowledge sources than non-green technologies (Horbach *et al*., 2013). SMEs, which face significant resource constraints, depend heavily on external knowledge to innovate and remain competitive (Hervas-Oliver *et al*., 2020). Knowledge spillovers provide SMEs with access to various green knowledge subsets, helping them overcome internal limitations.

Second, green technologies typically have broader objectives and require a more complex range of knowledge elements than non-green technologies (Barbieri *et al*., 2020). The integration of diverse and multidisciplinary knowledge needed for green technologies can be challenging for SMEs with limited in-house expertise (Cecere *et al*., 2020). Green knowledge spillovers allow SMEs to access innovative ideas and practices from other firms and industries, enabling them to adopt and develop new green technologies.

Third, prior studies highlight the potential for greater knowledge spillovers from green technologies due to their diversified technological bases and applications across a broad range of industries (Battke *et al*., 2016). This indicates that green knowledge spillovers could benefit SMEs from various industries.

In summary, green knowledge spillovers are particularly relevant for SMEs due to their resource constraints, the need for enhanced innovation capabilities, and the potential economic benefits from green innovation. By understanding and leveraging green knowledge spillovers, SMEs can overcome their limitations and develop capacity for the green transition.

3. Hypotheses development

3.1 Horizontal green knowledge spillovers

Technologies aimed at improving efficiency, such as clean production, rely on multidisciplinary knowledge to modify industrial design and engineering mechanisms (Marzucchi and Montresor, 2017). To adopt green technologies, firms often need to change components or raw materials, modify technical integration with external partners, and link new knowledge with their existing base (De Marchi, 2012). However, firms adopting green innovation may lack the knowledge to alter production processes. Interactive learning is crucial for firms to acquire and integrate externally sourced knowledge into their operations (Tubiana *et al.*, 2022). Firms that have adopted green innovation can demonstrate its benefits, generating positive knowledge spillovers (Fritsch and Kauffeld-Monz, 2010). Green innovation can stimulate further innovation among co-located SMEs. The frequent introduction of new green technologies creates competition, encouraging SMEs to accelerate green innovation or engage in reverse engineering (Song *et al.*, 2013).

Labor mobility can transfer green knowledge from green innovation-producing firms to others (Burger *et al.*, 2019). This includes recruiting staff trained by competitors, using the same business service providers and equipment suppliers, and transferring knowledge through friendships and acquaintances (Bryson and Daniels, 2006). Green knowledge providers must understand client operations to identify opportunities to improve processes and infrastructure efficiency, such as energy utilization (Koirala, 2019). Skills related to green knowledge are critical for green product design, adopting clean production approaches, developing collaborative strategies with suppliers, and understanding customers' needs (Vona *et al.*, 2015). Such knowledge and skills can be disseminated through labor turnover, helping other firms adopt green practices and technologies.

3.2 Vertical green knowledge spillovers

Green innovation typically encompasses a more diverse knowledge base and incorporates more technological components than non-green innovation. It is also more frequently cited across a broader spectrum of technological domains in subsequent patents (Barbieri *et al.*, 2020). As such, green innovation is increasingly critical for successive technological development and has wide applicability across different industries (Pearson and Foxon, 2012; Popp and Newell, 2012). These characteristics suggest that green innovation could generate significant economic benefits across a wide range of industries.

First, collaboration between green technology suppliers and users can disseminate green innovation along value chains, maximizing benefits for both parties across industries (Neffke *et al.*, 2011). Continuous interactions with suitable green innovation providers help firms acquire new green knowledge that may be distant from their core expertise, enabling users to realize the economic benefits of adopting green innovation (Ghisetti *et al.*, 2015). In industries that frequently produce customized products, small downstream firms rely heavily on acquiring tacit green knowledge and information from primary green technology suppliers (Hansen and Hansen, 2020).

Second, downstream industries facing stringent regulatory frameworks or rising production costs may need to alter their production processes to achieve cleaner production. The demand for new environmentally friendly technologies and intermediate inputs can trigger green innovation in upstream suppliers (Antonelli, 1998). In turn, upstream suppliers can differentiate themselves from competitors by offering downstream buyers green technology-based intermediate inputs. The interactions between the production and adoption of green innovation can ultimately enhance green innovation and economic performance along value chains (Ghisetti and Quatraro, 2017).

Third, suppliers and buyers of intermediate products can jointly develop sorting and collection technologies for waste management. Waste can be reused, and products at the end of their life cycle can be recycled to capture value, helping industries along value chains reduce costs and improve efficiency (McKinsey, 2016).

There is a limited understanding of the importance of green knowledge spillovers for SMEs. Faced with resource constraints, SMEs can reduce costs and risks by acquiring green knowledge from external sources (Kapetaniou and Lee, 2019). Accessing external green knowledge can compensate for the lack of internal investment in its development (Ghisetti *et al*., 2015). Compared to large firms, SMEs are particularly challenged by the technological uncertainty associated with the feasibility and functionality of green innovation, which can lead to underinvestment in green innovation production (Aranda-Usón *et al*., 2019). Demand uncertainty hinders the creation and utilization of green innovation, as the direct link between green innovation and commercialization can be unpredictable (Feng *et al*., 2016).

Intra-industry learning between firms producing green innovation and SMEs that do not necessarily engage in in-house green innovation activities can generate knowledge spillovers for the latter. This process alleviates the demand and technological uncertainty related to the imitation, creation, and implementation of green innovation for SMEs. Moreover, SMEs tend to rely extensively on supply chains to achieve economic goals (Hervas-Oliver *et al*., 2020). Green knowledge, particularly knowledge related to improving efficiency, tends to be multidisciplinary and may be distant from an SME's core knowledge (Marzucchi and Montresor, 2017). Inter-industry learning from green innovation-producing suppliers is important for SMEs as it encourages the adoption of green technologies, leading to enhanced innovation and economic performance.

In summary, green knowledge spillovers are vital external knowledge sources supporting SMEs' green innovation production and economic efficiency. Without assuming whether such benefits arise from horizontal or vertical linkage channels, we follow the literature to measure innovation production by the likelihood and intensity of innovation (Rezende *et al*., 2019) and economic performance by firm productivity and profitability (Vasileiou *et al*., 2022). This leads to the following hypotheses:

Hypothesis 1a: *Green knowledge spillovers are positively related to the green innovation production of SMEs.*

Hypothesis 1b: *Green knowledge spillovers are positively related to the economic performance of SMEs.*

3.3 Green innovation and international expansion through exporting

To arrive at a more comprehensive understanding of the effects of green knowledge spillovers, the next hypothesis examines how SMEs can leverage such green knowledge spillovers through international expansion via exporting. This means that the green knowledge and practices acquired from other firms or industries can be integrated into their own operations, leading to SMEs developing autonomous capacity to exploit economic benefits from their own green innovation.

