Green Innovations and their Barriers in Small and Medium-sized Enterprises in Central Europe

Maria Bartekova [1,*], **Sabina Janikovicova** [1]

[1] Bratislava University of Economics and Business, Slovakia
[*] Corresponding author: Maria Bartekova, maria.bartekova@euba.sk

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Abstract: The transition toward a low-carbon and environmentally sustainable economy has become a strategic priority in the European Union. This shift places increasing pressure on firms to adopt green innovations. Small and medium-sized enterprises (SMEs) play a crucial role in economic development and industrial production in Central Europe; however, their engagement in green innovation activities remains limited. Despite growing regulatory demands and societal expectations, SMEs often face structural, financial, and organizational constraints that hinder the effective implementation of environmentally sustainable practices. Existing empirical evidence suggests that these barriers are not uniform and may vary depending on firm size and organizational characteristics. This study aims to fill this gap by systematically examining the key barriers to the adoption of green innovations among manufacturing SMEs in Central Europe, with a particular focus on differences related to employment size. The empirical analysis is based on primary quantitative data collected through a structured questionnaire administered via computer-assisted telephone interviewing (CATI). The final sample consists of 184 senior managers from manufacturing SMEs operating in Central Europe, classified as micro, small, and medium-sized enterprises according to OECD criteria. The respondents assessed fourteen potential barriers to the adoption of green innovations using an ordinal Likert-type scale. The reliability of the research instrument was confirmed, with a Cronbach's alpha of 0.82. Given the nonnormal distribution of the data, nonparametric statistical methods were applied. The Kruskal–Wallis test was used to identify differences across firm size categories, whereas the Dwass–Steel–Critchlow–Fligner post hoc test was applied to examine pairwise group differences. The findings reveal statistically significant differences in perceived barriers to the adoption of green innovations among SMEs of different sizes. Micro and small enterprises report greater challenges related to several factors. These include a lack of skilled personnel, limited technological capabilities, weak cooperation with research institutions, and market dominance by established firms. In contrast, medium-sized enterprises more frequently perceive the low prioritization of energy consumption reduction as a relevant obstacle. Financial constraints, regulatory complexity, and insufficient access to knowledge and external expertise emerge as the most critical barriers, disproportionately affecting smaller firms. The results highlight the heterogeneous nature of green innovation barriers within the SME sector and highlight the need for size-specific policy interventions. Targeted financial support schemes, regulatory simplification, and stronger linkages between SMEs, research institutions, and policymakers are essential to accelerate the diffusion of green innovations. By providing empirical evidence from Central European manufacturing SMEs, this study contributes to the literature on sustainable innovation and offers practical implications for the design of more effective green transition policies.

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1. Introduction. SMEs are a crucial component of the economic landscape in Central Europe and contribute significantly to employment, economic stability, and innovation. Their role in promoting regional development and technological advancements has been widely acknowledged (Adamowicz & Machla, 2016; OECD, 2021; Olah et al., 2019). However, SMEs often fail to fully exploit their potential to drive sustainability (Khan et al., 2023) and environmental responsibility (Kubalek & Kudej, 2025; Raza et al., 2025). As a result, the adoption of green innovations remains a significant challenge.

Green innovations, defined as environmentally sustainable processes, products, and business models, have attracted considerable attention in recent years because of increasing regulatory pressure, market demand, and societal awareness of climate change (Klewitz & Hansen, 2014). These innovations are considered essential for achieving long-term economic resilience while minimizing environmental impact. However, SMEs often struggle with their implementation because of financial constraints, technological limitations, and a lack of knowledge or expertise in sustainability practices (Demirel & Kesidou, 2019; Inigo & Albareda, 2016).

Existing research suggests that barriers to the adoption of green innovations among SMEs are multifaceted and vary across industries and regions. Some scholars argue that regulatory support and government incentives play pivotal roles in enabling sustainable transitions (European Commission, 2023), whereas others highlight the importance of managerial commitment and organizational culture in fostering environmental innovation (Boiral et al., 2023; Del Rio et al., 2017). In contrast, some studies suggest that financial burdens and risk aversion in SMEs limit their willingness to invest in green technologies (Ghisetti & Pontoni, 2015; Giudici et al., 2023). This difference in perspectives underscores the need for a comprehensive examination of the specific challenges SMEs face in implementing green innovations in Central Europe.

The primary aim of this study is to identify and analyse the key barriers hindering the adoption of green innovations among SMEs operating in Central Europe. By investigating structural, financial, and regulatory constraints, this research seeks to provide valuable insights into the complexities of sustainable transformation in smaller enterprises. Understanding these challenges will enable policymakers, business leaders, and researchers to develop targeted strategies that facilitate the broader implementation of green innovations, ultimately fostering a more sustainable and competitive SME sector in the region.

This research focused on the manufacturing sector, as it represents one of the most significant sources of environmental impact in the region. Moreover, compared with services or agriculture, the manufacturing sector in Central Europe is characterized by a high proportion of SMEs, which face particular challenges in implementing innovations. This focus allows us to identify specific barriers that may differ from those in other sectors, such as logistics or agriculture.

