

DETERMINANTS OF SUSTAINABLE ECONOMIC DEVELOPMENT IN THE EU: THE ROLE OF INNOVATION AND INFRASTRUCTURE RESILIENCE

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Abstract. Technological innovation and infrastructure resilience are key pillars of sustainable economic development in the European Union, directly contributing to the achievement of Sustainable Development Goal 9 (SDG 9). This goal supports the transition to a competitive, climate-neutral and digitized economy by 2050 by strengthening resilient infrastructures, promoting sustainable industrialization and fostering innovation capacity. This study investigates EU Member States' performance against SDG 9, using a set of indicators provided by Eurostat and applying the Holt-Winters (AAA) forecasting model to project trends through 2030. The analysis covers key areas such as R&D expenditure, patent activity, sustainable mobility and industrial emissions intensity. The results reveal significant progress in strengthening innovation capacity in some Member States; however, considerable regional disparities remain, particularly in transport infrastructure and industrial decarbonization. The study therefore highlights the need for integrated public policies, enhanced trans-national cooperation and targeted financial support to reduce structural gaps and accelerate sustainable convergence at European level. The conclusions emphasize the importance of an adaptive policy framework that harnesses the potential of emerging technologies and strengthens the resilience of industrial and infrastructure systems to meet the EU's climate and economic objectives.

Keywords: sustainable development, 2030 Agenda, SDG 9, resilient infrastructure, inclusive industrialization, sustainable innovation.

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1. Introduction

In a geopolitical and climatic context marked by multiple instabilities, technological innovation and infrastructure resilience are emerging as two essential pillars of sustainable economic development in the European Union. Confronted with the pressures of accelerated climate change, resource depletion, and rising social inequalities, the European Union must adopt a sustainable growth model that maintains economic competitiveness while safeguarding ecological balance and social cohesion. With this in mind, Sustainable Development Goal 9 (SDG 9) has become a strategic benchmark, aiming to integrate technological progress and resilient infrastructure into structural transformation processes (Afeltra et al., 2023; Silvestre & Țircă, 2019).

Technological innovation plays a pivotal role in the transition to a circular economy by optimizing resource use, reducing negative externalities and facilitating the decoupling of economic growth from resource-intensive consumption. Emerging technologies – such as artificial intelligence, industrial digitization, renewable energy sources and nature-based solutions – are not only making value chains more efficient, but also profoundly restructuring the relationship between economic activity and the natural environment. These transformations underpin the emergence of a resilient economic framework that is adaptable to systemic crises and oriented towards climate neutrality.

In concrete terms, integrating innovation into industrial strategies makes it possible to reduce emissions intensity, increase energy efficiency and modernize infrastructure in line with the principles of sustainable development. Innovation is thus no longer just a technological vector, but an operational tool for reconciling economic performance with environmental responsibility, in line with the requirements of the European Green Pact and the European Union's energy transition policies (Oduro et al., 2022; Silvestre & Țîrcă, 2019).

At the same time, technological innovation is increasingly seen not as a reactive response to environmental and social crises, but as a strategic factor for economic reconstruction. The adoption of cutting-edge technologies – including smart automation, green infrastructures and digital platforms for energy efficiency – is driving significant transformations in production, distribution and consumption. These transformations facilitate the transition towards resilient economic models, where sustainability and innovation are not separate objectives but interdependent components of a new European socio-economic contract (Afeltra et al., 2023).

An increasingly relevant dimension in the architecture of sustainable development is the reorientation of investments towards projects with a cross-cutting impact – economic, social and environmental. The global trend towards systemic win-win solutions signals a paradigm shift in investment strategies, where profitability is linked to social cohesion and environmental responsibility. Innovations thus become multifunctional tools for inclusive growth and societal resilience (Oduro et al., 2022; Silvestre & Țîrcă, 2019).

This shift is facilitated by European regulatory and funding mechanisms such as the Structural Funds, the Sustainable Activity Taxonomy and smart specialization strategies, which channel resources into strategic areas such as green energy, sustainable mobility, energy efficiency and low-emission digital infrastructure. Investment evaluation is increasingly based on integrated economic, social and environmental performance indicators, reflecting a holistic view of sustainable competitiveness (Canfora et al., 2021; Tettamanzi et al., 2024).

In this regulatory and technological ecosystem, the European Union has enshrined innovation as a central pillar of its transition strategy through initiatives such as the European Green Pact, the Digital Agenda and Horizon Europe. These instruments promote integrated approaches to sustainability, where applied research, the uptake of emerging technologies and collaboration between public and private actors become key to achieving climate and social goals (Ghazy et al., 2022; Schmidt & Krimmer, 2022).

The European Digital Agenda, in particular, affirms digital transformation as a key driver of sustainability, by developing smart infrastructures, promoting responsible artificial intelligence, harnessing open data and ensuring systemic interoperability. Through these components,

integrated digital ecosystems are being created, capable of optimizing economic chains, reducing pressure on resources and informing real-time decision-making based on qualitative data (Ghazy et al., 2022; Schmidt & Krimmer, 2022).

All these initiatives converge towards the consolidation of an open, collaborative and impact-oriented European innovation ecosystem, where synergies between research, industry and public policy are mobilized to develop scalable and replicable solutions. Instruments such as the European Research and Innovation Partnerships, Horizon Europe missions and EIT networks constitute institutional infrastructures for integrating resources and expertise around major societal challenges such as climate change, energy transition and urban sustainability (Blanco et al., 2022; Lima et al., 2023; Wang et al., 2022).

Technological innovation and resilient infrastructure are therefore placed at the heart of the European strategy for sustainable transformation, with systemic implications for competitiveness, social cohesion and climate adaptability. Innovation policies oriented towards measurable impact, assessed in economic, social and environmental dimensions, reflect the shift towards a development model based on knowledge, sustainability and territorial equity.

Building on this context, the main objective of this paper is to provide an empirical and analytical assessment of the progress made by EU Member States toward achieving the targets of SDG 9, focusing on resilient infrastructure, sustainable industrialization, and the promotion of technological innovation.

To guide the analysis, the research addresses the following questions:

RQ1: How have EU Member States progressed over time in achieving SDG 9 targets, particularly in terms of innovation capacity, infrastructure resilience, and environmental performance?

RQ2: What differences and disparities exist among Member States, and what patterns of convergence or divergence can be identified?

RQ3: What are the likely trajectories of SDG 9 indicators through 2030, and how can these projections inform public policies and strategic decisions?

As the literature offers relatively little comparative analysis at EU level, the research contributes to filling a knowledge gap with up-to-date empirical evidence and multidimensional interpretations, providing solid foundations for public policies and institutional strategies tailored to the objectives of a resilient and sustainable European economy. The structure of this article is organized as follows: Section 2 provides a comprehensive review of the relevant literature and theoretical background; Section 3 describes the methodology and data sources used in the analysis; Section 4 presents and discusses the empirical results in depth, and Section 5 concludes by summarizing the main insights, outlining policy implications, and suggesting directions for future research.

2. Sustainable infrastructure in the European Union: resilience, innovation and sustainable transition

In the context of today's global challenges – such as climate change, accelerated urbanization and increasing pressure on natural resources – infrastructure is increasingly recognized as a critical element in the architecture of sustainable economic development. Without resilient,

efficient and inclusive infrastructure systems, capable of meeting today's demands without compromising the ability of future generations to meet their own needs, sustainable development cannot be achieved. Infrastructure thus becomes a vector for systemic transformation and its integration into national and regional development objectives requires a multidimensional approach, based on relevant statistical data, sound forecasts and adaptive policies.