First, green innovations can open up new markets and increase competitiveness, making a firm's products more attractive to environmentally conscious consumers. Green innovation, such as sustainable products and environmentally friendly technologies, is increasingly in demand in global markets. By adopting and developing these innovations, SMEs can meet environmental standards and cater to the preferences of foreign customers, thereby increasing their export potential (Martínez-Ros and Merino, 2023).

Second, green knowledge spillovers can provide SMEs with competitive advantages by enabling them to offer unique and advanced green products that differentiate their products from those of competitors. This differentiation is important for entering and succeeding in international markets (Henley and Song, 2020). The ability to innovate and offer sustainable solutions can help SMEs establish a stronger presence in global value chains and attract international customers. This represents greater opportunities for SMEs to participate in both local and global value chains (Kauffmann and Cusmano, 2022). Knowledge spillovers arising from a firm's connections with its regional setting strengthen its ability to compete internationally.

More specifically, we examine whether green innovation increases the likelihood and intensity of SME exports, which are widely used proxies for international expansion in the literature (Andrés and Min, 2020). This leads to our third hypothesis:

Hypothesis 2: SMEs' in-house green innovations enabled by spillovers are positively related to their international expansion through exporting.

In summary, green knowledge spillovers can enhance SMEs' green innovation and economic performance. This, in turn, facilitates their international expansion via exporting. We propose that SMEs can leverage green knowledge spillovers by enhancing their autonomous capacity to produce green innovation as well as compete in foreign markets. By explicitly linking these hypotheses, we can establish a more comprehensive understanding of the mechanisms through which green knowledge spillovers drive SMEs' innovation and economic development.

4. Data and modeling

4.1 Data

The empirical analysis is based on the Bureau van Dijk Orbis balance sheet data and Orbis Intellectual Property data that provide patent information. The sample used for estimation has 8552 German manufacturing SMEs between 2009 and 2019 covering high-technology (782 SMEs), medium high-technology (2811 SMEs), medium low-technology (2192 SMEs), low-technology (655 SMEs), and utility (2112 SMEs) sectors. We define a green innovation-producing firm as one that holds at least one green patent in a given year. Table 1 presents variable definitions and summary statistics for the estimation sample. To illustrate the distribution of green innovation-producing firms, Appendix 1 reports the share of employment in green innovation-producing firms relative to total employment for each NUTS-2 German region during 2009-2019.

4.2 Measures

4.2.1 Green knowledge-spillovers variables

To fully account for the effects of green innovation, the green innovation spillovers variables are constructed using green patents held by all sizes of firms, including large firms with more than 250 employees. We follow the approach developed by Javorcik (2004), which has been widely applied in the knowledge-spillovers literature (Wu *et al.*, 2023; Qu *et al.*, 2024). First, horizontal green knowledge spillovers ($Horizontal\_green_{srt}$) are the spillovers from green innovation-producing firms to other firms in the same industry. It is defined as green innovation-producing firms' employment presence in NACE2 industry *s* in NUTS-2 region *r* in year *t*, averaged over all firms in the same industry and weighted by each firm's green patent intensity (i.e., the ratio of green patent counts to total patent counts of firm *i* in industry *s* and region *r* in year *t*). The value of this variable increases with the employment presence of green innovation-producing firms and the firms' green patent intensity. In other words:

$$Horizontal\_green_{srt} = \sum_{i \in srt} \frac{Green\ patent\ counts_{isrt}}{Total\ patent\ counts_{isrt}} * Employees_{isrt} / \sum_{i \in srt} Employees_{isrt}$$

Second, inter-industry green knowledge spillovers arise from within-nation transactions between vertically integrated industries based on national Input–Output Table coefficients measured by purchases of domestically sourced inputs as a share of total inputs. Backward green knowledge spillovers ($Backward\_green_{rst}$) is a proxy for green innovation-producing firms' presence in the upstream supplying industries to the focal firm in the downstream industry *s*. It is defined as:

$$Backward\_green_{rst} = \frac{1}{n1} \sum_{j=1}^{n1} \alpha_{sj} * Horizontal\_green_{rjt}$$

where α_{sj} is the proportion of industry *j*'s output supplied to industry *s*.[1] Inputs supplied within the same industry are not included, as this effect is already captured by the horizontal variable.

[1] α_{sj} and α_{sk} are the coefficients from the Input–Output Table from the Germany Federal Statistical Office (2018), available at NACE2 industry level defined according to Eurostat. This table is a symmetric matrix that informs the share of intermediate products purchased by each industry from all other industries, and the share of intermediate products supplied by each industry to all other industries. The former (α_{sj}) is used to generate backward green innovation spillovers, and the latter (α_{sk}) to calculate forward green innovation spillovers.

Table 1. Summary statistics

	Mean	Std. dev.	Min	Max
Green knowledge-spillovers variables: employment presence				
Green horizontal spillovers	4.57	6.25	0	100
Green backward spillovers	0.02	0.04	0	2.37
Green forward spillovers	0.03	0.05	0	0.77
Green knowledge-spillovers variables: turnover presence (for robustness checks)				
Green horizontal spillovers: turnover	3.91	5.84	0	100
Green backward spillovers: turnover	0.03	0.05	0	1.88
Green forward spillovers: turnover	0.03	0.04	0	0.91
Green innovation				
Green innovation dummy: 1 if the SME has a green patent, 0 otherwise	0.03	0.17	0	1
Green innovation intensity: green patent stock per 100 employees (logarithm)	0.08	0.30	0	5.94
Green innovation intensity: green patent stock to total patent stock share (%)	5.49	18.25	0	100
Economic performance				
Productivity (Levinsohn and Petrin method)	5.03	1.12	−3.72	10.77
Profitability: profit to turnover ratio	0.03	0.24	−4.14	0.71
Export				
Export dummy: 1 if the SME exports, 0 otherwise	0.20	0.40	0	1
Export intensity: export sales to turnover ratio	7.84	19.92	0	97.20
Technological capabilities				
Patent stock (logarithm)	0.85	1.29	0	8.39
Technology diversity (logarithm)	0.10	0.28	0	1.90
Core technological competence (logarithm)	0.39	0.80	0	2.56
Intangible to total assets ratio	0.02	0.05	0	0.38
Control variables				
Tangible fixed assets to total assets ratio	0.25	0.23	0	0.95
Employees (logarithm)	4.17	1.08	0.69	5.52
Age	31.30	28.13	1	131
Herfindahl–Hirschman index (NACE2)	0.02	0.05	0.001	1
Observations	22,333			

(1) Appendix 2 summarises statistics by SME size. (2) Appendix 3 presents the correlation matrix for all variables. SME, small- and medium-sized enterprise.