On the basis of the identified research gap, this paper makes a primarily empirical contribution to the literature on green innovation in SMEs, complemented by practical policy implications. Unlike many previous studies, this research does not treat SMEs as a homogeneous group. Instead, it differentiates between micro, small, and medium-sized enterprises. The study also demonstrates how firm size shapes the perception and intensity of barriers to green innovation adoption. The novelty of the study lies in its size-sensitive and sector-specific approach. It focuses on manufacturing SMEs in Central Europe, a region that remains underrepresented in empirical green innovation research. On the basis of the identified research gap and the study's objectives, this paper seeks to answer the following research questions:

RQ1: Do manufacturing SMEs of different employment sizes perceive barriers to the adoption of green innovations differently?

RQ2: Which specific barriers to the adoption of green innovations are most strongly affected by firm size among manufacturing SMEs operating in Central Europe?

By addressing these questions, this study aims to provide size-sensitive empirical evidence on green innovation barriers and to contribute to a more nuanced understanding of sustainability challenges within the SME sector.

The added value of this research stems from three main aspects. First, it provides original primary data collected directly from senior managers, offering insights grounded in managerial experience rather than secondary indicators. Second, by employing robust nonparametric statistical methods, the study identifies statistically significant differences in green innovation barriers across SME size categories, thereby extending existing findings that often rely on aggregated analyses. Third, the results generate actionable implications for policymakers by highlighting the need for differentiated financial instruments, targeted regulatory support, and stronger cooperation between SMEs and research institutions to support the green transition.

In addition to its empirical contribution, the paper offers practical relevance for public authorities, innovation agencies, and business support organizations by identifying the specific constraints faced by

smaller enterprises. These findings may support the design of more effective, size-tailored sustainability and innovation policies in the context of the European Green Deal and national decarbonization strategies.

The rest of the paper is structured as follows. Section 2 reviews the relevant literature on green innovations, sectoral applications, and barriers to their adoption in SMEs. Section 3 describes the research methodology, data collection process, and applied statistical methods. Section 4 presents the empirical results and discusses size-related differences in perceived barriers to green innovation. Section 5 compares the findings with those of prior research and outlines their theoretical and practical implications. Finally, Section 6 concludes the paper by summarizing the main findings, acknowledging limitations, and suggesting directions for future research.

2. Literature Review.

2.1. Green innovations

Green innovations encompass the development and implementation of products, services, and processes designed to minimize environmental impact while simultaneously generating economic benefits. This concept is strongly associated with sustainability principles, eco-innovation, and corporate social responsibility (CSR), all of which play crucial roles in shaping the strategies of businesses, particularly SMEs. Green innovations are increasingly recognized as key drivers of sustainable development, as they encourage businesses to adopt environmentally friendly practices without compromising their competitiveness (Biondi et al., 2002; Oduro et al., 2022).

Several theoretical perspectives provide valuable insights into the factors influencing green innovation adoption among SMEs. The resource-based view (RBV) suggests that companies that invest in sustainable practices can gain competitive advantages by improving their operational efficiency, reducing costs, and differentiating themselves from competitors. By leveraging internal capabilities such as technological expertise, human resources, and financial investments in green technologies, firms can enhance their long-term profitability while reducing their environmental footprint. This perspective highlights that businesses that proactively integrate sustainability into their operations are more likely to succeed in the long term (Borsatto & Bazani, 2021).

Institutional theory, on the other hand, emphasizes the significant role of external pressures, including regulatory frameworks, societal expectations, and government policies, in shaping corporate sustainability strategies. Regulations such as environmental standards, carbon emission limits, and waste management laws encourage businesses to innovate and comply with sustainable practices. Additionally, societal norms and consumer preferences increasingly favour environmentally responsible businesses, further pushing companies to adopt green innovations. Institutional theory highlights the importance of external factors in driving corporate environmental responsibility and influencing decision-making processes (Bamel et al., 2024).

Moreover, evolutionary economics offers a dynamic perspective on green innovations, focusing on the continuous changes in market conditions, technological advancements, and industry transformations. This theory emphasizes that innovation is not a static process but rather an ongoing adaptation to external and internal challenges. Businesses must continuously evolve by adopting new technologies, improving processes, and responding to shifting consumer preferences (Dorcak et al., 2015). The transition toward greener practices is influenced by factors such as advancements in renewable energy, circular economy models, and digitalization, which provide firms with opportunities to develop more sustainable business models (Arici & Uysal, 2022; Afeltra et al., 2023).

Green innovations are multifaceted concepts driven by both internal capabilities and external pressures. Understanding these theoretical perspectives can help SMEs navigate the challenges and opportunities associated with adopting sustainable business practices (Feng et al., 2024), ultimately contributing to both environmental and economic sustainability.

