
Research article

Digital transformation, innovation, and green transitions: A panel data analysis of structural drivers in the European economy

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Abstract: In this paper, we investigated the structural relationships between digital transformation, sustainability-related factors, and research and development (R&D) expenditure across European Union (EU) member states. We examined how renewable energy adoption, digital connectivity, e-commerce activity, and labor taxation are associated with innovation dynamics within the broader context of the European green and digital transition agendas. The empirical analysis relied on balanced panel data covering 27 EU countries over the period 2013–2023 using harmonized Eurostat indicators. The empirical framework relied on fixed-effects panel estimation complemented by robustness procedures suitable for structurally interconnected EU macro-panel data. Additional diagnostic tests supported the stationarity and adequacy of the estimated panel specifications. The empirical findings indicated that renewable energy adoption and enterprise-level internet access were positively associated with R&D expenditure in the baseline contemporaneous fixed-effects estimations. In contrast, e-commerce-related indicators exhibited weaker and less stable relationships once broader dimensions of digital maturity and robustness specifications were considered. Labor taxation displayed a negative association with R&D expenditure in the baseline models; however, the lagged robustness estimations revealed weaker and less consistent effects over time. The additional lagged and PCSE specifications suggest that several estimated relationships become less stable once potential simultaneity and panel-specific disturbances are more explicitly addressed. The results therefore support the existence of broader structural complementarities between sustainability transition, digitalization, and innovation capacity across EU economies rather than strong unidirectional causal relationships. We also identified significant regional heterogeneity, indicating that the

interaction between renewable energy development and innovation differs across European regions. Overall, the findings highlight the importance of institutionally adapted and structurally differentiated policy approaches for supporting innovation performance within the EU.

Keywords: Innovation policy; R&D expenditure; digital economy; green transition; fiscal policy; EU27; panel data analysis

JEL Codes: C23, O32, O33, Q56

1. Introduction

In the context of accelerating structural transformations within the European Union (EU), the interaction between digitalization, sustainability-oriented development, and innovation has become increasingly important for long-term economic competitiveness and resilience. European policy frameworks, including the European Green Deal (European Commission, 2023), the Digital Compass 2030 (European Commission, 2021), and Horizon Europe (European Commission, 2024a), emphasize the need to strengthen digital infrastructure, support renewable energy transition, and stimulate research and development (R&D) capacity. These strategic priorities reflect the growing recognition that innovation dynamics are closely connected to broader structural conditions related to technological modernization, sustainability transition, and institutional adaptation. Despite this policy emphasis, empirical evidence regarding the interconnections between these dimensions remains fragmented, particularly in relation to the structural factors associated with innovation expenditure across EU member states.

Researchers frequently examine digital transformation, energy transition, fiscal conditions, or innovation separately, while relatively limited attention has been devoted to their simultaneous interaction within a unified macroeconomic framework. In particular, the literature provides insufficient evidence regarding how digital connectivity, sustainability-related indicators, and labor taxation are structurally associated with national R&D expenditure within the EU. This limitation is particularly relevant in the context of post-pandemic economic restructuring, where innovation capacity, technological resilience, and digital readiness have become central components of European development strategies. Against this background, we investigate the structural relationships between renewable energy adoption, enterprise digitalization, e-commerce activity, labor taxation, and R&D expenditure across EU member states during the period 2013–2023.

Accordingly, our main objective of the paper is to assess the extent to which selected structural indicators related to digitalization, sustainability transition, and fiscal conditions are associated with innovation expenditure within the EU. For the empirical analysis, we focus on gross domestic expenditure on research and development (GDERD) as the dependent variable and examines its relationship with the share of renewable energy in final energy consumption (SRNWEN), the value of e-commerce sales (ECOMSALE), enterprise internet access (ENTRINTAC), the implicit tax rate on labor (ITXRL), and the percentage of enterprises receiving online orders (ENTRORDONLINE). We aim to identify broad structural patterns characterizing innovation dynamics across EU economies rather than to establish strict causal relationships between the analyzed variables.

The methodological framework is based on balanced panel data covering the 27 EU member states over the period 2013–2023 using harmonized Eurostat indicators. For the empirical analysis, we combine fixed-effects panel estimation with Driscoll–Kraay robust standard errors to address heteroskedasticity, serial correlation, and cross-sectional dependence. Additional robustness procedures, including Panel-Corrected Standard Errors (PCSE) estimations and lagged panel specifications, are employed to evaluate the stability of the estimated relationships under alternative econometric assumptions. Furthermore, panel diagnostic procedures and cross-sectionally augmented unit root tests are implemented to assess the adequacy of the empirical specification.

The novelty of the study resides in its integrative macro-structural perspective, which simultaneously considers digitalization, sustainability transition, and fiscal conditions within the analysis of innovation expenditure dynamics in the EU. Unlike researchers who investigate these dimensions separately, our analysis emphasizes their interconnected nature within the broader context of European economic transformation. Furthermore, the study contributes methodologically by combining robustness procedures adapted to structurally interconnected macro-panel data characterized by cross-sectional dependence and heterogeneous national trajectories.

Several broader research questions guide the analysis: To what extent are renewable energy adoption and enterprise digitalization structurally associated with higher levels of R&D expenditure? How are labor taxation and innovation dynamics related across EU member states? Do sustainability-oriented structural transformations coincide with stronger innovation investment patterns? These questions are particularly relevant for understanding the economic architecture of contemporary European transformation processes and for evaluating the conditions associated with long-term innovation capacity within heterogeneous European economies.

The theoretical perspective underlying the analysis combines Schumpeterian approaches to innovation-driven structural transformation with endogenous growth theory. From a Schumpeterian perspective, technological change, knowledge creation, and innovation are central mechanisms of economic restructuring and long-term competitiveness (Ebner, 2025; Yoruk et al., 2023). Furthermore, endogenous growth theory emphasizes the importance of technological progress, human capital, and policy-supported investment in sustaining long-run economic development (Kerner et al., 2023; Saeed & Klugah, 2025). Within this framework, renewable energy transition, digital infrastructure, and fiscal conditions can be interpreted as structural dimensions associated with the capacity of economies to support innovation-related investment.

The study is limited to the EU-27 due to considerations related to data comparability, policy homogeneity, and the availability of harmonized indicators. Moreover, for the analysis, we focus on macroeconomic structural indicators and do not directly incorporate firm-level dynamics or broader institutional governance variables, which may also influence innovation expenditure patterns. Consequently, the empirical results should be interpreted as evidence of structural associations within a macroeconomic comparative framework rather than definitive causal mechanisms.

Overall, we seek to provide empirical insights into the structural relationships between digital transformation, sustainability transition, fiscal conditions, and innovation expenditure within the EU. By identifying broader structural complementarities associated with R&D dynamics, the findings contribute to the understanding of European innovation patterns and provide evidence relevant for policy discussions concerning digitalization, sustainability, and long-term economic competitiveness.

The remainder of the paper is structured as follows: In Section 2, we present the literature review and hypothesis development. In Section 3, we describe the data, variables, and econometric

methodology employed in the analysis. This is followed by the empirical results and robustness analysis in Section 4. In Section 5, we conclude the paper by summarizing the major findings, discussing their implications, and outlining directions for future research.

2. Literature review

In a European context marked by multiple structural pressures, from the imperative of decarbonizing the economy to accelerating digital transformation and strengthening competitiveness through innovation, the literature has seen a significant proliferation of research dedicated to these topics. However, most researcher address phenomena such as digitization, green transition, or innovation in isolation, without fully capturing their systemic interdependencies. This gap has led to the need for integrative econometric models capable of simultaneously assessing the influence of structural variables on research and development efforts. Our aim of this section is to critically review the relevant literature on the relationships between digital transformation, labor taxation, the green transition, and R&D investment, focusing on their results and limitations.

2.1. Digitization and innovation capacity

A robust body of literature recognizes digitization as an essential determinant of innovation, in terms of access infrastructure and the use of advanced technologies by businesses. Researchers supporting this view (Capurro et al., 2021; Johnson et al., 2022; Ma & Chang, 2024) have shown that digitization accelerates the adoption of innovative processes through automation, big data, and artificial intelligence. In the same vein, studies (Sun et al., 2024; Zhao et al., 2024) have emphasized that digital connectivity is not an end in itself, but a catalyst for the modernization of business models and the diffusion of knowledge in interconnected economic networks.