We weight the share of green innovation-producing firms' employment presence in each upstream ($Horizontal\_green_{rjt}$) for the focal industry s in region r in year t by the relative importance of vertical linkages between each industry pair (α_{sj}), and averaging across all backward industries (j).[2] The more green innovation-producing firms are present in the supplying industries and the larger the share of intermediates from the upstream industries j supplied to the downstream industry s, the higher the value of this variable.

In a similar vein, forward green knowledge spillovers ($Forward\_green_{rst}$) is a proxy for green innovation-producing firms' presence in the downstream buying industries to the focal firm in the upstream industry s. It is defined as:

$$Forward\_green_{rst} = \frac{1}{n2}\sum_{k=1}^{n2} \alpha_{sk} * Horizontal\_green_{rkt}$$

where α_{sk} is the proportion of upstream industry s's output supplied to downstream industries k. We weight the share of green innovation-producing firms' employment presence in each downstream ($Horizontal\_green_{rkt}$) for the focal industry s in region r in year t by the relative

[2] n1 and n2 are the number of backward supplying industries and the number of forward buying industries of the focal industry s, respectively.

importance of vertical linkages between each industry pair (α_{sk}), and averaging across all forward industries (k). The higher the green innovation-producing firms' presence in the buying industries, and the larger the share of intermediates from the upstream industry s supplied to the downstream industries k, the higher the value of this variable.

4.2.2 Control variables

As for the control variables, firms' technological capabilities are captured by four proxies: patent stock, technological diversification, core technology competence, and the intangible assets ratio (defined in Supplementary Appendix 4). First, patent stock accounts for firms' accumulated knowledge over time; this is expected to drive innovation and economic performance (Leoncini *et al.*, 2019). It is generated using the perpetual inventory method following Guellec and Potterie (2004). Second, firms diversify their technological base to exploit knowledge-based economies of scope, reduce innovation-related risks, and better adapt to the fast-changing technological environment. Technological diversification could compensate for diminishing marginal returns on technological investment and improve performance (Patel and Pavitt, 1997). Third, core technology competence reflects a firm's competitive advantage in specific technology fields. Higher values of core technology competence indicate that the focal firm specializes in certain technological domains (Kim *et al.*, 2016). Firms with strong core technology competences are better at identifying opportunities and allocating resources to gain efficiency (Choi and Lee, 2021). Fourth, the ratio of intangible assets to total assets controls for additional knowledge-related factors that can impact firm performance (Howell, 2020).

Moreover, the ratio of tangible fixed assets to total assets is included as a control variable (Leoncini *et al.*, 2019). Firm size is measured by the number of employees, and firm age by the number of years since establishment. Sector dummies and year dummies are included to control for industry- and year-specific effects, respectively.

4.3 Models

Three sets of models are specified to test the impacts of green innovation knowledge spillovers on SMEs, with each model being tailored in terms of control variables following the literature on each dependent variable.[3]

$$\begin{aligned} Green\_innovation_{isrt} &= \beta_0 + \beta_1 Horizontal\_green_{srt} + \beta_2 Backward\_green_{srt} \\ &+ \beta_3 Forward\_green_{srt} + Controls_{it} + Sector_{it} + Year_t + c_i + u_{it} \end{aligned} \quad (1)$$

where $Green\_innovation_{isrt}$ is either a green innovation dummy or intensity of the SME i in NACE2 industry s in NUTS-2 region r in year t. The green innovation dummy equals 1 if the SME i produces one or more green patents in the given year t, and 0 otherwise. The green innovation intensity is proxied by (i) the green patent stock that the SME i possesses weighted by the number of employees, and (ii) the percentage share of green patent stock to total patent stock that the SME i has in year t (Gkypali *et al.*, 2021). The patent stock variables are generated according to the perpetual inventory method (Guellec and Potterie, 2004). c_i is the unobserved individual heterogeneity, and u_{it} is the idiosyncratic errors. Equation (1) includes market competition, proxied by the Herfindahl–Hirschman index, as an additional control variable. Competitive pressure is the main driver of innovation (Arrow, 1962), but it may discourage innovation because monopolies are faced with less potential to obtain rent (Schumpeter, 1934).

$$\begin{aligned} Economic\ performance_{isrt} &= \beta_0 + \beta_1 Horizontal\_green_{srt} + \beta_2 Backward\_green_{srt} \\ +\beta_3 Forward\_green_{srt} &+ \beta_4 Green\_innovation_{it} + Controls_{it} + Sector_{it} + Year_t + c_i + u_{it} \end{aligned} \quad (2)$$

where $Economic\ performance_{isrt}$ is either productivity or profitability of the SME i in NACE2 industry s in NUTS-2 region r in year t. Productivity is measured by total factor productivity in

[3] We do not expect the three models to behave in a systematic simultaneous way because each stage is not expected to depend on the previous stage(s). They are therefore estimated individually by the most robust estimators that suit the feature of the dependent variable rather than in simultaneous equations.

logarithms, according to Levinsohn and Petrin (2003) (see Supplementary Appendix 5 for more details). Profitability is measured by the ratio of operating profit to turnover (Kang *et al*., 2019). Green innovation is added as an additional control because firms that engage in green innovation are expected to have competence to acquire and internalize green knowledge spillovers to increase economic performance (Dzhengiz and Niesten, 2020).

$$Export_{isrt} = \beta_0 + \beta_1 Horizontal\_green_{srt} + \beta_2 Backward\_green_{srt} + \beta_3 Forward\_green_{srt} + \beta_4 Green\_innovation_{it} + \beta_5 Productivity_{it} + Controls_{it} + Sector_{it} + Year_t + c_i + u_{it} \quad (3)$$

where $Export_{isrt}$ is either an export status dummy which equals 1 if the SME i exports and 0 otherwise, or the export intensity proxied by the ratio of export sales to turnover of the SME i in NACE2 industry s in NUTS-2 region r in year t (D'Angelo *et al*., 2020). Green innovation and productivity are added in equation (3) because both are commonly controlled for in explaining exporting behavior (Driffield *et al*., 2021). Innovation is a key driver of exporting, making firms more likely to provide unique and superior products and have product appeal in foreign markets (Gkypali *et al*., 2021). Productivity is another important determinant of exporting in the international trade literature. Only sufficiently productive firms can overcome the sunk costs required to enable exporting. These costs include conducting market research and setting up distribution networks, negotiating with potential foreign business partners, and adjusting product features for foreign markets (Love and Roper, 2015).