2.2. Technologies and Key Sectors

SMEs in Central Europe operate in diverse industries, with some sectors making notable strides in adopting green innovations. The manufacturing sector, for instance, has increasingly embraced sustainable practices by integrating energy-efficient production methods, utilizing recycled and biodegradable materials, and optimizing waste management strategies (Pollak et al., 2023). Many SMEs align their operations with circular economy principles by reducing resource consumption, reusing materials, and designing products for extended life cycles. These efforts not only contribute to environmental sustainability but also enhance cost efficiency and competitiveness (Agrawal et al., 2024).

Another key area of green innovation among SMEs is the renewable energy sector. Small businesses are actively involved in the development of decentralized energy solutions, such as small-scale solar and wind

projects, as well as advancements in energy storage technologies. By improving battery efficiency and promoting smart grid integration, SMEs play a crucial role in enhancing energy sustainability at both the local and regional levels.

Sustainable agriculture and food production are also gaining prominence, with SMEs investing in organic farming techniques, precision agriculture, and environmentally friendly food packaging. These innovations help reduce chemical use, conserve water, and minimize food waste, contributing to a more sustainable food system (Gottardo et al., 2021).

The transportation and logistics sector is similarly evolving, with SMEs adopting green fleet management practices. This includes the use of electric and hybrid vehicles, route optimization through digital tools, and sustainable supply chain management. These initiatives help reduce carbon emissions and improve overall efficiency, reinforcing the role of SMEs in advancing sustainability across industries (Boix-Fayos & de Vente, 2023).

2.3. Barriers and challenges to green innovation among SMEs

Despite increasing awareness and growing regulatory support, SMEs in Central Europe continue to face numerous obstacles in adopting green innovations. One of the most significant barriers is financial constraints. Many SMEs operate with limited budgets and struggle to secure the necessary funding for sustainability-focused investments. Green technologies and eco-friendly production methods often require high initial costs, while the return on investment (ROI) may take several years to materialize. Traditional financing institutions may be hesitant to provide loans because of the perceived risks associated with long payback periods, resulting in many SMEs being dependent on government grants, subsidies, or alternative financing options, which are not always easily accessible (Bilal et al., 2021).

Regulatory and administrative complexity is another major challenge. Environmental policies and sustainability regulations vary across Central European countries, creating an inconsistent and often confusing framework for SMEs. Frequent legislative changes and bureaucratic hurdles further complicate compliance, discouraging businesses from pursuing green initiatives. The lack of clear guidance and support mechanisms makes it difficult for SMEs to navigate evolving sustainability requirements, leading to delays or reluctance in the adoption of green innovations (Sikandar et al., 2024).

Technological limitations also hinder the effective integration of sustainable solutions. Many SMEs lack access to the cutting-edge green technologies, infrastructure, and expertise necessary for transitioning to environmentally friendly operations. Limited in-house technical capabilities prevent companies from fully leveraging energy-efficient systems, circular economy principles, or renewable energy sources. Additionally, the high costs of acquiring and implementing advanced green technologies further exacerbate this issue, making it challenging for SMEs to compete with larger corporations that have greater resources (Kougias et al., 2021).

Market uncertainty and fluctuating consumer demand also play crucial roles in shaping SMEs' decisions regarding green innovation. While sustainable products and services are gaining popularity, consumer behavior remains inconsistent. Many customers are reluctant to pay premium prices for green alternatives, making it difficult for SMEs to justify investments in eco-friendly solutions. The lack of widespread consumer education on the long-term benefits of sustainable products further contributes to hesitation in market adoption (Elavarasan et al., 2022).

Additionally, a lack of awareness and knowledge among SME owners and managers further slows the transition toward sustainable business practices. Many businesses are unaware of available green innovation opportunities, funding programs, or technical support initiatives. Without access to relevant information, SMEs struggle to identify the most suitable sustainable strategies for their operations. Overcoming these challenges requires a combination of targeted financial support, regulatory simplification, improved technological access, and educational initiatives to encourage SMEs to integrate green innovations effectively (Bonoli et al., 2021; Matos et al., 2022).

2.4. Tools to promote the implementation of green innovation

To accelerate the adoption of green innovations among SMEs, targeted policy interventions and strategic support mechanisms are crucial. One of the most effective measures is the expansion of financial incentives and funding schemes. Governments should offer a range of financial tools, including grants, low-interest loans, and tax benefits, which would lower the initial cost burden for SMEs adopting sustainable technologies. These financial mechanisms can help offset the high upfront investment costs associated with green innovations and reduce the long payback periods that often discourage SMEs from pursuing sustainability (Cifuentes-Faura, 2022; Davies et al., 2021).

Regulatory harmonization across Central European countries is another critical factor. By standardizing environmental policies and creating consistent regulations, governments can reduce the bureaucratic complexities that SMEs face when they are operating across borders. A more predictable regulatory environment will encourage businesses to invest in sustainable practices, as they can better anticipate the long-term implications of their investments without the fear of sudden regulatory change (Buttol et al., 2012).

Encouraging public–private partnerships (PPPs) is also an effective strategy for promoting green innovation. Collaborations between small and medium-sized enterprises, research institutions, and larger enterprises can foster knowledge transfer, enabling SMEs to access cutting-edge technologies, technical expertise, and best practices. This approach can accelerate the adoption of green solutions by providing SMEs with the resources and support they might not otherwise have (Filipović et al., 2022; Lagioia et al., 2023).