With regard to Europe, the European Commission's Digital Economy and Society Index (DESI) (European Commission, 2024b) indicates a positive correlation between the degree of digitization and innovation performance, as measured by indicators such as R&D expenditure and the number of technology patents. However, there is considerable heterogeneity among Member States, with some economies characterised by business digitisation that does not translate into concrete investment in innovation, a phenomenon documented as the digitalization–innovation gap (European Commission, 2025b).

More specifically, the use of e-commerce has been investigated by researchers (Palmié et al., 2022; Song et al., 2022; Wulfert, 2024), who have highlighted that e-commerce can stimulate competitiveness and innovation, but only when integrated into a mature digital ecosystem. Studies conducted for European economies (Brodny & Tutak, 2022; García-Romanos & Martínez-Ros, 2024; Kádárová et al., 2023) show that digitized SMEs are significantly more likely to hire qualified personnel in research and development activities, provided that broadband infrastructure and institutional support are in place.

This literature thus supports the importance of the indicators used in this study, in particular ENTRINTAC and ENTRORDONLINE, as relevant proxies of digital maturity at the national level, with a potential impact on the intensity of innovation. Although the literature consistently (Gong et al., 2022; Meng & Wang, 2023) highlights the positive impact of digitalization on innovation capacity, the findings are not always fully consistent, particularly regarding the relative importance of different

dimensions of digitalization. Moreover, several researchers (Bao et al., 2025; Zygiaris, 2022) focus on specific aspects, such as infrastructure or e-commerce, without capturing their combined effects within a broader innovation framework.

2.2. The green transition and investment in research and development

The transition to a sustainable and decarbonized economic model requires not only changes in the energy structure, but also a profound redefinition of strategic priorities in research and innovation, as climate challenges call for cutting-edge technological solutions. According to the European Commission in the European Green Deal (European Commission, 2023), innovation is recognized as a central pillar in achieving the goal of climate neutrality by 2050, and research and development policies are being mobilized to support the decarbonization of key sectors, from industry and transport to agriculture and construction.

The hypothesis that stringent environmental policies can stimulate innovation processes among firms has been explored and supported by multiple empirical studies over the past two decades. For example, the study by Fabrizi et al. (2024) provides a theoretical and empirical synthesis of the hypothesis, arguing that environmental regulations, when designed effectively, can reduce negative externalities and, at the same time, generate incentives for technological innovation, thus creating a win-win situation for firms and society. In the same vein, numerous empirical studies (Dai et al., 2025; Karlilar Pata, 2024; Zhang et al., 2024) have shown that environmental regulatory policies, when designed in a coherent and predictable manner, can lead to a significant increase in investment in research and development geared towards green solutions, which in the medium and long term leads to improvements in both the economic performance of firms and environmental outcomes. Such policies act not only as corrective instruments for negative externalities, but also as drivers of technological innovation with a sustainable impact (Ahmad et al., 2025; Xu et al., 2024).

Other researchers (Huang et al., 2023; Usman et al., 2022), applying econometric models to European industry data panels, argue that the intensity of environmental regulations is positively linked to innovation performance, especially in sectors with high emission reduction potential. These results are consistent with other findings (Alcalde-Heras & Carrillo Carrillo, 2023; Casady et al., 2024; Naruetharadhol et al., 2024), which show that environmental policies become effective in stimulating green innovation especially when complemented by public support mechanisms such as subsidies, tax credits, or public-private partnerships. These studies reinforce the idea that environmental regulations should not be viewed exclusively as an economic constraint, but as a potential catalyst for technological transformation, especially in a European context marked by ambitious decarbonization and sustainability goals.

A series of studies (Bilgili et al., 2024; Grafström et al., 2023; Macedo & Marques, 2023) have confirmed the validity of the hypothesis for European economies, showing that investments in renewable sources are associated with increased research spending, as the energy transition requires new and costly technologies with long development cycles.

The literature has reinforced this view. For example, Tchorzewska (2024) and Ziaei & Roshani (2024) have shown that investments in eco-innovation are stimulated by environmental regulations only when they are accompanied by public support schemes and easy access to capital. In a similar vein, Zambrano-Monserrate et al. (2024) and Balcilar & Agan (2024) demonstrate that support policies

for renewable energy lead to a significant increase in patents in clean technologies, suggesting a causal relationship between regulation, financing, and innovative output.

At the EU level, studies (Cocker, 2025; Doğan et al., 2025; Fragkiadakis et al., 2025) have highlighted that market-based instruments for decarbonization, in particular emissions trading schemes and subsidies for green technologies, positively influence private and public spending on clean energy R&D. These effects are amplified in energy-intensive industries, where the pressure to transition is stronger.

Thus, the SRNWEN indicator used in the empirical analysis of this study captures not only progress in the use of renewable sources, but also the level of structural commitment to sustainable innovation. The literature convincingly supports the hypothesis that progress in the green transition and R&D efforts are interdependent phenomena, mutually reinforced by coherent public policies and systemic pressures for ecological transformation. While the relationship between environmental policies and innovation is widely supported in the literature, studies often emphasize specific channels, such as regulation or renewable energy investments, without fully addressing their interaction with digital and fiscal factors (Rastegar et al., 2024; Siddika et al., 2025;). This suggests the need for more integrative approaches to understand the systemic nature of sustainability-driven innovation.

2.3. Taxation of labor and innovative efforts

The relationship between labor taxation and the intensity of research and development spending is a relatively neglected topic in the established economic literature, often approached from a simplistic perspective that treats the tax burden as a barrier to economic performance. Traditionally, high labor taxation is related to increased employment costs, labor market rigidity, and reduced incentives for private investment, including in innovation (Camino-Mogro, 2023; Ding et al., 2025; Ernst et al., 2025). This approach, specific to the neoclassical school, has underpinned numerous recommendations to reduce the tax burden on labor in order to increase competitiveness.

However, contemporary economic literature has begun to nuance this perspective, arguing that the effects of taxation on innovation do not depend exclusively on the level of taxation, but rather on the efficiency with which the collected resources are used. In this regard, various studies (Cahyadi, 2024; OECD, 2024; Song & Zhao, 2024) have shown that a robust tax system, combined with effective redistributive policies, can support innovation by allocating funds to education, digital infrastructure, and public research programs. This approach is also supported by the literature (Filippetti & Vezzani, 2022; Jungo, 2024; Mohamed et al., 2022), which emphasizes that ‘quality of public spending’ is a determining factor for economic productivity and innovation performance, especially in knowledge-based economies.

In the European context, there is empirical evidence supporting the idea that progressive and structurally investment-oriented tax systems contribute to stimulating innovation. For example, a number of analyses have shown (Belanová et al., 2025; European Investment Bank, 2025; OECD, 2023) that countries that maintain high tax pressure but use it effectively to finance public research, technological infrastructure, and advanced education systems perform better in terms of innovative output (patents, R&D expenditure, value-added products). In contrast, economies that adopt low-tax-low-investment models fail to generate a sustainable innovation ecosystem (Bocken & Short, 2021; Kouam & Asongu, 2022; Tan & Zhou, 2025).

In this logic, the inclusion of the ITXRL in the econometric model reflects not only a fiscal cost but also the potential capacity of the state to intervene in support of innovation. Thus, this variable becomes a proxy for the fiscal-structural context, revealing the extent to which revenues

collected from labor taxation are transformed into resources for the development of human capital and innovative infrastructure.

2.4. Integrative models and research

Economic literature seeking to integrate the dimensions of digitalization, taxation, and ecological transition into a coherent analytical framework has developed significantly against the backdrop of the increasingly evident interconnection of European strategic agendas.

In the past, these areas were analyzed in isolation, and recent contributions point to a clear trend toward the formulation of theoretical and empirical models capable of capturing the synergies and tensions between these structural dimensions. Relevant examples include (Cefis & Scrofanì, 2025; Leceta & Könnölä, 2021; Vărzaru et al., 2023), which propose a mapping of innovation ecosystems in the EU, integrating technological (digital readiness), institutional (quality of governance), and fiscal (structure of public revenues and subsidies for innovation) factors. They argue that public policies should be designed in a systemic manner, in which fiscal decisions, digital strategies, and sustainability objectives are perfectly aligned to avoid implementation inconsistencies and resource fragmentation. Additional contributions further emphasize the importance of integrated frameworks that combine digital transformation, sustainability, and innovation policies, highlighting the role of interdisciplinary approaches and systemic thinking in addressing complex structural challenges in modern economies (Erokhin & Gao, 2024; Yu et al., 2025).