4.4 Estimation methods

The discreteness of the dependent variables (i.e., dummies or intensities) in equations (1) and (3) suggests the use of nonlinear estimation methods within a panel data structure rather than linear estimation methods. Panel Random Effects Probit and Tobit estimators are unsuitable for two reasons. First, they cannot eliminate the individual unobserved heterogeneity (c_i) in the error term like the Linear Panel Fixed Effects method. Second, using conditional maximum likelihood estimation, the consistency of these estimators relies on the strong serial independence assumption of the idiosyncratic error terms (u_{it}). This assumption can be easily violated, leading to biased estimates. Fernández-Val and Weidner (2016) propose a bias-corrected version of Fixed Effects estimators for nonlinear dependent variables. However, estimating unobserved heterogeneity for each unit usually introduces an incidental parameters problem, and this method relies on the strong assumption of serial independence, which is often violated due to idiosyncratic errors. An alternative is the conditional maximum likelihood estimation for a Logit model that does not impose the serial independence assumption. However, because it leaves the heterogeneity distribution unspecified, this estimator cannot compute the marginal effects of covariates (Wooldridge, 2019). Hence, this article uses the Wooldridge (2019) method of probit correlated random effects (Probit CREs) because it does not impose the weak dependence assumption and requires few assumptions to estimate marginal effects. This method allows unrestricted serial correlations in u_{it} across time periods and models how the unobserved heterogeneity (c_i) depends on the covariates. In other words, it allows for the correlation between the explanatory variables and unobserved heterogeneity (c_i).

The continuous nature of the dependent variable in equation (2) suggests the use of the Linear Panel Fixed Effects method to allow for any correlations between the explanatory variables and individual unobserved heterogeneity (c_i) in the error term, which is known as heterogeneity endogeneity. Green innovation, as a firm-level control in this equation, could be endogenous if it is correlated with the idiosyncratic error terms (u_{it}), which is known as idiosyncratic endogeneity (Lin and Wooldridge, 2019). For instance, feedback effects occur when past shocks to economic performance shape SMEs' green innovation, violating the strict exogeneity assumption. To address this potential idiosyncratic endogeneity, this article adopts a two-step test proposed by Wooldridge (2010) to test if green innovation is correlated with u_{it} (Supplementary Appendix 6 provides details on this method, and Supplementary Appendix 7 presents the test results). In the first step estimation, we select NACE2 industry-level instruments for the firm-level green innovation variable: (i) the flow of green innovation in logarithms and (ii) the share of green patents flow to total patents flow in the industry s in region r in year t. This article argues that both instruments are correlated with firm-level green innovation but are unlikely to be influenced by firms' idiosyncratic shocks. This approach to instrumental variable selection has been adopted by prior studies (Acemoglu and Restrepo, 2020). In short, the selected instruments significantly influence firms' green innovation in the first step estimation (demonstrated in Supplementary Appendix 7 step 1). Additionally, the Mundlak residuals from the first step estimations do not show statistical significance in the second step estimations (shown in Supplementary Appendix 7 step 2). This means that past shocks to economic performance did not make SMEs adjust to green innovation, and idiosyncratic endogeneity is not a concern. Hence, the Linear Panel Fixed Effects estimator is robust and appropriate to use.

The key econometric issue when estimating equation (3) is the potential endogeneity of green innovation and productivity. The unobserved heterogeneity (c_i) in the error term could be correlated with innovation and/or productivity, such as human resource management, marketing, skills, and strategies (Love and Roper, 2015). Firms may make strategic decisions to innovate based on their awareness of export opportunities and self-select into exporting based on the productivity level, a widely discussed issue in the international trade literature (Gkypali *et al.*, 2021). Similar to equation (1), this endogeneity can be addressed using Probit CRE to allow possible correlations between explanatory variables and c_i.

Moreover, past export shocks could have feedback effects on green innovation and/or productivity. To account for such potential correlation between green innovation and/or productivity specifically arising from the idiosyncratic error terms (u_{it}), a two-step test method proposed by Lin and Wooldridge (2019) is adopted. In the first step, the endogenous variables are respectively regressed on all the explanatory variables in the model and the selected instrumental variables. More specifically, for the firm-level green innovation variable, its instruments are the same as those in equation (2). For productivity, the average productivity of SMEs at the NACE2 industry level in the given year is selected, as it is related to firm-level productivity but is unlikely to be affected by idiosyncratic shocks to firms. In the second step, the Mundlak residuals obtained from the first step are included in the pooled Probit estimation. Using a cluster-robust Wald test, these residuals are statistically insignificant, indicating no signs of idiosyncratic endogeneity (Supplementary Appendix 8 shows the test results and interpretation). Hence, Probit CRE estimation is a fully robust estimation method. For the export intensity outcome in equation (3), Tobit Correlated Random Effects (Tobit CRE) estimation is chosen following Wooldridge (2019). It is a robust estimator for nonlinear panel models that allows for potential correlations between green innovation, productivity, and the error term.

5. Results

5.1 Main findings

Table 2 presents the marginal effects of green innovation knowledge spillovers on the propensity and intensity of SMEs producing green innovation. The dependent variables are measured by a green innovation dummy in column (1), green innovation intensity in columns (2) and (3), proxied by green patent stock per hundred employees (in logarithmic form) and the share of green patent stock to total patent stock, respectively. As other firms operating in the same industry as the SMEs produce more green innovation, the co-located SMEs are more likely to produce green innovation (column 1: $\beta_{\text{Green horizontal spillovers}} = 0.0001$, $P < 0.05$) and produce green innovations more intensively (column 2: $\beta_{\text{Green horizontal spillovers}} = 0.0013$, $P < 0.01$; column 3: $\beta_{\text{Green horizontal spillovers}} = 0.0001$, $P < 0.05$). This finding supports Hypothesis 1a. Green knowledge spillovers may occur through labor turnover, where workers who previously worked in green innovative firms subsequently join other SMEs (Ejdemo and Örtqvist, 2020). The green knowledge embedded in human capital is critical, particularly because SMEs often lack the human resources needed to develop green innovations (Burger *et al.*, 2019). Additionally, these positive horizontal spillovers could arise from demonstration effects, as exposure to green innovative competitors provides SMEs with opportunities to appreciate the value of investing in green innovation. This is particularly important given that the process can incur high costs and risks, with benefits that are difficult to realize in the short term (Feng *et al.*, 2016). This is especially true for SMEs, which are often risk-averse due to their small size.