Given the central role that infrastructure plays in strengthening economic, social and territorial development at EU level, there is a need to identify the determinants and operational tools that can facilitate the integration of the Sustainable Development Goals (SDGs) – in particular SDG 9 – into decentralized decision-making processes. In this regard, the 2030 Agenda for Sustainable Development promotes a system of indicators designed to analyze countries' performance and convergence towards their commitments. This system aims, in particular, to assess the impact of the implementation of sustainable policies – including those on infrastructure investment – on the overall progress of sustainable development (European Commission, n.d.; United Nations, 2015).

From a long-term perspective, infrastructure is the physical and functional basis of the economy, indispensable for carrying out productive activities, providing essential public services and maintaining a high quality of life. In the context of the EU's transition towards a green and circular economy, it is imperative to reconfigure existing and emerging infrastructures by integrating environmental sustainability criteria. This reconfiguration must reflect a balance between economic growth objectives and environmental protection imperatives, involving not only the upgrading of existing networks, but also the adoption of innovative planning and implementation models that simultaneously respond to local (rapid urbanization, environmental degradation) and global (climate crisis, depletion of natural resources) challenges.

In this context, green infrastructure and the green economy are increasingly being conceptualized as interdependent elements of a new sustainability-oriented development model. They include natural and semi-natural networks capable of providing valuable ecosystem services – such as microclimatic regulation, water retention or air filtration – and contribute to reducing environmental impacts while fostering social inclusion and well-being (Adamowicz, 2022; Firoiu et al., 2023; Wang et al., 2024).

As Reda Taha et al. (2021) underline in their research, infrastructure can no longer be analyzed solely from the perspective of functional efficiency and economic return, but must be conceived as a strategic dimension of the transition to sustainable development. Within this framework, green infrastructure plays a central role in integrating environmental, social and economic aspects, supporting the implementation of the Sustainable Development Goals (SDGs) in a coherent and cross-sectoral manner. Coherent public policies that support green infrastructure and the circular economy thus become essential for strengthening the resilience of communities and promoting intergenerational equity in spatial planning processes.

Emerging technologies – such as smart materials, advanced building technologies and sensing systems – are becoming increasingly accessible, offering new opportunities for the design and operation of smart green infrastructures. These technological solutions increase the capacity of infrastructures to absorb, adapt and restore, enabling green urban solutions to operate efficiently in the face of climate and environmental risks. For example, sustainable

green roofs and drainage systems equipped with smart sensors enable real-time monitoring and rapid adaptive responses, reinforcing the key characteristics of resilience: redundancy, robustness, speed of response and innovative flexibility (Reda Taha et al., 2021).

At the same time, in today's highly digitized and interconnected critical infrastructure, especially in sectors such as energy, systemic risks and operational complexity are increasing exponentially. Green infrastructure, empowered by emerging technologies, offers a viable solution to mitigate structural vulnerabilities and prevent cascading effects in critical networks. The transition from a traditional physical hardening approach to one based on systemic resilience requires the development of advanced methodologies for assessing, monitoring and managing complex infrastructures. Within this framework, rigorous quantification of the resilience of green infrastructure is becoming a strategic imperative to support decision making and ensure long-term urban sustainability (Kröger, 2019; Reda Taha et al., 2021).

The concept of sustainable infrastructure also emphasizes the critical importance of critical infrastructure resilience, which involves reducing vulnerabilities, minimizing the impact in the face of disruptions, and facilitating effective response and rapid recovery. Understanding the operational environment and identifying the technical (such as robustness and resilience) and organizational (such as adaptability) factors that influence performance in shock situations are essential elements for building this resilience. Thus, a transition is emerging from exclusively technical hardening solutions to a comprehensive vision focusing on the integrated resilience of socio-ecological and technical systems. In this framework, green infrastructure becomes an integral part of the transformation process, providing functional and environmentally friendly solutions to reduce urban risks and increase sustainability (Popirlan & Stefanescu, 2011; Rehak et al., 2018).

In order for green infrastructure to be effectively integrated into critical infrastructure systems, advanced resilience assessment and quantification methodologies need to be developed that reflect the complexity and current interdependencies of urban networks. Through its capacity to reduce climate risks, support adaptation and optimize the functionality of the urban space, green infrastructure becomes a strategic vector of systemic resilience and a central element for achieving sustainable development goals.

Infrastructure systems are deeply interconnected with society, providing essential services and playing a key role in reducing vulnerabilities and strengthening the capacity of communities to cope with natural and man-made hazards. Although the literature offers multiple definitions of resilience as applied to infrastructure, interdisciplinary and cross-sectoral analyses remain fragmented in both research and implementation. Three major directions are highlighted in this regard: (1) conceptual challenges and methodological tensions, (2) applicable engineering and non-engineering measures, and (3) emerging priorities for future research. In this approach, infrastructure is conceptualized as an interdependent socio-ecological-technical system, and resilient infrastructure is defined by its ability to anticipate and absorb disturbances, adapt, recover, and learn from past events (Ionescu et al., 2024; Mehvar et al., 2021).

Conceptual and operational challenges therefore persist in systematically integrating resilience into design, planning and implementation processes. While many theoretically validated measures – both engineering and non-engineering – are available, their practical applicability

remains limited, affecting the ability of infrastructures to respond effectively to systemic shocks. In this context, urgent research and public policy priorities include the development of a coherent framework for integrating the social, environmental and technological dimensions of resilience, with a particular focus on the interdependencies and cascading effects characteristic of complex systems. There is also a need to promote emerging technologies to enable the predictive assessment of the absorptive, adaptive and regenerative capacities of infrastructures, thereby strengthening resilience in the face of an uncertain future.

These strategic directions are fundamental to achieving the objectives set out in SDG 9, which aims to build resilient infrastructure, promote sustainable industrialization and stimulate technological innovation (The Global Goals, n.d.). Strengthening the resilience of infrastructure – including through the integration of green infrastructure – contributes not only to supporting sustainable economic growth and promoting social inclusion, but also to strengthening the capacity of European societies to cope with multiple crises, such as climate disasters, economic shocks or systemic technological disruptions.

In this context, integrating the principles of resilience, sustainability and innovation into territorial development policies and infrastructure projects becomes essential to ensure the long-term sustainability and adaptability of critical infrastructures in the face of future uncertainties.

3. Strategic convergences for sustainable development: SDG 9 and innovative infrastructure

Building on the objectives set out under SDG 9, it highlights the importance of developing resilient infrastructure, promoting inclusive and sustainable industrialization and supporting technological innovation as central pillars of sustainable economic development in the European Union. Robust and functioning infrastructure is the foundation of a competitive economy and a prosperous society, ensuring equitable access to essential services and supporting economic activity. In the context of emerging global challenges – from the climate crisis to accelerated digitization – modernization of industrial and infrastructural systems is becoming a critical necessity for long-term resilience (Sachs et al., 2019; United Nations, 2015).

This transition requires the uptake of sustainable and innovative technologies, along with expanding equitable access to information, financial markets and economic opportunities. Implementing these measures can support the creation of green jobs, boost sustainable economic growth and strengthen the resilience of European communities to systemic shocks. Thus, SDG 9 contributes to building equitable, resilient and prosperous societies, fully in line with the guidelines set by the 2030 Agenda for Sustainable Development (Coaffee & Clarke, 2017; Lafortune & Schmidt-Traub, 2019; Nicola-Gavrilă & Dincă, 2023).

Developing a smart and sustainable infrastructure, promoting sustainable industrialization and supporting innovation are fundamental elements of SDG 9, which aims to increase the capacity of economic systems to adapt to economic, social and environmental change. A sound infrastructure is essential for efficient service delivery, and the modernization of industrial processes through clean technologies is indispensable to align with new demands for

competitiveness and sustainability. In this framework, the SDG 9 indicators provide relevant tools for monitoring progress. For example, gross expenditure on R&D (SDG_09_10) and the number of R&D personnel (SDG_09_30) reflect the institutional and investment capacity to generate knowledge and innovative solutions.