In the same vein, other researchers (Liu et al., 2024; Wang & Zhao, 2024) introduce the concept of “digital green innovation,” demonstrating that the interaction between digitalization and climate policies leads to a multiplier effect on factor productivity and R&D intensity, particularly in energy-intensive industries. This convergence is considered a key element in achieving the dual goals of climate neutrality and industrial competitiveness.

Moreover, Dahmani (2024) and Simionescu (2025) emphasize the importance of integrating environmental taxation strategies (such as carbon taxes or energy efficiency subsidies) into public research and innovation programs in order to maximize socio-economic impact and avoid regressive effects on certain social categories.

From a methodological perspective, other researchers (Masoud, 2025; Osei et al., 2025; Zang & Xiong, 2025) have used dynamic panel models to capture the impact of structural factors on innovation intensity, demonstrating the validity of using cross-national comparative data sets. These works reinforce the empirical reasoning of the present study, which proposes an integrative model applied to European economies to highlight the interdependencies between digitalization, taxation, and sustainability.

The literature robustly supports the scientific approach of this study, highlighting the originality of integrating the three pillars into a single econometric model and its usefulness for developing coherent and transformative public policies in the context of the post-2030 European agendas.

2.5. Gaps in the literature and contribution of the study

A critical review of the literature shows that, although each of the dimensions addressed, digital, fiscal, and environmental, has been extensively studied in relation to innovation, contributions remain fragmented and often focus on isolated relationships, without fully capturing the interactions between these structural drivers. As a result, few researchers integrate these aspects into a common analytical

framework. In particular, there is a lack of research analyzing simultaneously the effect of firm digitization, tax pressure on labor, and the energy transition on national R&D expenditure in a comparative manner across EU countries.

The original contribution of the study lies in this integrative approach, complemented by a rigorous econometric estimation based on panel data, which enables the isolation of common structural effects and the identification of contextual differences between countries. The article therefore adds value to a fragmented literature and opens new research perspectives for the evaluation of convergent public policies in an era of multiple transformations.

The literature provides a solid foundation for understanding the relationships between digitalization, taxation, the green transition, and innovation, but remains incomplete in terms of analyzing the systemic interdependencies between these dimensions. In this study, we respond to this need by formulating an econometric model that integrates these variables into the analysis of R&D expenditure at the EU-27 level. It thus follows an emerging research direction dedicated to exploring the convergence of sustainability, digitalization, and innovation policies in a coherent and applicable framework for European policymakers.

3. Methodology

3.1. Research design, data, and variables

We adopt a quantitative research design aimed at identifying the structural determinants of research and development (R&D) expenditure across EU member states, within the broader context of digital transformation and the green transition. The empirical approach is based on panel data econometrics, which enables the simultaneous consideration of cross-country heterogeneity and temporal dynamics. The dataset consists of a balanced panel of the 27 EU member states observed over the period 2013–2023, resulting in 297 observations. The time horizon captures a phase characterized by intensified digitalization, consolidation of post-crisis recovery mechanisms, and the progressive implementation of sustainability-oriented policies at the European level.

The data are collected from harmonized statistical sources, primarily Eurostat, complemented by indicators provided by the European Commission. The use of standardized datasets ensures comparability across countries and methodological consistency in measurement. The variables included in the analysis are presented in Table 1.

Table 1. Presentation of the indicators analyzed.

No.	Symbol	Indicators	Unit of measurement	Source
1.	GDERD	Gross domestic expenditure on R&D	Percentage of gross domestic product (GDP)	(Eurostat, 2025b)
2.	SRNWEN	Share of renewable energy in gross final energy consumption	Percentage	(Eurostat, 2026)
3.	ECOMSALE	Value of e-commerce sales by NACE Rev. 2 activity	Enterprises' total turnover from e-commerce sales/ Percentage of turnover	(Eurostat, 2025d)
4.	ENTRINTAC	Internet access by size class of enterprise	Percentage of enterprises	(Eurostat, 2025c)
5.	ITXRL	Implicit Tax rate on labor	Percentage	(European Commission, 2025c)
6.	ENTRORDONLINE	Enterprises having received orders online (at least 1%) - % of enterprises	Percentage of enterprises/ Enterprises with e-commerce sales of at least 1% turnover	(Eurostat, 2025a)

Source: Author's contribution using Eurostat information.

GDERD, expressed as a percentage of GDP, is employed as the dependent variable, reflecting national innovation intensity. The explanatory variables are selected to capture three structural dimensions: the green transition (SRNWEN), digital transformation (ENTRINTAC, ECOMSALE, ENTRORDONLINE), and the fiscal framework (ITXRL). The selection is grounded in theoretical considerations and empirical evidence linking these domains to innovation performance.

The selection of variables included in the empirical model is grounded in the theoretical literature on innovation systems, endogenous growth, digital transformation, and sustainability transitions. Within this conceptual framework, innovation performance is interpreted not as an isolated economic outcome, but as the result of structural interactions between technological infrastructure, energy transformation, institutional conditions, and fiscal policy mechanisms. Contemporary approaches to innovation economics emphasize that research and development dynamics are strongly influenced by the broader structural environment in which firms and public institutions operate, particularly in economies undergoing simultaneous digital and ecological transitions (Ebner, 2025; Tiron-Tudor et al., 2025; Xing et al., 2024).

The dependent variable, GDERD, expressed as a percentage of GDP, is employed as a proxy for national innovation intensity. In the literature on endogenous growth and innovation economics, R&D expenditure is widely considered one of the most relevant indicators of a country's capacity to generate technological progress, knowledge accumulation, and long-term productivity growth. The use of GDERD reflects the assumption that innovation performance depends on the scale of resources allocated to research activities, technological development, and innovation-oriented investment. Researchers focusing on European innovation systems have consistently used R&D expenditure as a central indicator for evaluating national innovation capacity and structural competitiveness (Caglar et al., 2026; Marti & Puertas, 2023).

The variable SRNWEN, representing the share of renewable energy in gross final energy consumption, operationalizes the green transition dimension of the model. From a theoretical perspective, sustainability transition theories argue that the transition toward low-carbon and renewable-based economic systems generates increasing demand for technological adaptation, eco-innovation, and research-intensive industrial transformation. Renewable energy expansion requires continuous investments in energy efficiency, storage technologies, smart infrastructure, and green technological upgrading, thereby stimulating innovation processes at the public and private levels (Doğan et al., 2025; Hossain et al., 2026; Petersen et al., 2025). In Schumpeterian terms, the green transition may be interpreted as a process of structural technological transformation characterized by the replacement of carbon-intensive production systems with new technological paradigms. Consequently, higher levels of renewable energy integration are theoretically expected to be associated with stronger R&D efforts.

The digital transformation dimension is captured through three complementary indicators: enterprise-level internet access (ENTRINTAC), ECOMSALE, and enterprises receiving online orders (ENTRORDONLINE). These variables reflect different dimensions of digital maturity and digital business integration within national economies. ENTRINTAC captures the degree of digital infrastructure and connectivity available to firms and represents the structural capacity of enterprises to access information networks, digital platforms, and communication technologies. The literature on digital innovation systems emphasizes that digital connectivity facilitates knowledge diffusion, technological adoption, organizational modernization, and innovation collaboration across firms and sectors (Cheng et al., 2025; Jiao et al., 2025; Serrano-Ruiz et al., 2025). In this context, enterprise internet access can be interpreted as a foundational condition for the development of digital innovation ecosystems.

By contrast, ECOMSALE and ENTRORDONLINE capture more transactional dimensions of digitalization associated with the practical integration of online commercial activities into firms' operational structures. These indicators reflect the extent to which enterprises participate in digitally mediated market exchanges and online business models. However, the literature suggests that transactional digitalization does not automatically generate innovation capacity unless accompanied by broader technological capabilities, organizational adaptation, and advanced digital infrastructure (García-Romanos & Martínez-Ros, 2024; Li et al., 2025; Vărzaru & Bocean, 2024). This distinction is particularly relevant in the European context, where several economies display relatively high levels of digital commercial activity without corresponding increases in research intensity or technological sophistication. Consequently, the inclusion of multiple digital indicators enables the empirical analysis to differentiate basic digital connectivity and more advanced forms of digital economic integration.