Table 2. Green knowledge-spillovers impact on SMEs' green innovation production

	(1) Probit correlated random effects (CREs) Dependent variable: green innovation dummy (1 if has a green patent, 0 otherwise)	(2) Tobit CRE Dependent variable: green innovation intensity (green patent stock per 100 employees)	(3) Tobit CRE Dependent variable: green innovation intensity (green stock to patent stock share)
Green knowledge spillovers			
Green horizontal spillovers	0.0001*	0.0013**	0.0001*
	(0.0001)	(0.0004)	(0.0001)
Green backward spillovers	−0.0055	−0.0153	0.0062
	(0.0092)	(0.0452)	(0.0061)
Green forward spillovers	0.0002	0.0253	−0.0090
	(0.0084)	(0.0488)	(0.0073)
Control variables			
Patent stock	0.0039***	0.0674***	
	(0.0011)	(0.0065)	
Technology diversity	0.0046***	−0.0066	0.0042**
	(0.0011)	(0.0046)	(0.0015)
Core technological competence	0.0157***	0.0010	0.0019**
	(0.0011)	(0.0014)	(0.0006)
Intangible to total assets ratio	−0.0194+	−0.1036*	−0.0129
	(0.0111)	(0.0434)	(0.0145)
Tangible fixed assets to total assets ratio	0.0027	0.0181+	0.0044
	(0.0043)	(0.0102)	(0.0031)
Employees	−0.0017+	−0.0280***	−0.0011
	(0.0009)	(0.0059)	(0.0015)
Age	−0.0002	−0.0006	0.0000
	(0.0005)	(0.0015)	(0.0003)
Herfindahl–Hirschman index	0.0186	0.0922+	0.0195
	(0.0118)	(0.0547)	(0.0125)
Observations	22,333	22,333	22,333

(1) Sector dummies and year dummies are included in all estimations. (2) Standard errors clustered at firm-level are in parentheses. (3) $^{***}P < 0.001$, $^{**}P < 0.01$, $^{*}P < 0.05$, $+P < 0.10$. SME, small- and medium-sized enterprise.

Regarding the control variables, SMEs' technological capabilities are important drivers of their green innovation production. Patent stock, technology diversity, and core technological competence are positively related to the dependent variables. This underscores the importance of internal capabilities in accumulating knowledge, diversifying technological portfolios, and gaining a competitive advantage in specific technological fields when launching green innovations (Love *et al.*, 2011).

Table 3 columns (1)–(3) report the marginal effects of green innovation knowledge spillovers on SMEs' productivity. There are strong spillovers from backward green linkages (column 1: $\beta_{\text{Green backward spillovers}} = 0.1393$, $P < 0.05$; column 2: $\beta_{\text{Green backward spillovers}} = 0.1404$, $P < 0.05$; column 3: $\beta_{\text{Green backward spillovers}} = 0.1400$, $P < 0.05$), indicating that if upstream suppliers produce more green innovation, downstream SMEs can, on average, achieve higher productivity, supporting Hypothesis 1b. This finding reflects a push effect, as green technologies are disseminated to downstream SMEs, which eventually gain production efficiency (Cainelli and Mazzanti, 2013). SMEs typically lack the resources to develop new technologies and are often challenged by rising energy and raw material prices. Backward linkages serve as important external knowledge sources for SMEs to enhance efficiency. Accessing intermediate inputs embedded with green technologies from upstream suppliers can help downstream SMEs improve process efficiency. This may include redesigning products to reduce required inputs, waste, and energy costs, and increasing the use of recycled materials. With the help of green suppliers, SMEs could identify materials and products that can be looped back into the procure and production process to improve efficiency. Additionally, new technologies could enable the development of recyclable materials and advance waste recycling facilities.

Furthermore, Table 3 columns (4)–(6) show the marginal effects of green innovation knowledge spillovers on SMEs' profitability. As upstream suppliers produce more green innovation, downstream SMEs can, on average, achieve higher profitability (column 1: $\beta_{\text{Green backward spillovers}} = 0.1194$, $P < 0.05$; column 2: $\beta_{\text{Green backward spillovers}} = 0.1190$, $P < 0.05$; column 3: $\beta_{\text{Green backward spillovers}} = 0.1204$, $P < 0.05$), further supporting Hypothesis 1b. Although it could be challenging for SMEs to meet green quality standards, they may access green inputs from suppliers in upstream industries to alter products. This may assist SMEs to redesign products to target niche markets, expand markets, and improve profitability.

Table 4 reports the marginal effects for equation (3). Green innovation strongly encourages SMEs to export (column 1: $\beta_{\text{Green patent dummy}} = 0.0406$, $P < 0.05$) and export more intensively (column 2: $\beta_{\text{Green patent dummy}} = 1.7589$, $P < 0.05$), supporting Hypothesis 2. The findings are consistent when green innovation is alternatively measured by green patent intensity in columns (3) and (4) using green patent stock per hundred employees, and columns (5) and (6) using the share of green patent stock to total patent stock, respectively. Although this article does not find that SMEs' green innovation directly leads to enhanced productivity or profitability in the domestic market, it enables them to gain market access abroad via exporting.

5.2 Heterogeneous green knowledge-spillover effects by region and industry

There is great geographical heterogeneity in green innovation spillovers, illustrated in Figure 1A–C. Figure 1A highlights the average marginal effect of horizontal green innovation spillovers on the likelihood of SMEs producing green innovation, based on the estimation from Table 2 column (1). The largest effects are experienced in the West such as Baden-Württemberg (DE12, DE13, DE4), Bavaria (DE25, DE26), and the East such as Berlin (DE30) and Dresden (DED2). Figure 1B shows the average marginal effects of backward green innovation spillovers on SMEs' productivity based on the estimation from Table 3 column (1). SMEs across Germany benefit from backward green innovation spillovers, including Hesse (DE72) and North Rhine-Westphalia (DEA2, DEA3, DEA5). Even in East Germany (e.g., Mecklenburg-Vorpommern DE80), which does not have the highest level of green innovation, backward spillovers have large impacts on enhancing productivity. Figure 1C shows the average marginal effect of backward green innovation spillovers on SMEs' profitability based on estimation from Table 3 column (4). Most regions in West Germany have received positive spillovers (e.g., North Rhine-Westphalia DEA4, DEA5, and Bavaria DE21), while some regions in East Germany experienced negative externalities (e.g., Dresden DED2).