In addition, increasing training and awareness programs is essential to help SME owners and employees fully understand the economic and environmental benefits of green innovations. Educational initiatives can highlight the potential cost savings, efficiency improvements, and competitive advantages that come with sustainable practices. Governments and industry associations should also work together to increase market demand through the promotion of sustainable procurement policies, green labelling initiatives, and consumer awareness campaigns, which can further incentivize businesses to invest in eco-friendly solutions (Aboelmaged & Hashem, 2019; Kluza et al., 2021).

2.5. Research Hypothesis

The literature on green innovations consistently indicates that SMEs face substantial barriers related to financial constraints, limited technological capabilities, regulatory complexity, and insufficient access to knowledge and external networks (Demirel & Kesidou, 2019; Ghisetti & Pontoni, 2015; Klewitz & Hansen, 2014). However, existing empirical studies often treat SMEs as a homogeneous group, overlooking differences between micro, small, and medium-sized enterprises. As a result, the extent to which firm size influences the perception and severity of green innovation barriers remains insufficiently explored, particularly in the context of manufacturing SMEs in Central Europe.

From the perspective of the resource-based view, smaller firms are expected to face more pronounced internal constraints because of limited financial, human, and technological resources (Borsatto & Bazani, 2021). Moreover, institutional theory suggests that regulatory pressures and external support mechanisms may affect firms differently depending on their organizational capacity to respond (Del Rio et al., 2017). These theoretical arguments imply that barriers to the adoption of green innovations are likely to vary systematically with firm size.

On the basis of these considerations, the following hypotheses are formulated:

H1: There are statistically significant differences in the perceived barriers to the adoption of green innovations among manufacturing SMEs depending on firm size.

H2: Compared with medium-sized enterprises, micro and small enterprises perceive internal barriers related to human capital and technological capabilities as more severe.

H3: Compared with SMEs, microenterprises perceive external barriers related to market dominance and limited cooperation with research institutions as more severe.

3. Data and Methods.

The aim of this research study was to identify key barriers to the implementation of green innovations in manufacturing enterprises in Central Europe, considering the structure and size of businesses. Additionally, the study examined whether the identified barriers represent crucial factors that hinder the faster and more efficient adoption of green innovations across different industries.

3.1. Data

This study is based on primary quantitative data collected from SMEs operating in the manufacturing sector in Central Europe. The target population consists of manufacturing SMEs, as this sector is among the most environmentally intensive and plays a key role in the regional transition toward sustainable production.

The empirical data were obtained through a structured questionnaire administered using the computer-assisted telephone interviewing (CATI) method. Data collection was carried out among senior managers and owners who are directly involved in strategic decision-making related to innovation and sustainability. This approach ensured that the responses reflected informed managerial perspectives on green innovation barriers.

The final research sample comprises 184 manufacturing SMEs. Enterprises were classified according to the OECD definition on the basis of employment size: microenterprises (fewer than 10 employees), small enterprises (10–49 employees), and medium-sized enterprises (50–249 employees). This classification allows for a size-sensitive analysis of perceived barriers to the adoption of green innovations. The questionnaire

consisted of eleven substantive questions and three classification questions. The core part of the survey focused on identifying barriers to the adoption of green innovations. The respondents evaluated fourteen predefined barriers, covering financial, regulatory, technological, organizational, and market-related constraints. The respondents evaluated 14 specific barriers, each presented separately: uncertain market demand (Q03_01_A), uncertain return on investment or excessively long payback periods for green innovation adoption (Q03_01_B), lack of financial resources within the company (Q03_01_C), insufficient access to existing subsidies and tax incentives (Q03_01_D), existing regulations and structures not providing incentives for green innovation adoption (Q03_01_E), lack of external financing (Q03_01_F), energy consumption reduction that is not an innovation priority (Q03_01_G), technical and technological barriers (e.g., outdated technical infrastructure) (Q03_01_H), lack of skilled workers and technological capacity within the company (Q03_01_I), market dominance by established manufacturers (Q03_01_J), material consumption reduction that is not an innovation priority (Q03_01_K), limited access to external information and knowledge, including underdeveloped technical support services (Q03_01_L), lack of suitable business partners (Q03_01_M), and lack of cooperation with research institutions and universities (Q03_01_N).

Each barrier was assessed using a five-point ordinal scale reflecting the perceived severity of the barrier: very severe barrier (1), somewhat severe barrier (2), not a severe barrier (3), not a barrier at all (4), and not applicable (5). For analytical purposes, the ordinal nature of the variables was preserved.

Prior to the main data collection, the questionnaire was pilot tested on a sample of 15 SME managers who were not included in the final dataset. This pilot test helped refine the wording and structure of the questions. Content validity was ensured through alignment with established survey instruments, including the Eurobarometer approach. The internal consistency of the measurement scale was verified using Cronbach's alpha, which reached a value of 0.82, indicating satisfactory reliability.