In parallel, the number of patent applications at the European Patent Office (SDG_09_40) measures the degree of technological transformation and the potential for transfer of innovation to productive sectors (Eurostat, n.d.; United Nations, 2015).

The transition towards sustainable infrastructures also involves reconfiguring transportation systems and reducing the intensity of environmental impacts of industrial activities. In this respect, the shares of buses and trains in passenger transport (SDG_09_50) and of railways and inland waterways in freight transport (SDG_09_60) are strategic indicators for orienting mobility policies towards low-emission and energy-efficient solutions.

Likewise, industrial air emissions intensity (SDG_09_70) provides a concrete measure of the environmental performance of industrial systems and underlines the urgency of accelerating the decarbonization process in productive sectors. The integration of these indicators into the strategic infrastructure planning process enables the formulation of evidence-based public policies geared towards resilient, innovative and ecosystem compatible economic development within the ecosystem boundaries of the European Union (European Environment Agency, 2022; Eurostat, 2023).

Based on these considerations, this research focuses on the analysis of a set of policy indicators: gross R&D expenditure (SDG_09_10), R&D personnel (SDG_09_30), patent applications at the EPO (SDG_09_40), shares of collective transport in domestic mobility (SDG_09_50 and SDG_09_60) and emissions intensity of industry (SDG_09_70). These indicators are assessed at EU Member State level, as they directly and complementarily reflect the relationships between resilient infrastructure, technological innovation and development sustainability (Eurostat, n.d.; United Nations, 2015).

Therefore, these indicators allow an integrated analysis of the investment, institutional and environmental dimensions of progress in the EU towards SDG 9. The simultaneous assessment of these dimensions provides a sound empirical framework for the formulation of tailored and impact-oriented public policies, facilitating the transition towards a European model of sustainable growth based on innovation and infrastructural resilience.

The R&D-related indicators (SDG_09_10 and SDG_09_30) are essential for assessing the capacity of EU Member States to produce scientific knowledge, generate emerging technologies and develop sustainable solutions aimed at modernizing national and regional infrastructure (European Commission, 2023; Organization for Economic Co-operation and Development [OECD], 2010).

In parallel, the indicator on patent applications (SDG_09_40) functions as a barometer of applied innovation potential, reflecting the extent to which knowledge is harnessed in productive sectors and supporting both economic competitiveness and the transition towards greener and more energy-efficient industry (World Intellectual Property Organization, 2022). Together, these three indicators form a solid analytical core for understanding the relationship between innovation and infrastructure, with direct implications for European policy directions in the field of research and innovation.

On the other hand, indicators on sustainable transport (SDG_09_50 and SDG_09_60) are indispensable for assessing the evolution of mobility infrastructure in the context of the European Union's objectives of decarbonization and increased energy efficiency in passenger and freight transport (European Commission, 2020; European Environment Agency [EEA], 2022; International Transport Forum, 2023). The increasing share of rail, inland waterways and public transport indicates a clear shift towards more sustainable infrastructures, marking a notable transition from the traditional model centered on polluting road transport.

At the same time, the intensity of industrial emissions to air (SDG_09_70) allows linking industrial development to European climate goals, providing essential empirical data for assessing the environmental impacts of economic infrastructures (European Commission, 2021; EEA, 2019; United Nations Environment Programme, 2022). This indicator is particularly relevant for the analysis of the compatibility between industrial performance and the requirements imposed by the European Ecological Pact, in particular in terms of decarbonization and achieving climate neutrality.

Through the analysis of these indicators associated with SDG 9, the research provides the opportunity for a rigorous examination of the contribution of resilient infrastructure and technological innovation to building a sustainable future within the European Union. Identifying specific features and structural trends at Member State level helps to create a robust empirical framework for assessing progress, identifying territorial disparities and formulating tailored public policy interventions.

By linking the level of performance in the areas of R&D, sustainable transport and reduction of industrial environmental impact, it becomes possible to highlight the role of infrastructure and innovation as determinants of the transition towards a sustainable, inclusive and equitable development model at European level.

4. Research methodology

This study aims to conduct a critical evaluation of the progress made by European Union Member States in implementing the objectives of SDG 9 – Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation – as established in the 2030 Agenda for Sustainable Development. To this end, we performed a comprehensive analysis of data published by Eurostat (n.d.), concentrating on key indicators that track SDG 9 implementation at the national and regional levels across the EU.

The methodological framework adopted in this study integrates both historical and contemporary analytical dimensions, utilizing longitudinal data to examine the temporal evolution of six key indicators associated with SDG 9. The selected indicators cover the period 2008- to the latest statistical data published by Eurostat. This extended temporal scope allows for a comprehensive assessment that captures both pre- and post-2015 dynamics, particularly in relation to the adoption and implementation of the Paris Agreement. By situating current trends within a broader historical trajectory, the analysis uncovers structural transformations and policy inflection points relevant to industrial growth, infrastructure resilience, and innovation capacity within the EU.

To assess the dynamics of indicator evolution and to generate forward-looking in-sights, we employed traditional time series forecasting models, with a focus on Exponential Smoothing methods – specifically the Error-Trend-Seasonal (ETS) framework. Traditional forecasting models such as ARIMA, SARIMA, and ETS are particularly suited to datasets with relatively stable, interpretable temporal structures, offering practical advantages such as computational efficiency and methodological transparency (Canela et al., 2019; Deetchiga et al., 2018; Hyndman & Athanasopoulos, 2019; Kirbaş et al., 2020; Verma et al., 2021; Ventura et al., 2019).

Within the scope of this analysis, ETS models prove particularly well-suited for examining SDG 9-related indicators, owing to their explicit decomposition of time series into error, trend, and seasonal components. The incorporation of both additive and multiplicative Holt-Winters variants within the ETS framework facilitates the effective management of irregularities and non-linear patterns frequently observed in socio-economic and industrial datasets. The methodological flexibility of ETS has been validated in numerous empirical studies (Shrivastri et al., 2022; Ventura et al., 2019; Visnu Dharsini & Babu, 2022), confirming its robustness in environments marked by high volatility and structural heterogeneity – conditions often resulting from technological disruptions, climate-related risks, or geopolitical instability.

ETS models demonstrate significant analytical flexibility, rendering them highly suitable for modeling complex temporal dynamics across a wide spectrum of domains, including those relevant to infrastructure development, industrial performance, and innovation capacity. This versatility is particularly advantageous in contexts where trends and seasonal variations evolve over time – conditions frequently observed in the implementation of SDG 9 across EU Member States. Empirical studies by Petropoulos et al. (2019) and Makridakis et al. (2018) provide robust evidence of the broad applicability of ETS models, highlighting their capacity to capture nuanced fluctuations and turning points within time series data. Such characteristics are especially valuable in forecasting scenarios influenced by abrupt economic, technological, or environmental disruptions, which often produce non-linear shifts in key performance indicators. Furthermore, Hyndman and Athanasopoulos (2019) emphasize the efficacy of ETS in capturing trend and seasonal components, reinforcing its suitability for analyzing and projecting the evolution of SDG 9-related indicators under varying structural and policy conditions.

In the AAA (additive error, additive trend, additive seasonality) configuration of the Holt-Winters model, exponential weighting $\{1, (1 - \alpha), (1 - \alpha)^2, \dots\}$ is applied to the observed values, preserving the influence of past patterns while allowing for smoothed and adaptive forecasting (Akpınar & Yumusak, 2016; Held et al., 2018; Kays et al., 2018). This modelling approach enhances both the accuracy and reliability of forecasts by preserving a coherent temporal progression. Moreover, it provides a valuable analytical tool for exploring potential future trajectories of key indicators under varying policy interventions or environmental conditions, thereby supporting informed decision-making in the context of sustainable infrastructure, industrial development, and innovation planning.