The ITXRL is included in the model as an indicator of the fiscal and institutional environment influencing innovation dynamics. Theoretical approaches provide mixed expectations regarding the relationship between labor taxation and innovation performance. From a neoclassical perspective, higher labor taxation may reduce innovation incentives by increasing production costs, limiting firms' investment capacity, and reducing labor market flexibility (Chadha & Samiri, 2026; Khanna & Sharma, 2025). Conversely, institutional and public finance approaches argue that taxation may indirectly support innovation when public revenues are efficiently allocated toward education systems, research infrastructure, technological modernization, and innovation-support policies (Chen et al., 2025; Ivanková et al., 2025). In this regard, labor taxation reflects not only a production cost, but also the broader fiscal capacity of the state to sustain innovation-oriented public investment. The expected effect therefore depends on the efficiency of public spending and the institutional capacity to transform fiscal revenues into innovation-supporting mechanisms.

Overall, the integration of these variables into a unified econometric framework reflects the assumption that innovation performance in the EU is shaped by structural complementarities between digitalization, sustainability transitions, and fiscal conditions. Rather than acting independently, these dimensions interact within broader economic and institutional systems that influence the capacity of national economies to generate technological development and sustain long-term innovation dynamics. The operationalization of the variables therefore follows theoretical arguments and empirical evidence from the literature, ensuring consistency between the conceptual framework and the econometric specification adopted in the study.

3.2. Econometric framework and model specification

The empirical analysis is based on the following panel data model:

$$GDERD_{it} = \alpha + \beta_1 \cdot SRNWEN_{it} + \beta_2 \cdot ECOMSALE_{it} + \beta_3 \cdot ENTRINTAC_{it} + \beta_4 \cdot ITXRL_{it} + \beta_5 \cdot ENTRORDONLINE_{it} + \varepsilon_{it} \quad (1)$$

where $GDERD_{it}$: dependent variable, gross expenditure on research and development as a percentage of GDP in country i at time t ; α : constant term (intercept); $\beta_1, \beta_2, \dots, \beta_5$: regression coefficients reflecting the effect of each explanatory variable on the dependent variable; ε_{it} : idiosyncratic error term varying across cross-sectional units and time periods; i : index for cross-sectional units (EU countries); and t : the time index (year, between 2013 and 2023).

A central econometric concern in this context is the presence of unobserved country-specific characteristics, including institutional quality, structural economic composition, technological capabilities, and innovation capacity, which may simultaneously influence the dependent variable and the explanatory variables. If such unobserved effects are correlated with the regressors, pooled estimation may generate biased and inconsistent coefficient estimates.

To assess the appropriate panel specification, fixed effects and random effects estimators are initially considered. The selection between the two approaches is evaluated using the Hausman specification test (Hausman, 1978). The fixed effects estimator controls for time-invariant country-specific heterogeneity by enabling each country to have its own intercept, thereby isolating within-country variation over time. By contrast, the random effects approach assumes that the unobserved individual effects are uncorrelated with the explanatory variables and incorporates them into the composite error structure.

The results of the Hausman test ($\chi^2 = 247.367$, $p < 0.001$) reject the null hypothesis of no systematic difference between estimators, indicating that the random effects estimator is inconsistent in this context. This finding suggests the existence of correlation between the explanatory variables and unobserved country-specific effects across EU member states. Consequently, the fixed effects specification is retained as the baseline econometric model to improve the consistency and reliability of the estimated coefficients.

Additional robustness and diagnostic procedures are implemented to address econometric issues commonly encountered in macro-panel datasets involving European economies. Driscoll-Kraay robust standard errors are employed to correct for heteroskedasticity, serial correlation, and potential cross-sectional dependence. Furthermore, Panel-Corrected Standard Errors (PCSE) estimations and lagged panel specifications are introduced as complementary robustness approaches to evaluate the stability of the estimated relationships under alternative assumptions and to reduce the potential influence of contemporaneous simultaneity and reverse causality. In addition, panel unit root tests based on the

Pesaran Cross-sectionally Augmented IPS (CIPS) procedures are implemented to assess the stationarity properties of the variables and the adequacy of the panel specification under cross-sectional dependence conditions.

Within this econometric framework, the empirical analysis is guided by a set of testable hypotheses derived from the theoretical and empirical literature on innovation, digital transformation, and sustainability transitions (Mäkitie et al., 2023; Montresor & Vezzani, 2023; Sun et al., 2025).

Based on the theoretical framework, we propose the following hypotheses: An increase in the share of renewable energy is expected to be positively associated with R&D expenditure (H1); a higher level of internet access among enterprises is expected to exert a positive influence on R&D intensity (H2); and higher labor taxation is expected to exhibit a negative association with R&D expenditure (H3).

This methodological framework provides an appropriate empirical basis for examining the structural relationships between digitalization, sustainability-related factors, fiscal conditions, and innovation expenditure across EU member states.

4. Research results and discussion

For the empirical analysis, we aim to examine the relationships between digital transformation, the green transition, fiscal factors, and R&D expenditure across EU member states. The results are structured in several steps, starting with descriptive statistics, followed by correlation and multicollinearity analysis, and concluding with panel regression estimates based on a fixed effects specification. This structure enables a progressive evaluation of the data, from general patterns to econometric relationships.

4.1. Descriptive statistics and sample characteristics

In the context of the digital and ecological transition promoted at EU level through strategic initiatives such as the European Green Deal, the Digital Agenda for Europe, and the Circular Economy Action Plan, a thorough understanding of the major drivers of structural change in Member States' economies is essential. In this regard, descriptive statistical analysis of selected indicators is a fundamental starting point for investigating causal relationships in the proposed econometric model.

Table 2. Descriptive statistics.

Variable	Obs.	Mean	Std. Dev.	Min	Max
GDERD	297	1.655	0.886	0.380	3.60
SRNWEN	297	22.42	12.07	3.494	66.393
ECOMSALE	297	16.247	7.648	1.580	43.95
ENTRINTAC	297	96.472	4.092	78.82	100
ITXRL	297	34.335	5.490	21.313	45.575
ENTRORDONLINE	297	18.211	7.690	4.760	38.40

Source: Author's calculations using STATA ver. 19.

Table 2 presents a summary of descriptive statistics for the six variables used in the panel regression model, analyzed for a sample of 27 EU Member States over the period 2013–2023.

The descriptive statistics reveal substantial heterogeneity across EU member states in terms of innovation capacity, digital development, and structural transformation. The dispersion of R&D expenditure suggests that, despite common strategic objectives at the European level, national innovation systems remain unevenly developed. The variability observed in renewable energy adoption indicates that the green transition is progressing at different speeds across countries, reflecting structural, institutional, and resource-based differences. Furthermore, digital indicators suggest a distinction between widespread access to basic infrastructure and the actual integration of digital tools into economic activity. While connectivity appears to be nearly universal, the extent to which firms engage in digital transactions varies considerably.

The fiscal variable also reflects significant cross-country differences, pointing to diverse policy frameworks and labor market structures within the EU. Taken together, these patterns indicate that the analyzed variables do not evolve uniformly across countries, but rather reflect distinct national trajectories of digitalization, sustainability, and innovation. This variability supports the use of panel data techniques that explicitly account for unobserved heterogeneity and dynamic adjustments within countries, as simple cross-sectional comparisons may conceal important structural differences.

4.2. Correlation and multicollinearity assessment

To assess the relationships between explanatory variables and to ensure the robustness of the econometric specification, a correlation analysis and multicollinearity diagnostics are conducted. Table 3 presents the Variance Inflation Factor (VIF) results.

Table 3. Variance inflation factor.

Variables	VIF	/VIF
ENTRORDONLINE	2.553	0.392
ECOMSALE	2.497	0.400
ITXRL	1.268	0.789
SRNWEN	1.252	0.799
ENTRINTAC	1.240	0.807
Mean VIF	1.762	0.000

Source: Author's calculations using STATA ver. 19.

The VIF values are well below conventional thresholds (5), indicating that multicollinearity is not severe and does not compromise the stability of the estimated coefficients. The overall structure of the model suggests that the explanatory variables provide complementary rather than redundant information. Additionally, to investigate the bivariate relationships between the analyzed variables, the Pearson correlation matrix is calculated (Table 4).