3.2. Methods

The analytical strategy was designed to examine whether perceived barriers to the adoption of green innovations differ significantly across SME size categories. Given the ordinal nature of the data and the results of the Shapiro–Wilk test, which indicated deviations from normality, nonparametric statistical methods were applied.

To test for overall differences among micro, small, and medium-sized enterprises, the Kruskal–Wallis H test was employed. This test is suitable for comparing more than two independent groups when parametric assumptions are not met and has been widely used in empirical research on innovation and sustainability in SMEs. The test allowed for the identification of barriers for which perceptions differ significantly across firm size categories.

For barriers for which statistically significant differences were detected, post hoc pairwise comparisons were conducted using the Dwass–Steel–Critchlow–Fligner (DSCF) test. This nonparametric post hoc procedure controls for Type I error in multiple comparisons and is appropriate for unequal sample sizes and ordinal data. The DSCF test enabled a more detailed examination of differences between specific pairs of SME size groups.

All the hypotheses were tested at a significance level of $\alpha = 0.05$. Random sampling and data processing were conducted using the statistical software Jamovi. Throughout the analysis, established methodological guidelines were followed to ensure the robustness, transparency, and reproducibility of the results.

This two-stage analytical approach – combining overall group comparison with targeted post hoc testing – allowed for a nuanced assessment of size-related heterogeneity in green innovation barriers and directly supported the study's research questions and hypotheses.

4. Results.

This section presents the empirical findings on barriers to the adoption of green innovations among manufacturing SMEs, with a particular focus on differences across firm size categories. The results are structured according to the applied statistical procedures. First, overall differences among micro, small, and medium-sized enterprises are examined using the Kruskal–Wallis test. Post hoc pairwise comparisons are subsequently reported for those barriers for which statistically significant differences were identified.

Table 1 presents the results of the Kruskal–Wallis test, which was applied to examine whether statistically significant differences exist in the perceived severity of green innovation barriers across micro, small, and medium-sized enterprises. The table reports the chi-square statistics, degrees of freedom, p values, and effect sizes for each analysed barrier.

As shown in Table 1, statistically significant differences across firm size categories were identified for four barriers: reducing energy consumption is not an innovation priority (Q03_01_G), a lack of skilled

personnel and technological capabilities within the enterprise (Q03_01_I), market dominance by established manufacturers (Q03_01_K), and a lack of cooperation with research institutions and universities (Q03_01_N).

Table 1. Nonparametric Kruskal–Wallis test was used.

Variables	χ^2	df	p	ε^2
Q03_01_A	3.0524	2	0.2174	0.0167
Q03_01_B	3.8454	2	0.1462	0.0210
Q03_01_C	0.8464	2	0.6549	0.0046
Q03_01_D	2.8026	2	0.2463	0.0153
Q03_01_E	3.7741	2	0.1515	0.0206
Q03_01_F	4.2715	2	0.1182	0.0233
Q03_01_G	6.2978	2	**0.0429**	0.0344
Q03_01_H	3.9124	2	0.1414	0.0214
Q03_01_I	13.7825	2	**0.0010**	0.0753
Q03_01_J	3.8459	2	0.1462	0.0210
Q03_01_K	7.6257	2	**0.0221**	0.0417
Q03_01_L	3.1043	2	0.2118	0.0170
Q03_01_M	4.0731	2	0.1305	0.0223
Q03_01_N	9.4233	2	**0.0090**	0.0515

Note: Values in bold indicate statistically significant results at the 0.05 significance level ($p < 0.05$).
Source: Created by the authors.

These results indicate that firm size plays an important role in shaping how SMEs perceive specific obstacles to green innovation adoption. For the remaining barriers, no statistically significant differences were observed, suggesting that some constraints, such as financial limitations or regulatory complexity, are perceived relatively uniformly across SME categories.

Following the identification of statistically significant differences among the tested variables using the Kruskal–Wallis test, we conducted the Dwass–Steel–Critchlow–Fligner (DSCF) test, a nonparametric post hoc test, to further examine pairwise differences between associated variables.

Table 2 reports the post hoc results for the barrier "reducing energy consumption is not an innovation priority" (Q03_01_G).

Table 2. Pairwise comparisons between groups – Q03_01_G.

Group 1	Group 2	W	p
Micro	Medium	-3.4975	0.0358
Micro	Small	-2.3823	0.2113
Medium	Small	1.4181	0.5754

Source: Created by the authors.

The purpose of this table is to identify which SME size categories differ significantly in their perceptions of this barrier. Adaptation barrier Q03_01_G ($\chi^2_{(2)} = 6.2978$, $p = 0.0429$) was found to be a greater challenge for medium-sized enterprises than for small enterprises and microenterprises.

The results shown in Table 2 indicate that compared with microenterprises, medium-sized enterprises perceive the low prioritization of energy consumption reduction as a significantly stronger barrier. No statistically significant differences were observed between micro and small enterprises or between SMEs. These findings suggest that energy-related innovation priorities vary with firm size, potentially reflecting differences in strategic focus or prior implementation of energy-efficiency measures.