The forecast values generated through this method extrapolate historical patterns to a designated future point, in accordance with the core computational structure of the Holt-Winters multiplicative algorithm (Makridakis et al., 1998):

$$\text{level: } L_t = \alpha \frac{Y_t}{S_{t-m}} + (1-\alpha)(L_{t-1} + B_{t-1}); \quad (1)$$

$$\text{trend: } B_t = \beta(L_t - L_{t-1}) + (1-\beta)B_{t-1}; \quad (2)$$

$$\text{seasonal: } S_t = \gamma \frac{Y_t}{L_{t-1} + B_{t-1}} + (1-\gamma)S_{t-m}; \quad (3)$$

$$\text{forecast: } F_{t+m} = (L_t + B_t m) + S_{t-s+m}, \quad (4)$$

where: L_t – the level of the series; B_t – the trend; S_t – the seasonal component; F_{t+m} – the forecast for m periods ahead; α , β , γ – smoothing parameters; s – length of seasonality (e.g., number of months or quarters in a year); m – denote the frequency of the seasonality (i.e., the number of seasons in a year).

By combining rigorous statistical modeling with a policy-relevant interpretation of SDG 9 indicators, this research contributes empirical evidence and methodological clarity to the discourse on sustainable industrial development in the European Union. The findings are intended to inform strategic decision-making, facilitate comparative assessments, and support the development of resilient infrastructure systems aligned with global sustainability targets.

The proposed research framework is guided by its strong applicability to socio-economic and environmental datasets characterized by complex temporal structures and limited historical data series. Unlike purely econometric or structural models, ETS does not require strict assumptions regarding the underlying data-generating process, making it highly suitable for analyzing SDG 9 indicators, which often display non-linear patterns, seasonality, and irregular fluctuations due to policy interventions, technological disruptions, and external shocks.

Previous studies have demonstrated the reliability of ETS models in forecasting sustainability-related indicators, including energy demand, industrial output, and environmental performance (Hyndman & Athanasopoulos, 2019; Ventura et al., 2019; Visnu Dharsini & Babu, 2022). Their flexibility to incorporate additive or multiplicative trend and seasonal components makes them particularly effective for projecting the evolution of innovation and infrastructure-related variables across EU Member States.

By adopting ETS, this study ensures methodological transparency while providing robust, policy-relevant forecasts of key SDG 9 metrics through 2030. This approach enables decision-makers to anticipate future developments and to design targeted interventions aimed at reducing disparities and accelerating sustainable convergence across the European Union.

5. Empirical results

In alignment with the methodological framework outlined above, this section presents and interprets the results corresponding to each key indicator associated with SDG 9. The data are systematically organized into a series of well-structured tables, each initially displaying indicator values for the years 2008, 2010, 2015, and the most recent reporting period available through Eurostat or other authoritative sources. These reference points serve as critical temporal benchmarks, allowing for a clear assessment of the progression in areas such as industrial value-added, research and development expenditure, infrastructure investment, and innovation output. By including these specific years, the analysis captures the trajectory

before and after the adoption of the Paris Agreement, thus contextualizing the observed developments within major policy and global sustainability milestones.

Subsequent columns in each table include projected estimates for the year 2030, accompanied by calculated rates of change relative to the 2015 baseline year. This comparative structure allows for a more granular understanding of both short-term and long-term progress, offering insights into the extent to which individual EU Member States are advancing toward the targets of SDG 9. By highlighting the pace of change over a fifteen-year interval, the model provides a multidimensional view of progress, stagnation, or regression in key performance areas.

The final column in each table synthesizes the temporal and quantitative data into an estimated overall trend for each indicator, producing a concise yet analytically grounded forecast that extends to the year 2030. This trend estimation, informed by robust time series models, facilitates a more informed interpretation of how current trajectories may unfold under existing policy and economic conditions.

Presenting information in this structured format allows readers to more easily identify emerging patterns, monitor the direction and speed of development change, and critically assess the effectiveness of ongoing national and EU-level strategies aimed at fostering resilient infrastructures, promoting sustainable industrial growth and strengthening innovation ecosystems. In addition, this approach enhances the interpretative value of the data by generating nuanced perspectives on how each indicator is likely to evolve in the near future. Such insights are essential for policymakers, institutional stakeholders and academic researchers who want to determine where current policies are proving effective, where stagnation or reversals may occur, and where additional policy interventions, regulatory adjustments or reallocations of resources may be urgently needed to ensure full alignment with the 2030 Agenda for Sustainable Development.

According to the results summarized in Table 1, Belgium, Germany, and Austria are among the highest performers in terms of gross domestic expenditure on Research and Development (R&D), consistently maintaining or exceeding the 3% threshold by 2023, with projections indicating continued growth through 2030. These countries exhibit strong upward trends, supported by stable innovation systems and significant policy commitments. Similarly, countries such as Poland, Greece, and Croatia demonstrate notable improvements, with R&D expenditure nearly doubling or showing accelerated growth compared to the 2015 baseline. These patterns suggest that targeted national strategies and increased public or private investment are positively influencing innovation capacity in several EU Member States.

In contrast, Ireland, Luxembourg, and Finland show signs of decline or deceleration in R&D intensity. Ireland and Luxembourg are projected to experience continued decreases in R&D as a percentage of GDP, falling well below their 2015 levels by 2030, while Finland, despite its historically high R&D investment, is expected to experience a gradual contraction. Additionally, several countries such as Malta, Sweden, and France present relatively stable patterns with limited upward momentum, indicating either stagnation or cautious investment approaches. The overall variation in trajectories highlights persistent disparities in innovation investment across the EU, with some Member States progressing steadily toward SDG 9 targets, while others risk lagging without additional strategic interventions.

Table 1. SDG_09_10 – Gross domestic expenditure on R&D (percentage of GDP)
(source: Eurostat, own calculations)

Countries	2008	2010	2015	2023	2030 ^f	2023/2015	2030/ 2015	Trend
EU-27	1.87	1.96	2.10	2.22	2.47	1.06	1.18	UP
Belgium	1.94	2.06	2.43	3.32	4.16	1.37	1.71	UP
Bulgaria	0.45	0.56	0.95	0.79	1.06	0.83	1.11	UP
Czech Republic	1.24	1.31	1.91	1.83	2.33	0.96	1.22	UP
Denmark	2.76	2.91	3.06	2.99	3.08	0.98	1.01	UP
Germany	2.57	2.68	2.88	3.11	3.46	1.08	1.20	UP
Estonia	1.25	1.58	1.44	1.84	1.82	1.27	1.28	UP
Ireland	1.39	1.59	1.14	1.02	0.79	0.90	0.69	DOWN
Greece	0.67	0.6	0.97	1.49	1.99	1.54	2.05	UP
Spain	1.32	1.35	1.21	1.49	1.39	1.23	1.15	NONE
France	2.06	2.18	2.22	2.19	2.29	0.99	1.03	UP
Croatia	0.88	0.73	0.82	1.39	1.53	1.70	1.87	UP
Italy	1.16	1.21	1.33	1.31	1.58	0.98	1.19	UP
Cyprus	0.39	0.44	0.48	0.68	0.92	1.42	1.92	UP
Latvia	0.61	0.62	0.64	0.83	0.84	1.30	1.32	UP
Lithuania	0.79	0.79	1.04	1.05	1.21	1.01	1.16	UP
Luxembourg	1.55	1.42	1.25	1.03	0.76	0.82	0.61	DOWN
Hungary	0.98	1.13	1.34	1.39	1.79	1.04	1.33	UP
Malta	0.52	0.58	0.7	0.61	0.61	0.87	0.87	NONE
Netherlands	1.61	1.69	2.12	2.08	2.57	0.98	1.21	UP
Austria	2.59	2.74	3.07	3.29	3.70	1.07	1.21	UP
Poland	0.6	0.72	1.00	1.56	1.94	1.56	1.94	UP
Portugal	1.44	1.53	1.25	1.68	1.69	1.34	1.35	UP
Romania	0.55	0.45	0.49	0.52	0.53	1.06	1.08	UP
Slovenia	1.63	2.07	2.22	2.13	2.32	0.96	1.04	UP
Slovakia	0.46	0.61	1.15	1.04	1.27	0.90	1.11	UP
Finland	3.54	3.71	2.89	3.09	2.40	1.07	0.83	DOWN
Sweden	3.49	3.19	3.24	3.57	3.54	1.10	1.09	NONE

Note: ^f forecasted values.