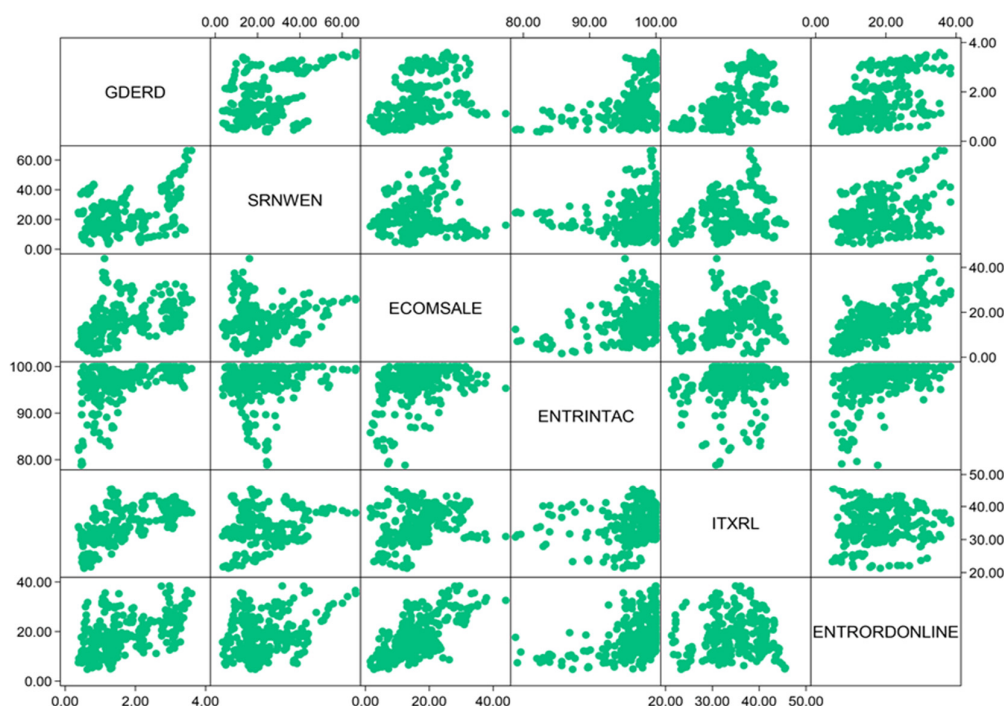
Table 4. Matrix of correlations.

Variable	(1)	(2)	(3)	(4)	(5)	(6)
(1) GDERD	1.000					
(2) SRNWEN	0.401	1.000				
(3) ECOMSALE	0.461	0.019	1.000			
(4) ENTRINTAC	0.468	0.164	0.350	1.000		
(5) ITXRL	0.609	0.161	0.326	0.171	1.000	
(6) ENTRORDONLINE	0.485	0.283	0.690	0.414	0.086	1.000

Source: Author's calculations using STATA ver. 19.

The correlation analysis indicates moderate associations between most variables, supporting their joint inclusion in the model. However, a relatively strong relationship is observed between ECOMSALE and ENTRORDONLINE, suggesting that these variables capture closely related dimensions of digital activity.

Although the VIF results do not indicate severe multicollinearity, the relatively strong correlation between ECOMSALE and ENTRORDONLINE suggests that these variables capture closely related dimensions of digital activity. As a result, their individual coefficients may reflect overlapping aspects of e-commerce adoption, which can reduce the distinct explanatory contribution of each variable within the fixed effects framework. Figure 1 provides a visual representation of the relationships between variables.

**Figure 1.** Matrix of scatter plots between variables of the econometric model.

Source: Author's contribution using STATA ver. 19.

The graphical analysis confirms the presence of generally positive associations between R&D expenditure and most structural variables while indicating dispersion patterns that reflect differences across countries. Furthermore, the clustering of observations suggests that the relationships are not purely cross-sectional, reinforcing the need for an econometric approach that captures temporal dynamics within EU member states. Taken together, these results support the specification of a panel data model that accounts for unobserved heterogeneity and provides a more accurate estimation of structural relationships.

4.3. Panel regression results (Fixed Effects)

The econometric estimation is based on a fixed effects specification, as indicated by the Hausman test results ($\chi^2 = 247.367$, $p < 0.001$), which reject the consistency of the random effects model. This confirms that unobserved country-specific characteristics are correlated with the explanatory variables and must be controlled for to obtain consistent estimates. The fixed effects approach therefore captures changes over time within countries, isolating structural changes rather than cross-country differences. Given the presence of heteroskedasticity, serial correlation, and potential cross-sectional dependence, we employ Driscoll–Kraay robust standard errors within the fixed-effects specification (Table 5). This estimator is appropriate for macro-panel datasets characterized by cross-sectional interdependence and provides robust inference even in finite samples (Hoechle, 2007).

Table 5. Comparative results: Fixed vs random effects models.

GDERD	Model 1 (Fixed Effects)	Model 2 (Random Effects)	Model 3 (FE Driscoll–Kraay)	Model 4 (FE Driscoll–Kraay excluding ENTRINTAC)
SRNWEN	0.016*** (0.004)	0.015*** (0.004)	0.223*** (0.054)	0.231*** (0.056)
ECOMSALE	−0.000 (0.004)	0.002 (0.004)	−0.000 (0.050)	0.011 (0.052)
ENTRINTAC	0.014*** (0.004)	0.014*** (0.004)	0.063*** (0.016)	— —
ITXRL	−0.016** (0.008)	−0.001 (0.008)	−0.102** (0.041)	−0.109** (0.043)
ENTRORDONLINE	0.002 (0.003)	0.003 (0.003)	0.015 (0.044)	0.019 (0.046)
Constant	0.506 (0.444)	−0.131 (0.470)	0.000 (0.017)	0.012 (0.019)
R-squared (Within)	0.205	0.192	0.206	0.198
R-squared (Overall)	0.066	0.303	—	—
Observations	297	297	297	297
Number of groups	27	27	27	27

Standard errors in parentheses

Models 3 and 4 use standardized variables.

Models 3 and 4 report Driscoll–Kraay robust standard errors correcting for heteroskedasticity, serial correlation, and cross-sectional dependence.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

The explanatory power of the estimated panel specifications (Table 5) remains moderate, with R^2 values ranging between 0.192 and 0.206 across the fixed-effects and robustness models. This result suggests that the selected variables capture only part of the within-country variation in R&D expenditure across EU member states. Such moderate explanatory power is relatively common in macro-panel analyses involving structurally heterogeneous economies and innovation-related indicators characterized by complex multidimensional determinants. The results indicate that innovation dynamics are influenced not only by digitalization, renewable energy adoption, labor taxation, and e-commerce activity, but also by additional institutional and structural factors not directly included in the present specification. In particular, institutional quality, human capital accumulation, industrial specialization, technological capabilities, and foreign direct investment may play an important complementary role in shaping innovation performance within the EU. Consequently, the estimated coefficients should be interpreted as partial structural associations rather than exhaustive determinants of R&D expenditure dynamics.

The fixed effects estimates indicate that the share of renewable energy (SRNWEN) has a positive and statistically significant coefficient, suggesting that increases in renewable energy adoption within countries are related to higher levels of R&D expenditure over time. Enterprise-level internet access (ENTRINTAC) also shows a positive and statistically significant effect, indicating that improvements in digital infrastructure contribute to strengthening innovation capacity. In contrast, the coefficients associated with e-commerce variables (ECOMSALE and ENTRORDONLINE) are not statistically significant. This result is consistent with the correlation patterns identified earlier and suggests that these variables capture overlapping aspects of digital activity, making their individual effects difficult to isolate within the regression framework.

A notable difference compared to pooled estimation is observed for the ITXRL, which exhibits a negative and statistically significant coefficient in the fixed effects model. This indicates that, within countries, increases in labor taxation are linked to a reduction in R&D expenditure. The fixed effects results highlight that structural changes in renewable energy and digital infrastructure are connected to innovation dynamics, while the effects of other variables are either context-dependent or absorbed by overlapping dimensions.

Variables included in Models 3 and 4 are standardized prior to estimation. Therefore, the coefficient differences relative to Models 1 and 2 reflect scale standardization rather than changes induced by the Driscoll–Kraay estimator itself. The results obtained using Driscoll–Kraay robust standard errors remain broadly consistent with the baseline fixed effects estimates. Renewable energy adoption (SRNWEN) and enterprise-level internet access (ENTRINTAC) continue to display positive and statistically significant associations with R&D expenditure, while the impITXRL maintains a negative and significant relationship. In contrast, the e-commerce-related variables remain statistically insignificant. The additional robustness specification excluding ENTRINTAC produces results that remain broadly consistent with the baseline estimates. In particular, the coefficients associated with renewable energy adoption (SRNWEN) and labor taxation (ITXRL) preserve their sign and statistical significance. This suggests that the major findings are not driven exclusively by the inclusion of ENTRINTAC, despite its limited within-country variability and near-ceiling distribution. The robustness analysis therefore provides additional support for the existence of structurally consistent relationships across alternative model specifications, although the magnitude and stability of several coefficients remain sensitive to model assumptions and estimation procedures.