Table 3 presents post hoc comparisons for the barrier "lack of skilled personnel and technological capabilities within the enterprise" (Q03_01_I), which was identified as highly significant by the Kruskal–Wallis test. Adaptation barrier Q03_01_I ($\chi^2_{(2)} = 13.7825$, $p = 0.0010$) was identified as a more pressing issue for microenterprises than for small enterprises and medium-sized enterprises.

Table 3. Pairwise comparisons between groups – Q03_01_I.

Group 1	Group 2	W	p
Micro	Medium	-5.2343	0.0006
Micro	Small	-3.2440	0.0567
Medium	Small	2.3849	0.2105

Source: Created by the authors.

As shown in Table 3, compared with medium-sized enterprises, microenterprises perceive this barrier as significantly more severe.

The difference between micro and small enterprises is also substantial, although it falls marginally below conventional significance thresholds. These results indicate that human capital and technological capacity constraints are particularly acute for the smallest firms, highlighting their limited internal resources for implementing green innovations.

Table 4 focuses on the barrier "market dominance by established manufacturers" (Q03_01_K) and presents pairwise comparisons across SME size categories. The adaptation barrier Q03_01_K ($\chi^2_{(2)} = 7.6257$, $p = 0.0221$) was identified as a more pressing issue for microenterprises than for small enterprises and medium-sized enterprises.

Table 4. Pairwise comparisons between groups – Q03_01_K.

Group 1	Group 2	W	p
Micro	Medium	-3.2519	0.0559
Micro	Small	-1.0170	0.7524
Medium	Small	3.3261	0.0490

Source: Created by the authors.

The results reported in Table 4 show that this barrier is perceived as significantly more restrictive by microenterprises than by medium-sized enterprises. This suggests that smaller firms face stronger competitive pressure from incumbent firms, which may limit their ability to introduce green innovations and compete in environmentally oriented markets.

Table 5 presents the post hoc analysis for the barrier "lack of cooperation with research institutions and universities" (Q03_01_N), which reflects external knowledge and collaboration constraints.

Table 5. Pairwise comparisons between groups – Q03_01_N.

Group 1	Group 2	W	p
Micro	Medium	-4.0904	0.0107
Micro	Small	-1.6246	0.4841
Medium	Small	3.0609	0.0775

Source: Created by the authors.

According to the data in Table 5, compared with medium-sized enterprises, microenterprises perceive a lack of cooperation with research institutions as a significantly stronger barrier ($\chi^2(2) = 9.4233$, $p = 0.0090$). Although the differences between micro and small enterprises are not statistically significant, the overall pattern indicates that access to research collaboration improves with firm size. These findings underscore the challenges faced by smaller firms in engaging with formal innovation and research networks.

One limitation of this study is its focus on the implementation of green innovations specifically within Central European enterprises. The findings are based on the views and experiences of businesses operating within the legislative and regulatory framework of the Central European region, which may not be directly applicable to enterprises in other geographic areas.

Green innovation is a complex and evolving topic that is significantly influenced by external factors that either facilitate or hinder its implementation. The research outcomes indicate that SMEs have received limited attention because of their barriers to the implementation of green innovations. Given these findings, we recommend that policymakers take proactive measures to enhance financial mobilization to support SMEs in overcoming these barriers and accelerating the transition across manufacturing industries.

Furthermore, governments should establish conducive legislative frameworks that support SMEs in their adaptation efforts. To build upon this study, future research will explore the extent of financial support available for SMEs in Central Europe from both the EU and national sources. This is particularly relevant in the context of the new EU strategy aimed at promoting green innovations, as outlined in the introduction of this paper.

The results cannot be generalized across all SME sectors, as the research focused exclusively on the manufacturing sector. Sectors such as services, agriculture or transport may face different barriers, especially in terms of consumer behavior or technological capabilities. Another limitation is the regional framework, as the legislative and institutional environments in other parts of Europe may differ significantly. The results should therefore be interpreted with regard to the specific context of Central Europe. Future research should

broaden both the geographical and sectoral focus to strengthen the validity and applicability of the conclusions.

5. Discussion.

The finding that micro and small enterprises perceive significantly stronger barriers related to human capital shortages, limited technological capabilities, and weak cooperation with research institutions is broadly consistent with earlier empirical studies on green innovation among SMEs. Previous research has repeatedly shown that SMEs often lack the internal resources, specialized skills, and technological expertise required to adopt environmentally sustainable innovations (Demirel & Kesidou, 2019; Pinget et al., 2015). The present study confirms these conclusions but extends them by demonstrating that such constraints are not evenly distributed across the SME sector. In line with the resource-based view, smaller firms face more pronounced limitations in developing innovation-related capabilities, which reduce their ability to respond to environmental challenges and regulatory pressures (Borsatto & Bazani, 2021).