Turning to industry heterogeneity in spillovers, based on the estimation from Table 2 column (1), Figure 2A[4] shows that industries that benefit most from horizontal spillovers in terms of producing green innovation are pharmaceutical products and pharmaceutical preparations (NACE2 code 21); sewerage (37); computer, electronic and optical products (26), and chemicals and chemical products (20). Based on the estimation from Table 3 column (1), Figure 2B shows that industries that benefit most from backward spillovers in productivity are sewerage (37); waste collection, treatment, and disposal activities, materials recovery (38); other manufacturing (32); and printing and reproduction of recorded media (18). Based on the estimation from Table 3 column (4), Figure 2C shows that industries benefiting the most from backward spillovers in terms of profitability are utility, sewerage (37); waste collection, treatment, and disposal activities, materials recovery (38); wood products (16); and wearing apparel (14). In short, these findings highlight that industries benefiting the most from green knowledge spillovers in producing green innovation belong to high-technology and medium-high-technology sectors. Appendix 9 lists all NACE2 industry codes, their names, and classification into high-technology, medium high-technology, medium low-technology, low-technology, and utility sectors. This outcome could be related to SMEs' capabilities to absorb technological know-how to internalize externally sourced green knowledge. The spillovers enhancing productivity and profitability are mostly

[4] The numbers on the horizontal axes in Figure 2A–C are NACE2 industries, according to Eurostat (ISSN 1977-0375).

Table 3. Green knowledge-spillovers impact on SMEs' productivity and profitability

	(1)	(2)	(3)	(4)	(5)	(6)
	Dependent variable: productivity			Dependent variable: profitability		
	Panel fixed effects			Panel fixed effects		
Green innovation						
Green innovation dummy (1 if has a green patent)	−0.0235			0.0111		
	(0.0250)			(0.0208)		
Green innovation intensity: green patent stock per 100 employees		0.0346			0.0440	
		(0.0812)			(0.0434)	
Green innovation intensity: green stock to patent stock share			0.0001			−0.0008
			(0.0008)			(0.0007)
Green knowledge spillovers						
Green horizontal spillovers	0.0004	0.0004	0.0004	0.0002	0.0002	0.0002
	(0.0005)	(0.0005)	(0.0005)	(0.0005)	(0.0005)	(0.0005)
Green backward spillovers	0.1393*	0.1404*	0.1400*	0.1194*	0.1190*	0.1204*
	(0.0681)	(0.0680)	(0.0681)	(0.0498)	(0.0498)	(0.0498)
Green forward spillovers	−0.0560	−0.0546	−0.0555	−0.0328	−0.0316	−0.0346
	(0.0427)	(0.0430)	(0.0427)	(0.0607)	(0.0611)	(0.0596)
Control variables						
Patent stock	0.0151	0.0111	0.0143	−0.0085	−0.0129	−0.0044
	(0.0128)	(0.0131)	(0.0128)	(0.0096)	(0.0091)	(0.0087)
Technology diversity	−0.0048	−0.0076	−0.0074	0.0107	0.0118	0.0121
	(0.0151)	(0.0157)	(0.0157)	(0.0151)	(0.0149)	(0.0149)
Core technological competence	−0.0022	−0.0026	−0.0029	−0.0005	0.0001	−0.0004
	(0.0045)	(0.0045)	(0.0045)	(0.0034)	(0.0033)	(0.0034)
Intangible to total assets ratio	−0.0691	−0.0613	−0.0663	−0.1598	−0.1557	−0.1685
	(0.1477)	(0.1476)	(0.1483)	(0.1530)	(0.1510)	(0.1534)
Tangible fixed assets to total assets ratio	−0.2739***	−0.2750***	−0.2743***	−0.1333**	−0.1344**	−0.1317**
	(0.0537)	(0.0537)	(0.0537)	(0.0510)	(0.0509)	(0.0507)
Employees	−0.0863***	−0.0824***	−0.0862***	0.0674*	0.0714*	0.0673*
	(0.0255)	(0.0236)	(0.0255)	(0.0278)	(0.0296)	(0.0278)
Age	0.0004	0.0003	0.0004	−0.0026	−0.0026	−0.0025
	(0.0013)	(0.0013)	(0.0013)	(0.0039)	(0.0039)	(0.0039)
Observations	22,333	22,333	22,333	22,333	22,333	22,333
Number of IDs	8552	8552	8552	8552	8552	8552

(1) Sector dummies and year dummies are included in all estimations. (2) Standard errors clustered at firm-level are in parentheses. (3) $^{***}P < 0.001$, $^{**}P < 0.01$, $^{*}P < 0.05$, $+P < 0.10$. SME, small- and medium-sized enterprise.

Table 4. Green innovation impact on SMEs' export

	(1) Probit correlated random effects (CREs) Dependent variable: export dummy (1 if exports, 0 otherwise)	(2) Tobit CRE Dependent variable: export intensity (export sales to turnover ratio)	(3) Probit CRE Dependent variable: export dummy	(4) Tobit CRE Dependent variable: export intensity	(5) Probit CRE Dependent variable: export dummy	(6) Tobit CRE Dependent variable: export intensity
Green innovation						
Green patent dummy: 1 if has a green patent	0.0406*	1.7589*				
	(0.0177)	(0.7682)				
Green patent intensity: green patent stock per 100 employees			0.0596*	2.3543+		
			(0.0299)	(1.3234)		
Green patent intensity: green stock to patent stock share					0.0010+	0.0488+
					(0.0006)	(0.0280)
Green knowledge spillovers						
Green horizontal spillovers	0.0006	0.0114	0.0006	0.0125	0.0006	0.0120
	(0.0007)	(0.0354)	(0.0007)	(0.0353)	(0.0007)	(0.0354)
Green backward spillovers	−0.1074	−5.4825	−0.1074	−5.5405	−0.1126	−5.8553
	(0.0840)	(4.3813)	(0.0839)	(4.3751)	(0.0839)	(4.3854)
Green forward spillovers	−0.0450	−3.4409	−0.0457	−3.4269	−0.0451	−3.4037
	(0.0757)	(3.9102)	(0.0754)	(3.8892)	(0.0753)	(3.8971)
Control variables						
Intangible to total assets ratio	0.1172	8.1461	0.1271	8.0584	0.1243	7.9367
	(0.1205)	(5.6524)	(0.1217)	(5.6483)	(0.1216)	(5.6698)
Tangible fixed assets to total assets ratio	−0.0958*	−3.5415	−0.0981*	−3.5464	−0.0969*	−3.5666
	(0.0447)	(2.2500)	(0.0445)	(2.2297)	(0.0447)	(2.2472)
Employees	0.0496***	2.4432***	0.0609***	2.9242***	0.0487***	2.4105***
	(0.0146)	(0.6341)	(0.0150)	(0.6782)	(0.0147)	(0.6343)
Age	−0.0057	−0.2269	−0.0060	−0.2709	−0.0059	−0.2667
	(0.0059)	(0.3778)	(0.0058)	(0.3838)	(0.0059)	(0.3831)
Productivity (Levinsohn and Petrin)	0.0228+	0.7351	0.0201	0.6591	0.0225	0.7601
	(0.0137)	(0.6610)	(0.0135)	(0.6611)	(0.0137)	(0.6592)
Observations	22,333	22,333	22,333	22,333	22,333	22,333

(1) Sector dummies and year dummies are included in all estimations. (2) Standard errors clustered at firm-level are in parentheses. (3) ***$P < 0.001$, **$P < 0.01$, *$P < 0.05$, +$P < 0.10$. SME, small- and medium-sized enterprise.