These findings suggest that the major conclusions of the analysis are robust to the correction of heteroskedasticity, serial correlation, and cross-sectional dependence across EU member states.

To assess the stationarity properties of the panel variables under potential cross-sectional dependence, Pesaran's Cross-sectionally Augmented IPS (CIPS) unit root test is also employed (Table 6).

Table 6. Pesaran CIPS panel unit root tests.

Variable	CIPS statistic	5% critical value	Conclusion
GDERD	-2.670	-2.17	Stationary
SRNWEN	-2.583	-2.17	Stationary
ECOMSALE	-2.766	-2.17	Stationary
ENTRINTAC	-2.511	-2.17	Stationary
ITXRL	-2.997	-2.17	Stationary
ENTRORDONLINE	-2.316	-2.17	Stationary

Null hypothesis: panels contain unit roots.

Pesaran CIPS test with cross-sectional augmentation and one lag specification, $N, T = (27, 11)$.

Source: Author's calculations using STATA ver. 19.

The results indicate that all variables reject the null hypothesis of homogeneous non-stationarity at conventional significance levels, supporting the stationarity assumption of the panel series and the appropriateness of the estimated fixed-effects specifications.

To validate the econometric specification, a set of diagnostic tests is conducted. The results are summarized in Table 7.

Table 7. Diagnostic tests of the panel model.

Test	Statistic	p-value	Interpretation
Hausman test	247.367	0.000	FE preferred
Breusch-Pagan LM	897.127	0.000	Panel effects present
Pesaran CD	2.498	0.0125	Cross-sectional dependence
Modified Wald	1333.20	0.000	Heteroskedasticity

Source: Author's calculations using STATA ver. 19.

The Hausman test confirms the appropriateness of the fixed effects specification, indicating that unobserved country-specific effects are correlated with the explanatory variables. The Breusch-Pagan LM test supports the presence of panel effects, rejecting the adequacy of pooled estimation.

The Pesaran test reveals cross-sectional dependence across countries, reflecting the interconnected nature of EU economies. The Modified Wald test indicates the presence of heteroskedasticity across panels, suggesting that error variances differ between countries. These results confirm the need for a panel data approach that accounts for heterogeneity and cross-sectional interactions in the estimation of structural relationships.

These findings provide the basis for a more detailed evaluation of the research hypotheses.

To further investigate whether the relationship between renewable energy adoption and innovation differs across European regions, an additional econometric specification is estimated using interaction terms between SRNWEN and regional groupings of EU member states within the FE

Driscoll–Kraay framework. This approach enables the identification of potential regional heterogeneity in the effect of the green transition on R&D expenditure while accounting for heteroskedasticity, serial correlation, and cross-sectional dependence (Table 8).

Table 8. Regional heterogeneity analysis using interaction terms.

GDERD	FE Driscoll-Kraay with Regional Interactions
SRNWEN	0.015*** (0.003)
ENTRINTAC	0.011*** (0.003)
ITXRL	−0.028*** (0.008)
ECOMSALE	0.002 (0.006)
ENTRORDONLINE	−0.002 (0.006)
SRNWEN × North	−0.010*** (0.002)
SRNWEN × East	0.011** (0.005)
SRNWEN × South	0.022** (0.008)
Constant	1.069*** (0.160)
R-squared (Within)	0.254
Observations	297
Number of groups	27

Standard errors in parentheses. Driscoll–Kraay robust standard errors are reported.

** $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$*

Source: *Author's calculations using STATA ver. 19.*

The interaction terms reveal statistically significant regional differences in the relationship between renewable energy adoption and R&D expenditure across EU member states. In particular, the positive and significant coefficients related to Eastern and Southern Europe suggest that the innovation-enhancing effect of renewable energy expansion is stronger in these regions compared to the baseline category. By contrast, the negative interaction coefficient for Northern Europe indicates a comparatively weaker marginal effect. These results confirm that the relationship between the green transition and innovation is not homogeneous across the EU and depends on broader structural and regional characteristics.

To further illustrate the presence of regional heterogeneity, Figure 2 presents the estimated average marginal effects of renewable energy adoption on R&D expenditure across the three regional groups of EU member states.

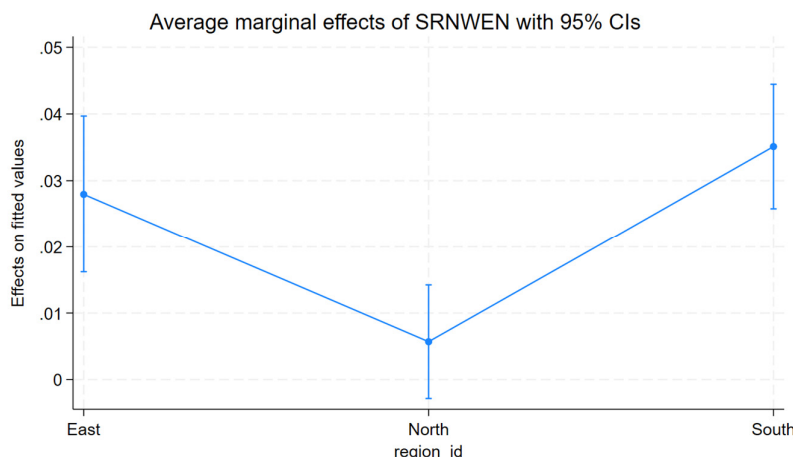


Figure 2. Average marginal effects of renewable energy adoption across EU regions.

Source: Authors' contribution using STATA ver. 19.

The graphical representation confirms the existence of differentiated regional patterns in the relationship between renewable energy adoption and innovation performance. Southern European countries exhibit the strongest positive marginal effects, followed by Eastern European economies, while the estimated effect appears comparatively weaker in Northern Europe. These findings reinforce the argument that the innovation implications of the green transition are conditioned by region-specific structural and institutional characteristics within the EU.

4.4. Interpretation of empirical findings

The empirical results provide differentiated support for the proposed relationships between R&D expenditure and its structural determinants, once unobserved country-specific heterogeneity is taken into account through the fixed effects specification. In this context, the findings should be interpreted as reflecting country-level dynamics rather than cross-country differences. The relationship between renewable energy and R&D expenditure remains positive and statistically significant, supporting the assumption that the green transition is connected to increased innovation efforts. This suggests that, within countries, the expansion of renewable energy is accompanied by a growing demand for technological development and research investment. These results are consistent with the strategic orientation of European policies aimed at integrating sustainability and innovation, as reflected in the European Green Deal (European Commission, 2023) and the broader 2030 Agenda (European Commission, 2022). The findings also align with the European Research and Innovation Pact (European Union, 2021), which emphasizes the role of R&D in supporting climate neutrality objectives.

The role of digitalization appears to be more nuanced. The positive and significant effect of enterprise-level internet access confirms that digital infrastructure functions as a structural enabler of innovation, facilitating knowledge diffusion and technological adoption. This result is consistent with the Strategy for a Digital Europe (European Commission, 2020) and the Digital Compass 2030 initiative (European Commission, 2021), which highlight the importance of connectivity for building innovation ecosystems. Furthermore, the lack of statistical significance for e-commerce-related

variables suggests that not all dimensions of digitalization exert independent effects on innovation. Given the correlation between ECOMSALE and ENTRORDONLINE, these variables appear to capture overlapping aspects of digital activity, which limits the ability to identify distinct effects in the regression framework. This distinction indicates that transactional digitalization alone may not be sufficient to drive R&D investment in the absence of broader digital capabilities.

The relationship between labor taxation and R&D expenditure requires a more careful interpretation. While earlier estimations suggest a positive association, the fixed effects results indicate a negative and statistically significant coefficient. This change reflects the importance of controlling for unobserved heterogeneity. The positive relationship observed in pooled estimations is likely driven by structural differences between countries with strong fiscal capacity and well-developed innovation systems. Once these factors are controlled for, increases in labor taxation within countries appear to be associated with a reduction in R&D expenditure.