The strong barrier associated with limited cooperation between microenterprises and research institutions supports earlier findings emphasizing the role of external knowledge networks in fostering green innovations (Boiral et al., 2023; Klewitz & Hansen, 2014). However, while many prior studies highlight collaboration as a general success factor for SMEs, the present results refine this argument by showing that the lack of such cooperation is particularly restrictive for microenterprises. This suggests that innovation ecosystems and support mechanisms may not be sufficiently inclusive or accessible for the smallest firms, especially in Central Europe, where institutional support for SME innovation varies considerably across regions. Compared with studies conducted in Western Europe, where university–industry linkages are often more developed, this regional context may partly explain the stronger negative perception observed in this study.

Financial constraints and regulatory complexity emerge as persistent barriers across all SME size categories, which strongly confirms the dominant consensus in the literature. Numerous studies have identified high upfront investment costs, long payback periods, and regulatory uncertainty as major deterrents to green innovation adoption (Ghisetti & Pontoni, 2015; Giudici et al., 2023). The present findings do not contradict this body of research but contribute additional nuance by showing that the perceived severity of these barriers intensifies as firm size decreases. This observation is consistent with institutional theory, which argues that regulatory pressure alone is insufficient to stimulate innovation when firms lack the financial and organizational capacity to comply (Del Rio et al., 2017).

An interesting and partially divergent finding is that compared with micro and small enterprises, medium-sized enterprises perceive a reduction in energy consumption as a lower innovation priority (Raza et al., 2025). These results contrast with studies suggesting that larger SMEs are generally more proactive in sustainability initiatives (Cainelli et al., 2015; Passaro et al., 2023). A plausible explanation lies in sectoral and developmental differences. Manufacturing SMEs in Central Europe may have already implemented basic energy efficiency measures, leading medium-sized firms to focus on other strategic objectives, such as productivity improvements or market expansion (Kubalek & Kudej, 2025). From an evolutionary economics perspective, innovation priorities evolve as firms progress through different stages of development, which may explain this shift in focus (Arici & Uysal, 2022; Dorcak et al., 2015).

Differences between the present findings and those of earlier studies may also stem from methodological factors. While much of the existing research relies on secondary data, case studies, or country-level indicators, this study uses primary data collected directly from senior managers and applies nonparametric statistical methods to capture size-related differences. As a result, subjective managerial perceptions and heterogeneity within the SME sector are more explicitly reflected. This methodological approach may explain why certain size-dependent barriers have been underreported or overlooked in previous aggregated analyses.

The findings both confirm and extend the existing knowledge on green innovation among SMEs. They confirm the central role of financial, regulatory, and knowledge-related barriers while extending the literature by providing size-sensitive, sector specific, and regionally grounded empirical evidence. By integrating insights from the resource-based view, institutional theory, and evolutionary economics, the study demonstrates that green innovation adoption in SMEs is shaped by the interaction of internal resource constraints and external institutional conditions.

This study contributes to the scientific discourse by challenging the widespread assumption that SMEs constitute a homogeneous group and by highlighting the need for differentiated analytical and policy approaches. This interpretative comparison with the literature underscores the theoretical relevance and empirical originality of the study and reinforces its contribution to research on sustainability-oriented innovation in SMEs.

6. Conclusions.

This study examined the key barriers to the adoption of green innovations among manufacturing SMEs in Central Europe, paying particular attention to differences related to firm size. The empirical findings confirm that SMEs face multiple and interrelated obstacles that hinder the implementation of environmentally sustainable innovations. Financial constraints, regulatory complexity, limited access to external financing, and technological and human capital deficiencies emerge as the most significant barriers, with micro and small enterprises being disproportionately affected compared with medium-sized enterprises. The results also demonstrate that barriers are not uniform across the SME sector, highlighting the importance of considering firm size when analysing green innovation challenges.

From a policy perspective, the findings suggest several important implications for policymakers at both the national level and the European level. First, public support schemes aimed at promoting green innovations should be more differentiated and explicitly tailored to firm size. Micro and small enterprises require targeted financial instruments, such as simplified grant schemes, low-interest loans, and tax incentives, that reflect their limited financial capacity and higher perceived risk. Second, regulatory frameworks should be streamlined and harmonized to reduce administrative burdens and uncertainty, which currently discourages SMEs from investing in green technologies. Clearer guidance, stable regulatory conditions, and improved access to information can significantly increase SMEs' willingness to engage in sustainable innovation activities.

For SME managers, the results highlight the strategic importance of building internal capabilities that support the adoption of green innovations. Investments in employee training, skills development, and technological upgrading can help mitigate the human capital and knowledge-related barriers identified in the study. Managers are also encouraged to actively seek collaboration with external partners, including research institutions, universities, and industry networks, as such cooperation can provide them with access to expertise, technological know-how, and innovation opportunities that are otherwise difficult to obtain internally. Integrating sustainability objectives into long-term business strategies rather than treating green innovations as isolated initiatives may further enhance firms' resilience and competitiveness.

Supporting institutions, such as innovation agencies, business associations, and research organizations, play a critical intermediary role in facilitating the green transition of SMEs. The findings indicate a need for stronger knowledge transfer mechanisms, advisory services, and partnership platforms that connect SMEs with researchers, technology providers, and funding opportunities. The development of accessible support structures, including training programs, innovation hubs, and applied research collaborations, can help overcome informational and technological barriers and foster a more inclusive innovation ecosystem.