Table 2 presents data on the proportion of Research and Development (R&D) personnel as a percentage of the active population across EU Member States, covering the period from 2008 to 2023, with projections for 2030. This indicator reflects the human capital dimension of innovation systems and is essential for assessing progress toward SDG 9, specifically the capacity to support inclusive and sustainable industrialization through a skilled and expanding R&D workforce.

The data indicate a general upward trend across the EU-27, with the average rising from 1.21% in 2015 to 1.55% in 2023, and a projected increase to 1.78% by 2030. Several countries demonstrate accelerated progress. Belgium, Austria, Germany, Denmark, and Sweden report high and growing shares of R&D personnel, exceeding 2% of the active population by 2023.

Belgium, in particular, shows remarkable growth, with its R&D workforce increasing from 1.57% in 2015 to 2.48% in 2023, and a forecasted value of 2.84% by 2030 (2030/2015 ratio: 1.81). Strong performance is also observed in the Netherlands, Czech Republic, and Portugal, all of which exhibit a sustained and consistent expansion of their R&D labor force.

Several emerging economies, such as Poland, Hungary, Greece, Croatia, and Cyprus, also show substantial improvements. Poland, for instance, increases its R&D personnel from 0.65% in 2015 to 1.15% in 2023, with a projected rise to 1.50% by 2030, reflecting a more than twofold growth (2030/2015 ratio: 2.30). Similarly, Croatia and Hungary more than double their R&D workforce shares over the same period, indicating targeted policy efforts to build national innovation capacity.

Table 2. SDG 09-30 — R&D personnel (percentage of active population)
(source: Eurostat, own calculations)

Countries	2008	2010	2015	2023	2030 ^f	2023/2015	2030/ 2015	Trend
EU-27	1.04	1.08	1.21	1.55	1.78	1.28	1.47	UP
Belgium	1.23	1.24	1.57	2.48	2.84	1.58	1.81	UP
Bulgaria	0.49	0.49	0.69	0.86	1.13	1.25	1.64	UP
Czech Republic	0.98	1.01	1.28	1.7	2.03	1.33	1.59	UP
Denmark	2.01	2.01	2.15	2.36	2.46	1.10	1.14	UP
Germany	1.28	1.39	1.58	1.91	2.19	1.21	1.39	UP
Estonia	0.76	0.79	0.86	1.24	1.27	1.44	1.48	UP
Ireland	0.87	0.89	1.45	1.43	1.98	0.99	1.37	UP
Greece	0.74	0.76	1.05	1.6	1.81	1.52	1.73	UP
Spain	0.94	0.96	0.88	1.19	1.18	1.34	1.35	UP
France	1.33	1.37	1.45	1.67	1.84	1.15	1.27	UP
Croatia	0.56	0.58	0.57	1.00	1.17	1.75	2.06	UP
Italy	0.91	0.94	1.05	1.34	1.73	1.28	1.65	UP
Cyprus	0.31	0.32	0.30	0.46	0.57	1.53	1.92	UP
Latvia	0.6	0.54	0.58	0.72	0.81	1.24	1.39	UP
Lithuania	0.84	0.82	0.74	0.98	1.09	1.32	1.47	UP
Luxembourg	2.18	2.17	1.92	1.84	1.63	0.96	0.85	DOWN
Hungary	0.66	0.73	0.8	1.25	1.62	1.56	2.03	UP
Malta	0.56	0.64	0.69	0.72	0.79	1.04	1.14	UP
Netherlands	1.07	1.14	1.55	1.92	2.40	1.24	1.55	UP
Austria	1.41	1.44	1.65	2.13	2.37	1.29	1.43	UP
Poland	0.44	0.5	0.65	1.15	1.50	1.77	2.30	UP
Portugal	0.92	0.95	0.98	1.53	1.74	1.56	1.78	UP
Romania	0.32	0.33	0.39	0.44	0.48	1.13	1.24	UP
Slovenia	1.14	1.29	1.45	1.78	2.06	1.23	1.42	UP
Slovakia	0.58	0.66	0.63	0.89	0.97	1.41	1.54	UP
Finland	2.12	2.15	1.95	2.19	1.97	1.12	1.01	NONE
Sweden	1.67	1.62	1.67	2.26	2.33	1.35	1.39	UP

Note: ^f forecasted values.

Among the outliers, Luxembourg stands out as the only Member State with a consistently declining trajectory in R&D personnel, decreasing from 1.92% in 2015 to an estimated 1.63% by 2030, which may indicate underlying structural barriers or policy re-orientations affecting research capacity. Although Finland maintains a relatively high share of R&D personnel, its projected 2030/2015 ratio of 1.01 signals a levelling off, suggesting limited expansion in workforce capacity. At the same time, Malta, Romania, and Slovakia continue to register modest levels of R&D personnel; nonetheless, the projected upward movement points to gradual improvements that could be reinforced through targeted policy initiatives and sustained investment in innovation-oriented human capital.

Table 3. SDG 09-40 – Patent applications to the European Patent Office (per million inhabitants) (source: Eurostat, own calculations)

Countries	2008	2010	2015	2023	2030 ^f	2023/ 2015	2030/ 2015	Trend
EU-27	137.47	138.84	140.96	152.82	161.89	1.08	1.15	UP
Belgium	177.31	187.69	181.03	216.9	241.22	1.20	1.33	UP
Bulgaria	2.00	1.49	4.60	6.20	9.27	1.35	2.02	UP
Czech Republic	10.59	15.94	20.20	22.26	27.50	1.10	1.36	UP
Denmark	288.33	327.52	337.82	437.58	537.01	1.30	1.59	UP
Germany	324.77	334.18	303.69	295.95	296.19	0.97	0.98	NONE
Estonia	5.24	20.28	24.33	51.98	69.13	2.14	2.84	UP
Ireland	107.81	139.69	130.58	200.52	251.63	1.54	1.93	UP
Greece	8.03	7.46	8.41	15.08	19.70	1.79	2.34	UP
Spain	28.88	30.70	32.68	43.90	49.04	1.34	1.50	UP
France	141.68	147.72	161.69	158.63	173.05	0.98	1.07	UP
Croatia	5.57	3.96	2.14	13.24	7.94	6.19	3.71	NONE
Italy	74.06	68.80	65.63	85.65	85.74	1.31	1.31	UP
Cyprus	71.19	59.08	46.01	57.56	49.54	1.25	1.08	NONE
Latvia	19.29	15.26	15.17	14.34	7.67	0.95	0.51	DOWN
Lithuania	3.44	2.91	13.43	45.15	40.30	3.36	3.00	UP
Luxembourg	560.73	828.48	746.13	582.62	662.95	0.78	0.89	UP
Hungary	10.76	10.70	9.85	11.25	11.53	1.14	1.17	UP
Malta	65.95	74.79	211.21	108.85	160.46	0.52	0.76	UP
Netherlands	447.54	359.00	421.90	394.86	381.75	0.94	0.90	NONE
Austria	180.62	208.53	230.14	258.66	318.09	1.12	1.38	UP
Poland	4.43	5.39	14.90	18.26	22.94	1.23	1.54	UP
Portugal	8.05	7.66	13.61	31.43	40.78	2.31	3.00	UP
Romania	0.88	0.69	1.51	2.20	3.39	1.46	2.25	UP
Slovenia	63.33	63.95	57.18	72.27	62.43	1.26	1.09	UP
Slovakia	5.21	4.64	8.67	10.32	12.25	1.19	1.41	UP
Finland	339.14	301.49	363.72	419.84	394.30	1.15	1.08	UP
Sweden	339.93	382.81	391.77	488.43	532.99	1.25	1.36	UP

Note: ^f forecasted values.