Furthermore, the model does not directly capture the mechanism through which tax revenues are transformed into innovation-supporting expenditures. As such, the effect of labor taxation should not be interpreted as purely causal, but rather as conditional on institutional quality and the efficiency of public spending. In contexts where public resources are effectively allocated, higher tax revenues may support innovation, as suggested by the Action Plan for Fair and Effective Taxation in the Digital Age (European Commission, 2025a). In less efficient systems, however, increased taxation may generate constraints without producing corresponding innovation benefits.

The results also suggest that the estimated relationships may not be uniform across all EU member states. Structural differences in institutional capacity, digital maturity, and economic development between Northern, Southern, and Eastern Europe may lead to heterogeneous effects.

To further explore this aspect, Figure 3 provides a graphical illustration of the relationship between renewable energy and R&D expenditure across groups of EU member states.

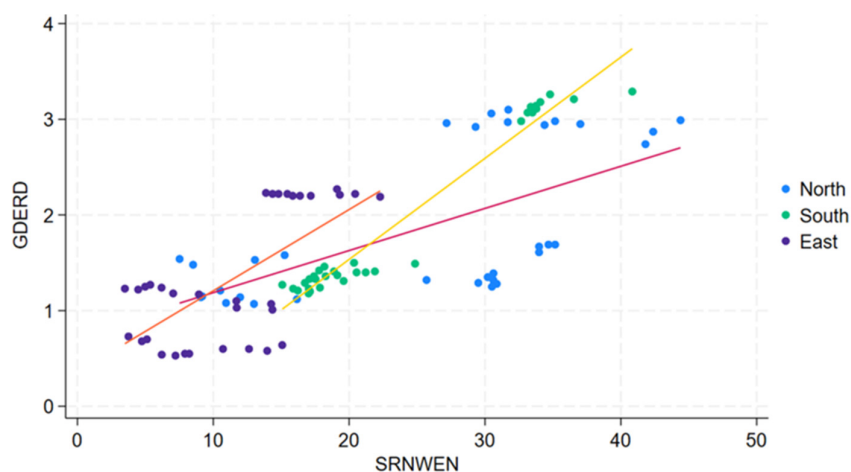


Figure 3. Heterogeneity across European regions.

Source: Authors' contribution using STATA ver. 19.

Figure 3 highlights distinct patterns between Northern, Southern, and Eastern European countries, suggesting that the slope and dispersion of the relationship vary across regions. In particular, higher levels of renewable energy integration in Northern and Southern Europe appear to be related to stronger

innovation performance, while Eastern European countries exhibit lower levels and greater variability. This visual evidence supports the argument that the relationship between structural variables and innovation is not uniform and may depend on broader institutional and developmental contexts.

The findings highlight that innovation performance in the EU is shaped by a combination of structural factors, with renewable energy and digital infrastructure playing a central role, while fiscal variables exhibit context-dependent effects. These results provide a more nuanced understanding of the interplay between sustainability, digitalization, and innovation, without implying uniform policy effects across countries.

From the perspective of the research hypotheses, the results provide differentiated outcomes. The first hypothesis (H1), regarding the positive relationship between renewable energy adoption and R&D expenditure, is supported by the fixed effects estimates. The second hypothesis (H2), related to digitalization, is only partially supported, as the positive effect is confirmed for digital infrastructure (ENTRINTAC), but not for e-commerce-related variables, whose coefficients are not statistically significant. The third hypothesis (H3), which assumes a negative relationship between labor taxation and R&D expenditure, is partially supported by the baseline fixed-effects results, where the ITXRL exhibits a negative and statistically significant coefficient. However, the relationship appears less stable across alternative robustness and lagged specifications, suggesting that the estimated effect should be interpreted cautiously as a structural association rather than a definitive causal relationship.

4.5. Robustness analysis using Panel-Corrected Standard Errors (PCSE)

To further assess the robustness of the estimated relationships and account for potential panel heteroskedasticity, serial correlation, and contemporaneous cross-sectional dependence, an additional robustness analysis is conducted using Panel-Corrected Standard Errors (PCSE). This estimator is particularly appropriate for macro-panel datasets involving EU member states, where cross-sectional interdependencies and structural heterogeneity may affect conventional fixed-effects estimations. Table 9 presents the PCSE estimation results. Compared to the baseline fixed-effects models, the estimated coefficients remain generally stable in terms of direction and magnitude, suggesting that the relationships identified are not driven by model specification issues. However, several coefficients display lower statistical significance once the error structure is corrected for panel-specific disturbances and cross-sectional correlations.

The robustness analysis based on Panel-Corrected Standard Errors (PCSE) indicates the existence of statistically significant relationships between innovation expenditure and several structural variables after accounting for heteroskedasticity, contemporaneous cross-sectional correlation, and serial correlation across EU member states. Compared to the baseline fixed-effects specifications, the PCSE estimator provides an alternative inference framework suitable for macro-panel data characterized by interdependencies among countries.

Table 9. Robustness analysis using Panel-Corrected Standard Errors (PCSE).

VARIABLES	PCSE
SRNWEN	0.0176*** (0.0030)
ECOMSALE	0.0084* (0.0049)
ENTRINTAC	0.0186*** (0.0070)
ITXRL	0.0568*** (0.0081)
ENTRORDONLINE	0.0093* (0.0049)
Constant	−2.6716*** (0.8447)
Year effects	Yes
Observations	297
Number of groups	27
R-squared	0.617
Wald $\chi^2(5)$	222.64
Prob > χ^2	0.0000
ρ (AR1)	0.877

Panel-corrected standard errors in parentheses.

Prais–Winsten regression with correlated panels and common AR(1) correction.

** $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$*

Source: *Author's calculations using STATA ver. 19.*

The results suggest that renewable energy adoption (SRNWEN), digital infrastructure (ENTRINTAC), labor taxation (ITXRL), and e-commerce-related indicators remain structurally associated with R&D expenditure across EU member states. In particular, the coefficient associated with digital infrastructure remains positive and statistically significant, indicating the existence of structural complementarities between digital connectivity and innovation expenditure within the EU. However, the relationship between labor taxation and R&D expenditure appears sensitive to model specification, as the sign and significance of the coefficient vary across robustness estimations. This finding suggests that the relationship may reflect broader institutional and fiscal heterogeneity across EU member states rather than a stable uniform effect.

The estimated autoregressive parameter ($\rho = 0.877$) suggests the presence of substantial persistence in the panel structure, supporting the importance of accounting for serial correlation in the estimation process. Furthermore, the explanatory power of the model ($R^2 = 0.617$) indicates that the selected structural variables capture a relevant share of the variation in innovation expenditure across EU member states.

Overall, the PCSE estimates provide additional support for the existence of broader structural relationships between digitalization, sustainability-related factors, and innovation expenditure at the European level. Nevertheless, the results should be interpreted cautiously, as the robustness

specifications also indicate that several estimated relationships become weaker and less stable once alternative assumptions and lagged structures are considered.

4.6. Lagged robustness analysis

Additional robustness specifications are estimated using one-year lagged explanatory variables. This approach reduces the likelihood that contemporaneous innovation expenditure directly influences renewable energy adoption, enterprise digitalization, or online commercial activity within the same period (Table 10).

Table 10. Robustness analysis using Panel-Corrected Standard Errors (PCSE).

VARIABLES	Model 1 (Lagged FE)	Model 2 (Lagged FE Driscoll-Kraay)	Model 3 (Lagged PCSE)
L.SRNWEN	−0.0008* (0.0005)	−0.0008** (0.0003)	−0.0002 (0.0006)
L.ECOMSALE	−0.0049 (0.0085)	−0.0049 (0.0047)	0.0125* (0.0065)
L.ENTRINTAC	−0.0000 (0.0001)	−0.0000 (0.0000)	0.0001 (0.0001)
L.ITXRL	0.0000 (0.0000)	0.0000 (0.0000)	0.0000** (0.0000)
L.ENTRORDONLINE	−0.0027 (0.0024)	−0.0027* (0.0013)	−0.0013 (0.0015)
Constant	177.9945*** (21.1979)	200.1703*** (10.8359)	121.1361*** (19.9148)
Year effects	Yes	Yes	Yes
R-squared (Within)	0.0848	0.0848	0.1173
Observations	270	270	270
Number of groups	27	27	27
ρ (AR1)	—	—	0.5136

Robust standard errors in parentheses.

Model 1 reports cluster-robust standard errors at the country level.