In terms of theoretical contribution, this study advances the literature on green innovations by providing size-sensitive empirical evidence from a Central European manufacturing context, an area that has received limited attention in previous research. By explicitly differentiating between micro, small, and medium-sized enterprises, the study demonstrates that when analysing innovation barriers, SMEs should not be treated as a homogeneous group. This nuanced approach contributes to a more refined understanding of how organizational size influences the capacity of firms to engage in sustainable innovation.

Practically, the study offers actionable insights for decision-making and strategy development among key stakeholders involved in the green transition. The results can inform the design of more effective and targeted policy instruments, guide SME managers in prioritizing strategic investments, and support intermediary institutions in tailoring their services to the specific needs of different SME groups.

Despite its contributions, the study has several limitations. The empirical analysis focuses exclusively on manufacturing SMEs in Central Europe, which may limit the generalizability of the findings to other sectors or regions. Future research should extend the analysis to service-oriented and agricultural SMEs, as well as to other European and non-European contexts, to enable broader comparisons. Future studies could also explore longitudinal data to assess how green innovation barriers evolve over time and evaluate the effectiveness of specific policy instruments, such as subsidies or market-based incentives, in reducing these barriers. Such research would deepen the understanding of the dynamics of green innovation adoption and support the development of more robust sustainability strategies for SMEs.

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Марія Бартекова, Братиславський університет економіки та бізнесу, Словаччина
Сабіна Яніковічова, Братиславський університет економіки та бізнесу, Словаччина

Зелені інновації та бар'єри їх впровадження на малих і середніх підприємствах Центральної Європи

Перехід до низьковуглецевого розвитку став стратегічним пріоритетом у Європейському Союзі, що тим самим провокує підприємства активізувати впровадження зелених інновацій. Малі та середні підприємства (МСП) відіграють ключову роль в економічному розвитку та промисловому виробництві Центральної Європи; однак рівень їх залученості до діяльності у сфері зелених інновацій залишається обмеженим. Незважаючи на зростання

регуляторних вимог і суспільних очікувань, МСП часто стикаються зі структурними, фінансовими та організаційними обмеженнями, які перешкоджають ефективному впровадженню екологічно сталих практик. Наявні емпіричні дослідження свідчать, що ці бар'єри є неоднорідними та можуть варіювати залежно від розміру підприємства й організаційних характеристик. Метою цього дослідження є заповнення зазначеної прогалини шляхом системного аналізу ключових бар'єрів впровадження зелених інновацій на промислових МСП Центральної Європи з особливим акцентом на відмінностях, пов'язаних із чисельністю зайнятих. Емпіричний аналіз базується на первинних кількісних даних, зібраних за допомогою структурованого опитувальника методом комп'ютеризованого телефонного інтерв'ю (CATI). Остаточна вибірка включає 184 топменеджерів промислових МСП Центральної Європи, класифікованих як мікро-, малі та середні підприємства відповідно до критеріїв ОЕСР. Респонденти оцінювали чотирнадцять потенційних бар'єрів впровадження зелених інновацій за порядковою шкалою типу Лайкерта. Надійність інструментарію дослідження підтверджено коефіцієнтом альфа Кронбаха на рівні 0,82. З огляду на ненормальний розподіл даних було застосовано непараметричні статистичні методи. Для виявлення відмінностей між групами підприємств за розміром використано тест Крускала–Уолліса, тоді як для попарного порівняння груп – пост-хок тест Двасса–Стіла–Крітчлоу–Флігнера. Отримані результати свідчать про наявність статистично значущих відмінностей у сприйнятті бар'єрів впровадження зелених інновацій серед МСП різних розмірів. Мікро- та малі підприємства стикаються з більш суттєвими труднощами, зокрема через нестачу кваліфікованого персоналу, обмежені технологічні можливості, слабку співпрацю з науково-дослідними установами та домінування усталених компаній на ринку. Натомість середні підприємства частіше розглядають низький пріоритет скорочення енергоспоживання як значущий бар'єр. Загалом фінансові обмеження, складність регуляторного середовища та обмежений доступ до знань і зовнішньої експертизи визначено як найважливіші перешкоди, що непропорційно впливають на менші підприємства. Результати дослідження підкреслюють неоднорідний характер бар'єрів зелених інновацій у секторі МСП та обґрунтовують необхідність розробки політик, диференційованих за розміром підприємств. Цільові програми фінансової підтримки, спрощення регуляторних процедур і посилення взаємодії між МСП, науковими установами та органами державної влади є ключовими умовами прискорення поширення зелених інновацій. Надані емпіричні результати щодо промислових МСП Центральної Європи роблять внесок у розвиток теорії сталих інновацій та мають практичне значення для формування більш ефективної політики зеленого переходу.

Ключові слова: довкілля; сталий розвиток; інновації; малі та середні підприємства; виклики.