The evolution of patent applications per million inhabitants across EU Member States, from 2008 to 2023, with projections to 2030, is summarized in Table 3. This indicator is a critical proxy for innovation output and technological advancement, directly linked to SDG target 9.5, which aims to enhance research and upgrade the technological capabilities of industrial sectors. At the EU-27 level, the number of patent applications rose from 140.96 in 2015 to 152.82 in 2023, with a projected increase to 161.89 by 2030 (2030/2015 ratio: 1.15), indicating a modest but steady improvement in innovation activity across the Union.

Leading innovation economies such as Sweden, Finland, Denmark, and Germany report high levels of patent activity, consistently exceeding 300 applications per million inhabitants. Notably, Denmark shows a strong upward trend, rising from 337.82 in 2015 to 437.58 in 2023, and a projected 537.01 in 2030 (2030/2015 ratio: 1.59). Sweden also demonstrates continued growth (from 391.77 to 488.43), affirming its position as a top-performing innovation hub. However, Germany shows a slight decline in patent activity (2030/2015 ratio: 0.98), suggesting stabilization or marginal regression, potentially due to shifts in industrial structure or R&D focus.

Several smaller and emerging economies exhibit remarkable relative gains. Estonia, Lithuania, and Portugal show the most dramatic increases in patent filings. For example, Lithuania expands from 13.43 in 2015 to 45.15 in 2023, with a projected 40.30 in 2030 (2030/2015 ratio: 3.00). Portugal more than doubles its patent output (2030/2015 ratio: 3.00), reflecting strengthened innovation ecosystems and greater engagement in formal intellectual property systems. Ireland and Italy also display significant upward trends, with Ireland forecasted to reach 251.63 applications per million inhabitants by 2030.

Conversely, countries such as Latvia, Luxembourg, and the Netherlands display stagnation or decline. Latvia shows the most significant drop, with a projected decrease from 15.17 in 2015 to 7.67 in 2030 (2030/2015 ratio: 0.51). Luxembourg, while still among the top performers in absolute terms, is projected to decline from 746.13 in 2015 to 662.95 in 2030. Croatia presents an anomalous increase in 2023, but the projection for 2030 suggests a reversion, resulting in an unstable trend classification. Similarly, Malta displays a sharp spike in 2015 followed by a decline, indicating volatility in innovation outputs possibly linked to small sample sizes or one-off corporate filings.

Regarding the share of buses and trains within total passenger transport across the EU-27, Table 4 reveals a general decline, with a decrease from 17.6% in 2015 to 15.5% in 2023, with a projected drop to 14.5% by 2030 (2030/2015 ratio: 0.82). This downward trend is indicative of a diminishing modal share of public and collective transport, raising concerns about the sustainability and efficiency of mobility systems in achieving the transport-related objectives of SDG 9. A declining reliance on public transport may reflect broader structural shifts, such as increasing private vehicle use, urban sprawl, or insufficient investment in public transport infrastructure and services.

A majority of EU Member States follow this downward trajectory. Countries like Bulgaria, Spain, Latvia, and Hungary show sharp decreases. For instance, Bulgaria experiences a drastic fall from 16.9% in 2015 to 3.7% in 2030, reflecting a dramatic shift away from public transport use (2030/2015 ratio: 0.22). Hungary also exhibits a significant decline from 30.5% to 18.1%, raising concerns over accessibility and modal sustainability. Even traditionally

higher-performing countries in terms of public transport usage—such as Belgium, Czech Republic, and Denmark – show substantial reductions, suggesting broader systemic challenges in maintaining and modernizing public transport modes.

Only a small subset of countries display a stable or positive trend. Sweden is the single Member State showing a clear upward movement, increasing from 16.8% in 2015 to 18.8% in 2023, and a projected 19.9% by 2030 (2030/2015 ratio: 1.19), likely reflecting effective investment in rail and bus infrastructure, urban mobility strategies, and strong public policy support. Germany, France, Luxembourg, Austria, and the Netherlands maintain relatively stable levels, with projected values close to 2015 baselines, indicating preservation rather than expansion of public transport's role in the modal split.

Table 4. SDG 09-50 – Share of busses and trains in total passenger transport (percentage)

(Source: Eurostat, own calculations)

Countries	2008	2010	2015	2023	2030 ^f	2023/2015	2030/ 2015	Trend
EU-27	17.3	17.1	17.6	15.5	14.5	0.88	0.82	DOWN
Belgium	21.6	19.8	18.5	15.7	13.2	0.85	0.71	DOWN
Bulgaria	24.9	20.0	16.9	9.8	3.7	0.58	0.22	DOWN
Czech Republic	24.0	26.5	25.0	20.3	17.6	0.81	0.70	DOWN
Denmark	18.1	20.3	19.0	16.0	14.2	0.84	0.75	DOWN
Germany	14.4	14.0	15.6	14.5	14.2	0.93	0.91	NONE
Estonia	18.6	16.4	17.7	14.9	13.3	0.84	0.75	DOWN
Ireland	17.7	17.4	16.7	16.3	15.6	0.98	0.94	DOWN
Greece	19.2	18.4	18.6	14.6	12.2	0.78	0.66	DOWN
Spain	19.7	17.7	18.6	12.9	9.7	0.70	0.52	DOWN
France	15.8	14.9	16.2	15.4	15.4	0.95	0.95	NONE
Croatia	17.8	16.3	14.1	12.7	10.8	0.90	0.77	DOWN
Italy	18.3	18.3	18.6	16.9	15.9	0.91	0.85	DOWN
Cyprus	18.8	18.1	18.7	15.4	13.5	0.82	0.72	DOWN
Latvia	21.3	21.8	19.3	13.7	9.4	0.71	0.49	DOWN
Lithuania	8.8	8.3	10.8	7.7	6.9	0.71	0.64	DOWN
Luxembourg	15.8	16.5	17.1	16.1	15.9	0.94	0.93	NONE
Hungary	34.3	31.5	30.5	23.2	18.1	0.76	0.59	DOWN
Malta	19.2	18.5	17.7	15.5	13.9	0.87	0.79	DOWN
Netherlands	12.7	13.5	13.8	13.2	13.0	0.95	0.94	NONE
Austria	22.4	21.6	21.9	21.3	21.0	0.97	0.96	NONE
Poland	14.5	23.9	21.3	16.9	14.6	0.79	0.69	DOWN
Portugal	10.8	10.9	10.0	9.4	9.0	0.94	0.90	DOWN
Romania	27.8	22.0	22.1	18.1	15.5	0.82	0.70	DOWN
Slovenia	13.6	13.2	13.9	12.5	11.9	0.90	0.85	DOWN
Slovakia	26.7	22.2	25.1	20.3	18.0	0.81	0.72	DOWN
Finland	15.5	15.1	15.0	14.6	14.2	0.97	0.95	DOWN
Sweden	16.7	16.6	16.8	18.8	19.9	1.12	1.19	UP

Note: ^f forecasted values.