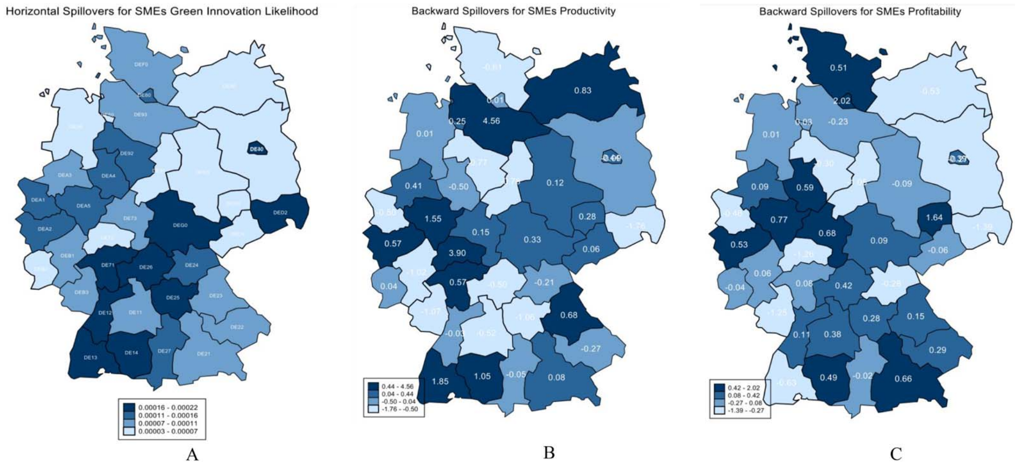

Figure 1. (A) Horizontal spillovers for SMEs green innovation likelihood. (B) Backward spillovers for SMEs productivity. (C) Backward spillovers for SMEs profitability.

experienced by medium-low and low-technology sectors, indicating that SMEs could have re-examined production processes to improve efficiency.

5.3 Robustness checks

Additional robustness checks are reported in the Supplementary Appendices. Supplementary Appendix 10 presents robustness checks for Table 2 and Table 3 by using an alternative measure of spillover variables. Instead of measuring by employment presence, horizontal and vertical spillovers are measured by the share of turnover of green innovation-producing firms in industry *s* region *r* and year *t* following the same method described in Section 4.2.1. The reported marginal effects consistently support Hypotheses 1a and 1b. Using these alternative spillover variables, Supplementary Appendix 11 shows robustness checks for Table 4 and reports consistent marginal effects supporting Hypothesis 2.

6. Discussion

This article highlights that green knowledge spillovers are disseminated through various channels. First, SMEs operating in the same industry as green innovation-producing firms are more likely to benefit by producing green innovations themselves. As competitors share similar contextual knowledge, their green knowledge spillovers can be highly relevant to SMEs' needs to generate green innovation. SMEs can analyze competing products and attempt to reverse engineer them (Un and Asakawa, 2015). Second, SMEs in downstream industries can benefit from green knowledge spillovers from upstream suppliers that develop green technologies to enhance productivity and profitability. Access to intermediate products embedded with green technologies from upstream suppliers can help SMEs modify their production processes or products. Upstream suppliers may work closely with downstream SMEs to understand their internal processes, thereby identifying where and how to make changes to reduce costs and improve input quality (Ambec and Lanoie, 2008).

Prior studies have highlighted the driving factors behind green innovation production (Becchetti *et al.*, 2022) and the subsequent economic benefits to green innovation producers (Colombelli *et al.*, 2020; Kesidou *et al.*, 2024). This has prompted scholars to examine how to promote green technological development. Top-down approaches propose altering institutions, creating supportive policies, investing in public R&D, and implementing specific programs (Lema *et al.*, 2020; Zhou *et al.*, 2020; Becchetti *et al.*, 2022). Additionally, the bottom-up approach emphasizes firms' internal capabilities to catch up and make significant investments in green technological development, including overseas mergers and acquisitions to acquire green technologies (Dai *et al.*, 2020). Due to differing market conditions, green technological trajectories, domestic market sizes, technological capabilities, and levels of public support, firms