Model 2 reports Driscoll–Kraay robust standard errors.

Model 3 reports Panel-Corrected Standard Errors (PCSE) with AR(1) correction.

** $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$*

Source: Author's calculations using STATA ver. 19.

The lagged fixed-effects specification reveals a substantial reduction in the statistical significance of several structural variables compared to the baseline contemporaneous models. In particular, the coefficients associated with digital infrastructure and renewable energy become weaker once lagged effects are introduced. Similar patterns emerge in the lagged Driscoll-Kraay and PCSE specifications, where only selected variables retain partial statistical significance.

These findings suggest that the relationships identified in the baseline models primarily reflect contemporaneous structural complementarities between innovation, digitalization, and

sustainability-related indicators rather than strong delayed causal mechanisms. Furthermore, the persistence of selected effects across alternative lagged specifications supports the existence of medium-term structural interactions among the analyzed variables.

Overall, the lagged robustness analysis reinforces a cautious interpretation of the empirical results and indicates that innovation expenditure dynamics within the EU are shaped by complex multidirectional relationships influenced by broader structural and institutional development patterns.

5. Conclusions

In this study, we examined the relationships between digital transformation, the green transition, and innovation performance across EU member states using a panel data framework that accounts for unobserved country-specific heterogeneity. By employing fixed-effects estimation complemented by Driscoll-Kraay robust standard errors, Panel-Corrected Standard Errors (PCSE), lagged robustness specifications, and panel diagnostic procedures for the period 2013–2023, the empirical approach provides a robust assessment of the structural relationships associated with R&D expenditure across the EU.

The empirical findings indicate that renewable energy adoption and digital infrastructure are positively associated with R&D expenditure within countries over time. Higher shares of renewable energy appear related to higher levels of innovation expenditure, suggesting the existence of structural complementarities between sustainability transitions and innovation dynamics. Similarly, enterprise-level internet access exhibits a positive association with R&D intensity, highlighting the importance of digital connectivity within contemporary innovation systems. Furthermore, the analysis indicates that not all dimensions of digitalization exert equally stable relationships with innovation expenditure. Variables associated with e-commerce activity display weaker and less consistent statistical significance once broader dimensions of digital maturity are considered, suggesting that transactional digitalization alone may not be sufficient to sustain higher levels of innovation expenditure.

The relationship between labor taxation and R&D expenditure appears to be more sensitive to model specification and institutional context than initially expected. While the baseline fixed-effects estimations suggest a negative association within countries over time, the robustness estimations reveal weaker and less stable relationships across alternative specifications. This finding suggests that the relationship between labor taxation and innovation expenditure may reflect broader institutional, fiscal, and structural heterogeneity across EU member states rather than a stable uniform effect.

The regional heterogeneity analysis further indicates that the relationship between renewable energy adoption and innovation expenditure is not uniform across the EU. The interaction effects suggest that Southern and Eastern European economies exhibit comparatively stronger positive associations between renewable energy expansion and R&D expenditure, whereas the estimated relationships appear weaker in Northern European countries. These findings indicate that the innovation-related implications of sustainability transitions depend on broader regional economic and institutional contexts within the EU.

5.1. Theoretical implications

The study contributes to the literature by integrating digital, environmental, and fiscal dimensions within a unified econometric framework while explicitly accounting for unobserved heterogeneity, cross-sectional dependence, regional interaction effects, and alternative robustness specifications. By distinguishing cross-country differences and within-country dynamics, the analysis provides a more nuanced understanding of the structural factors associated with innovation performance in the EU.

The findings also contribute to the broader debate on the relationship between sustainability transitions and innovation performance. Rather than supporting a simple linear interpretation, the results suggest that the relationships between digitalization, renewable energy adoption, fiscal conditions, and innovation expenditure are mediated by institutional, structural, and regional characteristics. This perspective reinforces the importance of conceptualizing innovation systems as multidimensional and context-dependent processes shaped by the interaction between technological, economic, and governance-related factors.

5.2. Policy implications

The empirical findings generate several implications for European innovation and sustainability strategies. Renewable energy development and digital infrastructure appear closely associated with higher levels of R&D expenditure across EU member states, suggesting that these dimensions may represent important structural components of contemporary innovation systems. However, digital policy should not focus exclusively on expanding access to digital technologies, but also on supporting more advanced and knowledge-intensive forms of digital transformation that are more closely connected to technological capabilities and innovation-related activities.

The results also indicate that fiscal policy should be approached cautiously in the context of innovation support. The estimated relationship between labor taxation and R&D expenditure appears to be sensitive to institutional and model-specific conditions, suggesting that taxation alone does not automatically support innovation dynamics. Consequently, the effectiveness of fiscal policy may depend not only on the level of taxation, but also on the institutional capacity to allocate public resources efficiently toward research, development, education, and technological infrastructure.

The presence of significant regional heterogeneity further suggests that a uniform policy framework may not generate equivalent outcomes across all EU member states. Policies supporting the green transition and digital innovation may therefore require adaptation to regional structural conditions, levels of economic development, and institutional capacities. More differentiated and regionally sensitive policy approaches could contribute to reducing disparities in innovation performance across the EU.

5.3. Limitations and future research directions

Several limitations should be acknowledged. Although the analysis combines fixed-effects estimation, Driscoll-Kraay robust standard errors, regional interaction effects, Panel-Corrected Standard Errors (PCSE), lagged robustness specifications, and panel diagnostic procedures, the empirical findings should be interpreted cautiously. The lagged robustness estimations suggest that

part of the relationships identified in the baseline fixed-effects models may reflect broader structural associations rather than stable directional effects over time.

The model does not explicitly incorporate institutional and governance-related variables that may mediate the relationship between fiscal policy, digital transformation, and innovation performance. The relatively moderate within R^2 values further indicate that a substantial share of the variation in R&D expenditure may be influenced by additional structural and institutional factors not explicitly included in the current specification. Innovation processes are inherently multidimensional and may also depend on variables such as human capital, industrial structure, financial development, public innovation support mechanisms, and differences in institutional quality across EU member states.

Although the analysis accounts for cross-sectional dependence and regional interaction effects, researchers could extend the empirical framework by employing spatial econometric techniques, panel ARDL/PMG approaches, or more disaggregated regional datasets to better capture long-run adjustment dynamics, cross-country spillovers, and heterogeneous innovation patterns within the EU. Additional research may also benefit from incorporating alternative indicators of digital maturity, institutional performance, and technological specialization.

Overall, the findings suggest that innovation dynamics within the EU are associated with complex interactions between sustainability transitions, digital infrastructure, fiscal conditions, and institutional characteristics. Consequently, understanding innovation performance in the European context requires integrated and context-sensitive analytical approaches capable of capturing the multidimensional nature of structural economic transformation.

Author contributions

Conceptualization: V.M.A., N.B.M., P.L.G., M.L.Z. and C.F.; Software: V.M.A., N.B.M., P.L.G., M.L.Z. and C.F.; Validation: V.M.A., N.B.M., P.L.G., M.L.Z. and C.F.; Formal Analysis: V.M.A., N.B.M., P.L.G., M.L.Z. and C.F.; Investigation: V.M.A., N.B.M., P.L.G., M.L.Z. and C.F.; Resources: V.M.A., N.B.M., P.L.G., M.L.Z. and C.F.; Data Curation: V.M.A., N.B.M., P.L.G., M.L.Z. and C.F.; Writing – Original Draft Preparation: V.M.A., N.B.M., P.L.G., M.L.Z. and C.F.; Writing – Review & Editing: V.M.A., N.B.M., P.L.G., M.L.Z. and C.F.; Visualization: V.M.A., N.B.M., P.L.G., M.L.Z. and C.F.; Supervision: V.M.A., N.B.M., P.L.G., M.L.Z. and C.F.; Project Administration: V.M.A., N.B.M., P.L.G., M.L.Z. and C.F. All authors have read and agreed to the published version of the manuscript.

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Use of AI tools declaration

AI-based tools were used solely to support linguistic refinement, improve the organization of the manuscript, and assist in the preliminary synthesis of publicly available information. All scientific concepts, methodological choices, data analyses, interpretations, conclusions, and the final content of

the manuscript were independently verified, critically revised, and approved by the authors, who assume full responsibility for the accuracy and integrity of the work.

Conflict of interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

Data Availability Statement

All data used in this study are publicly available from Eurostat and the European Commission and can be accessed through their official databases.

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