Table 5. SDG 09-60 – Share of rail and inland waterways in total freight transport (percentage) (source: Eurostat, own calculations)

Countries [†]	2008	2010	2015	2023	2030 ^f	2023/2015	2030/ 2015	Trend
EU-27	25.7	25.4	25.8	23.0	21.5	0.89	0.83	DOWN
Belgium	27.2	26.6	26.4	23.4	21.6	0.88	0.82	DOWN
Bulgaria	54.9	50.6	45.3	42.5	38.9	0.94	0.86	DOWN
Czech Republic	32.2	30.2	26.4	22.3	17.8	0.84	0.68	DOWN
Denmark	9.0	11.5	12.0	11.0	11.3	0.92	0.94	UP
Germany	30.0	29.5	28.1	25.7	23.7	0.91	0.84	NONE
Estonia	68.2	75.4	52.4	28.8	7.0	0.55	0.13	DOWN
Ireland	0.7	0.9	1.0	0.8	0.7	0.75	0.65	NONE
Greece	2.9	2.2	1.6	2.2	2.2	1.38	1.39	NONE
Spain	4.8	4.6	5.8	4.8	4.7	0.83	0.82	NONE
France	14.1	12.5	15.1	12.7	12.1	0.84	0.80	NONE
Croatia	28.3	31.0	27.1	28.9	29.2	1.07	1.08	UP
Italy	11.3	9.3	13.5	13.5	14.6	1.00	1.08	UP
Latvia	83.4	82.1	79.8	58.8	45.2	0.74	0.57	DOWN
Lithuania	73.0	72.8	65.9	58.5	51.5	0.89	0.78	DOWN
Luxembourg	23.0	24.5	15.1	10.3	4.3	0.68	0.28	DOWN
Hungary	30.9	34.5	34.9	33.0	32.6	0.95	0.94	NONE
Netherlands	50.9	51.6	50.8	47.8	46.1	0.94	0.91	DOWN
Austria	37.2	37.0	35.3	31.7	28.9	0.90	0.82	DOWN
Poland	34.0	29.6	25.6	20.6	15.3	0.81	0.60	DOWN
Portugal	9.7	10.9	14.1	14.3	16.1	1.02	1.14	UP
Romania	50.2	63.1	62.0	54.6	53.6	0.88	0.86	NONE
Slovenia	29.7	31.8	35.0	36.0	38.2	1.03	1.09	UP
Slovakia	45.1	44.1	39.8	32.0	25.8	0.80	0.65	DOWN
Finland	27.4	27.1	27.4	26.6	25.7	0.97	0.94	DOWN
Sweden	31.9	35.6	29.5	28.4	25.8	0.96	0.87	DOWN

Notes: ^f forecasted values. [†] Countries not listed in the table have not reported data.

Table 5 shows a general downward trend across the EU-27 in the share of rail and inland waterways in total freight transport, decreasing from 25.8% in 2015 to 23.0% in 2023, with a projected decline to 21.5% by 2030 (2030/2015 ratio: 0.83). This indicates a weakening modal shift toward more sustainable freight transport options, which may undermine efforts to reduce emissions, alleviate road congestion, and support multi-modal transport infrastructure as envisioned under SDG 9.

Most EU Member States reflect this declining trend. Bulgaria, Czech Republic, Poland, Austria, Slovakia, and the Baltic States (Estonia, Latvia, Lithuania) report significant reductions in the share of rail and inland waterways. Notably, Estonia's share dropped from 52.4% in 2015 to 28.8% in 2023, with a projected fall to 7.0% by 2030 (2030/2015 ratio: 0.13), while Latvia shows a comparable decline from 79.8% to 45.2%, reflecting broader systemic transformations in freight logistics, infrastructure constraints, or shifts toward road-based transport.

Even high-capacity logistics hubs like Germany, France, and the Netherlands are experiencing moderate declines, suggesting that the transition to lower-carbon freight modes is not being sustained at the EU level.

Nevertheless, a few Member States exhibit a positive or stable trajectory. Slovenia, Portugal, Croatia, and Italy show moderate increases in the share of rail and inland waterways. For example, Slovenia rises from 35.0% in 2015 to a projected 38.2% in 2030 (2030/2015 ratio: 1.09), and Portugal from 14.1% to 16.1%, indicating targeted efforts to integrate multimodal transport systems and reduce dependency on road freight. Croatia also shows slight growth, likely reflecting infrastructure modernization and better integration with EU transport corridors.

At the same time, some Member States, such as Hungary, Romania, and Italy, maintain relatively stable shares, suggesting consistent policies and capacity in support of rail and waterway freight. However, in many cases, the lack of significant improvement points to limitations in the implementation of sustainable freight strategies or underinvestment in intermodal infrastructure.

Table 6 illustrates a broad downward trend in air emission intensity from industry across the EU-27, with the average value declining from 0.08 grams/euro in 2015 to 0.06 grams/euro in 2022, and projected to reach 0.03 grams/euro by 2030 (2030/2015 ratio: 0.39). This significant reduction signals encouraging progress toward industrial decarbonization and cleaner production processes, consistent with SDG 9.4 objectives. The trend reflects increasing investments in emissions control technologies, enhanced environmental regulations, and shifts toward higher value-added, less polluting industrial outputs.

Most Member States demonstrate similar patterns of sustained emission intensity reduction. Countries such as Belgium, Czech Republic, Ireland, Lithuania, Austria, Slovakia, and Sweden show marked declines, often reaching near-minimal values by 2030. For example, Ireland reduces its emission intensity from 0.03 grams/euro in 2015 to near-zero by 2030, while Czech Republic moves from 0.05 to a minimum value over the same period. These trends point to successful implementation of cleaner technologies and structural transitions within the industrial sector toward less carbon-intensive activities.

A few Member States, such as Portugal and Hungary, diverge from the general pattern. Portugal stands out with a projected increase in air emission intensity, rising from 1.92 grams/euro in 2015 to 3.14 grams/euro by 2030 (2030/2015 ratio: 1.63), suggesting setbacks in emission efficiency or possible shifts toward more energy- or pollution-intensive industries. Hungary, while showing no deterioration, maintains a constant emission intensity between 2015 and 2022, indicating a plateau (2030/2015 ratio: 1.13), which may reflect insufficient improvements in industrial emissions reduction or a stagnation in technological upgrading.

Despite a generally positive outlook, certain countries with historically high emission intensities – such as Latvia, Lithuania, and Romania – still display values above the EU average, although declining. This underscores the need for continued policy support, technology transfer, and investment in industrial modernization to close the remaining environmental performance gaps among Member States.