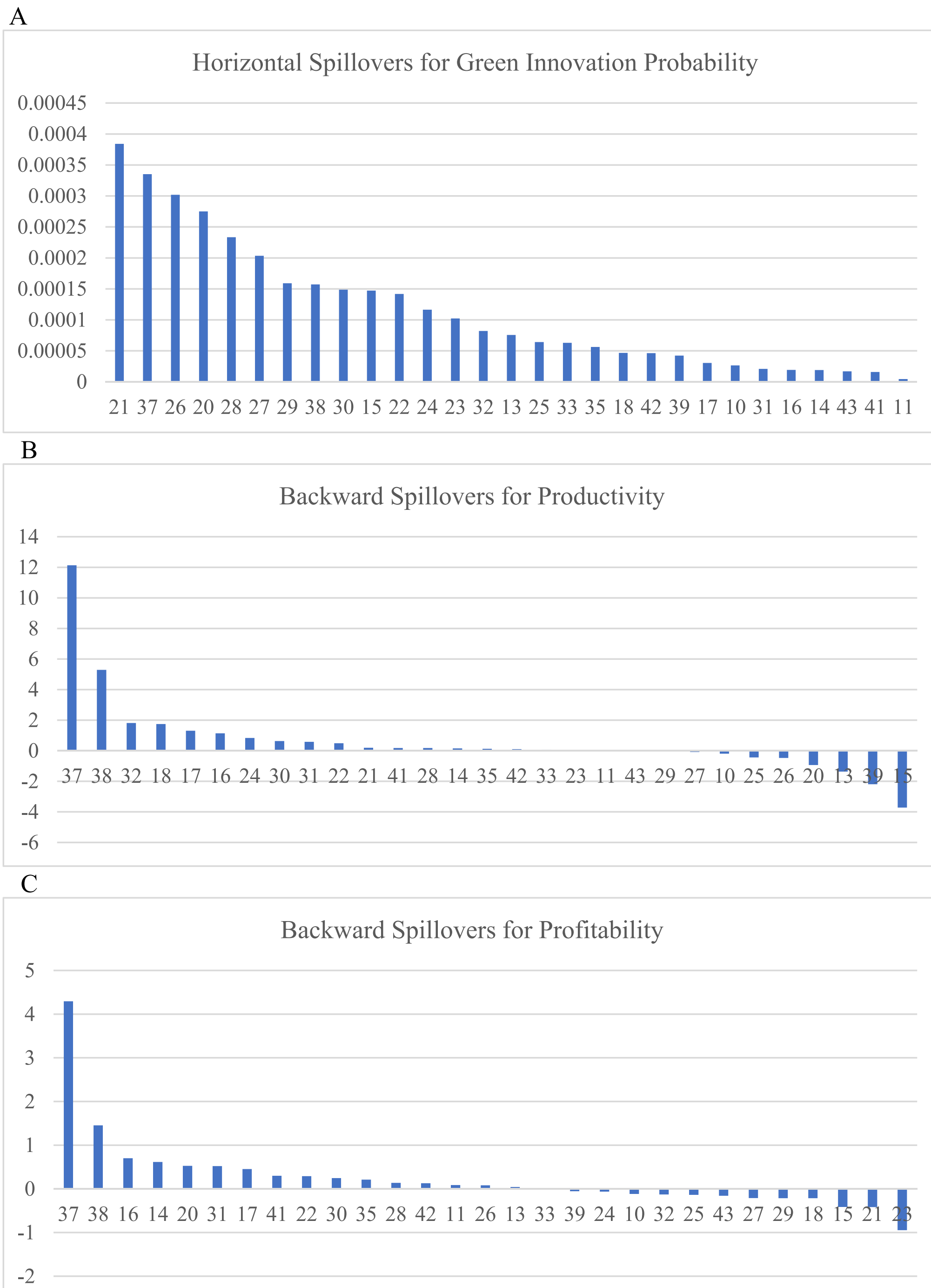

Figure 2. (A) Horizontal spillovers for green innovation probability. (B) Backward spillovers for productivity. (C) Backward spillovers for profitability.

in various countries respond differently when catching up in developing green technologies (Lema *et al.*, 2024).

Our analysis adds to the literature by highlighting how a wider range of firms can benefit from green innovation production, even for SMEs that typically lack the resources to engage in in-house green innovation. Green innovation dissemination via inter-industry transactions has been found to increase industry environmental efficiency along value chains (Costantini *et al*., 2017), but there is little discussion on other aspects of firm performance across industries. Existing discussions about green knowledge spillovers either assume that recipients require patents to benefit, or emphasize that spillovers occur when subsequent patents cite prior green patents (Dechezleprêtre *et al*., 2014; Aldieri *et al*., 2019). Both approaches assume that firms must own patents to benefit from any green knowledge spillovers. This article extends the most recent literature illustrating the benefits of green knowledge spillovers through case studies (Hansen and Hansen, 2020) by analyzing a broad sample of SMEs to identify heterogeneous green knowledge spillovers in different industries and sub-national locations. This article provides the first micro-level evidence that reveals that green innovation can generate knowledge spillovers, enhancing green innovation production and the economic performance of SMEs across a wide regional economy. Policymakers may consider industry- and region-specific policies to support the dissemination of benefits from green knowledge production.

Furthermore, our analysis provides a comprehensive understanding of how firms can leverage green knowledge spillovers to build autonomous capacity and utilize such capabilities for green innovation, economic performance, and international expansion through exporting. This broadens the scope of interventions through external context changes, such as institutions and market demand, in promoting green technological development. These factors are often examined in isolation among large firms (Landini *et al*., 2020; Martínez-Ros and Merino, 2023; Wu *et al*., 2023). This study suggests that SMEs can use green innovation to enter and exploit foreign demand through exporting. Green innovation may have helped SMEs upgrade product quality to meet environmental standards and match different demands set by foreign governments.

7. Conclusions

This study is one of the first to evaluate the broad impacts of green innovation knowledge spillovers on other firms' performance, without requiring spillover receivers to produce in-house innovation. Using German manufacturing SMEs, we identify positive horizontal green knowledge spillovers on their propensity and intensity of producing green innovation. Green innovation generates vertical spillovers that enhance downstream SMEs' productivity and profitability. SMEs can leverage green knowledge spillovers to expand into international markets through exporting.

As for policy implications, the development of green innovation is uneven across industries and sub-national locations. These findings are important for considering effective place-based policies, extending the range of policy intervention tools. Policy support could be extended to industries that lack essential competencies, basic information, and skilled labor to absorb green knowledge spillovers and develop green innovation in-house. Attention should be paid to enabling more SMEs to benefit from local green knowledge spillovers. For instance, support measures could encourage interactions between green innovators and non-green firms across industries or product markets to facilitate green knowledge dissemination and spillovers. The labor skills and technological capabilities of medium- to low-technology industries may need support to enhance spillover effects and benefit from green innovation along value chains. Furthermore, the role green innovation plays in preparing SMEs to export typically receives little attention in policymaking. Institutional efforts should prioritize policies that support SMEs' exports. This could help SMEs develop competitive advantages in green technologies and capitalize on the early life cycles of green technologies to secure future growth opportunities.

As for managerial implications, SMEs need to seek external green knowledge to enhance innovation, productivity, and profitability. Local social networks and geographical proximity to green innovation producers could provide SMEs with access to new green materials, production methods, and problem-solving ideas. Managers of SMEs could turn to upstream industries for green inputs, redesign production processes and products, and gather market information about the adoption and commercialization of green innovation. For instance, SMEs could examine resources along their value chains to reuse resources and reduce waste, seek technologies to cut production costs, and explore opportunities to sell green technologies. Interactions with firms that successfully export green products could be important knowledge sources for SMEs to collect information on exporting costs and risks, foreign market demand, and distribution channels, which can help non-exporting SMEs begin exporting and benefit from green innovation.

We envision several directions for further research to address the limitations of this analysis. First, this article cannot distinguish whether the positive horizontal green spillovers are due to demonstration effects or labor turnover. Our analysis does not examine how firms collaborate and learn from external green knowledge producers. Understanding these mechanisms is important for comprehensively explaining how green innovation is generated. Future research could conduct in-depth case studies to investigate these processes and to provide a deeper understanding of the dynamics.

Second, our findings suggest that forward linkages with green innovation-producing buyers in downstream industries do not seem to be related to upstream SMEs' innovation or economic performance. While this finding applies to our study context, it may not hold universally. Prior literature indicates that demand from buying industries can shape upstream industries' innovation and production efficiency. Therefore, our findings should not be interpreted as a one-size-fits-all claim. Future research should investigate whether such relationships vary across different industries and countries to determine the broader applicability of our results.

Third, more research is required to examine how firms can leverage green knowledge spillovers to enhance the quality of green innovation. This would help understand the full potential of green innovation in driving sustainable technological advancements. Future studies could explore the extent to which firms can improve green innovation quality by utilizing regional and cross-regional green knowledge, thereby providing insights into effective strategies for fostering green innovation production and dissemination.

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Supplementary data

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