Table 6. SDG 09-70 – Air emission intensity from industry (grams per euro, chain linked volumes 2010) (Source: Eurostat, own calculations)

Countries	2008	2010	2015	2022	2030 ^f	2023/2015	2030/ 2015	Trend
EU-27	0.11	0.1	0.08	0.06	0.03	0.75	0.39	DOWN
Belgium	0.16	0.11	0.08	0.06	0.02	0.75	0.28	DOWN
Bulgaria	0.68	0.29	0.32	0.29	0.17	0.91	0.54	DOWN
Czech Republic	0.12	0.1	0.05	0.03	min	0.60	n.a.	DOWN
Denmark	0.03	0.03	0.02	0.01	min	0.50	n.a.	DOWN
Germany	0.03	0.02	0.02	0.02	0.01	1.00	0.72	DOWN
Estonia	0.57	0.61	0.3	0.14	min	0.47	n.a.	DOWN
Ireland	0.06	0.05	0.03	0.01	min	0.33	n.a.	DOWN
Greece	0.25	0.22	0.25	0.17	0.14	0.68	0.58	DOWN
Spain	0.13	0.12	0.09	0.09	0.08	1.00	0.85	DOWN
France	0.11	0.12	0.09	0.08	0.06	0.89	0.66	DOWN
Croatia	0.26	0.3	0.23	0.11	0.06	0.48	0.25	DOWN
Italy	0.11	0.1	0.07	0.07	0.04	1.00	0.50	DOWN
Cyprus	0.55	0.46	0.19	0.24	min	1.26	n.a.	DOWN
Latvia	0.45	0.48	0.51	0.45	0.39	0.88	0.77	DOWN
Lithuania	0.11	0.09	0.11	0.06	0.03	0.55	0.31	DOWN
Luxembourg	0.11	0.11	0.05	0.05	0.00	1.00	0.04	DOWN
Hungary	0.1	0.08	0.07	0.07	0.08	1.00	1.13	NONE
Malta	0.02	0.01	0.02	0.01	0.01	0.50	0.30	DOWN
Netherlands	0.08	0.08	0.06	0.04	0.02	0.67	0.27	DOWN
Austria	0.05	0.05	0.03	0.02	min	0.67	n.a.	DOWN
Poland	0.32	0.25	0.2	0.13	0.03	0.65	0.16	DOWN
Portugal	1.07	0.8	1.92	2.24	3.14	1.17	1.63	UP
Romania	0.39	0.31	0.25	0.17	0.05	0.68	0.19	DOWN
Slovenia	0.15	0.15	0.14	0.09	0.05	0.64	0.39	DOWN
Slovakia	0.19	0.15	0.08	0.05	min	0.63	n.a.	DOWN
Finland	0.12	0.13	0.1	0.06	0.03	0.60	0.27	DOWN
Sweden	0.1	0.1	0.06	0.04	min	0.67	n.a.	DOWN

Notes: ^f forecasted values. min. minimum value. n.a. not available data.

The empirical results provide clear answers to the research questions formulated at the outset of this study. Regarding RQ1, the analysis shows that EU Member States have made uneven progress toward SDG 9 targets. Innovation-related indicators, such as gross R&D expenditure (SDG_09_10) and R&D personnel (SDG_09_30), display a general upward trend, with countries like Belgium, Germany, Austria, and Sweden consistently exceeding the EU average. Conversely, several Eastern and Southern Member States, including Romania, Bulgaria, and Malta, remain below the 1% threshold, signaling persistent structural gaps. Patent applications (SDG_09_40) also increased moderately at the EU level, though only a few high-performing economies such as Denmark, Sweden, and Finland show substantial growth, while others, like Latvia and Luxembourg, exhibit stagnation or decline.

With respect to RQ2, the comparative assessment highlights significant disparities among Member States. A clear divide emerges between innovation leaders in Northern and Western Europe and lagging economies in parts of Eastern and Southern Europe. This divergence is particularly evident in the sustainable mobility indicators (SDG_09_50 and SDG_09_60), where most countries show declining shares of public transport and rail freight, with Sweden and a few others being notable exceptions. Similarly, while industrial air emissions intensity (SDG_09_70) has generally declined across the EU, some Member States – such as Portugal and Hungary – have experienced stagnation or even increases, pointing to policy implementation gaps. These findings confirm that convergence is limited, with only a handful of Member States aligning rapidly with EU sustainability targets, while others are falling behind.

Finally, RQ3 is addressed through the Holt-Winters forecasts, which indicate that current trajectories are insufficient for fully achieving SDG 9 by 2030. Projections suggest modest improvements in R&D expenditure and human capital development but continuing declines in sustainable transport indicators, threatening progress in decarbonizing mobility systems. Although industrial emissions are expected to decrease further, the pace of reduction will remain uneven without coordinated interventions. These forward-looking results underscore the need for targeted policies and financial instruments to accelerate innovation-driven growth, reduce territorial disparities, and ensure a just and climate-resilient transition.

In summary, the results reveal that while certain Member States are well-positioned to meet the EU's SDG 9 objectives, persistent gaps in innovation capacity, infrastructure resilience, and environmental performance require stronger policy integration and cross-border collaboration to achieve sustainable and inclusive development across the European Union.

6. Discussion

Building on the goals formulated in SDG 9 on promoting sustainable industrialization, supporting innovation and developing resilient infrastructure, gross spending on R&D (SDG_09_10) plays a crucial role in stimulating economic growth, especially in emerging economies.

Recent studies (Fendoğlu & Polat, 2021; Firoiu et al., 2025; Islam et al., 2024; Nurpeisova et al., 2020) emphasize that although these economies are recognized as important sources of global economic dynamism, they have not received enough attention in the literature. However, the long-term relationship between economic growth and R&D investment is evident. Moreover, this expenditure generates a positive impact both directly and through interaction with other structural economic factors such as capital and education, thus helping to strengthen the conditions for sustainable development.

R&D expenditure, together with the number of active researchers, contributes significantly to economic growth and total factor productivity. The positive effect is particularly strong for specialized human capital, highlighting the importance of developing human resources in research. The strategic integration of research investment with education and innovation policies therefore becomes essential to underpin sustainable and long-term economic growth.

In this framework, the SDG_09_10 indicator should not be seen merely as a tool to monitor progress in research, but as a fundamental strategic benchmark to inform public policies geared towards avoiding the middle-income trap and facilitating the integration of emerging

economies among developed countries by strengthening their capacity for innovation and technological progress.

Thus, it is indisputable that sustainable development and economic competitiveness cannot be achieved in today's global society without innovation, which generally results from costly R&D processes that generate intellectual property assets such as patents or legally protected digital ideas (Pelikánová, 2019).

In particular, the lack of an integrated analysis linking the dynamics of these factors to the economic performance of Member States limits the ability to formulate effective policies tailored to the specific context of each economy. Therefore, further research is needed to highlight how these dimensions interact and contribute to achieving sustainable development objectives, particularly in the context of the digital transition and the requirements of the European Ecological Pact (Eurostat, 2023).

In this context, three fundamental questions need to be addressed at EU level: (1) what is the share of R&D expenditure in GDP and what are the emerging trends at EU level and in certain Member States; (2) how many European applications and patents have been filed and granted, what is the success rate and how is digitization evolving in these economies; (3) to what extent is there a relationship between these factors.

This analysis is all the more relevant given that: the 3% of GDP threshold for R&D set by the Europe 2020 Strategy is not reached in most Member States; the number of patent applications and patents granted is increasing in parallel with the digitization process; and the relationship between research investment, innovative performance and digitization is not yet sufficiently clearly defined or empirically proven.

Significant disparities also persist between Member States in terms of innovation capacity, justifying the need for further research and recalibration of innovation policies at European level to increase their efficiency and impact on sustainable development and economic competitiveness (European Commission, 2010; Kučera & Fiľa, 2020; Pelikánová, 2019).

Although R&D activities have been intensively analyzed in terms of their determinants and effects, the coherent integration of existing research lines can contribute to a deeper understanding of innovation-related decision-making mechanisms at the European country level.

Recent research results indicate that R&D performance is positively influenced by structural factors such as: the international mobility of human capital in managerial positions, labor market flexibility (including the use of fixed-term contracts), the existence of innovation-friendly regulations, and access to skilled labor with experience in external training. All these factors are associated with increased innovation capacity and sustained economic growth (Sá & de Pinho, 2019; Urbano et al., 2020).

The efficiency of the innovation process in high-tech industries is the result of a complex interplay between fiscal, institutional and human resource factors, which influence both the R&D stage and the transformation of innovative results into commercially valuable products and services.

In this context, preferential tax policies can have ambivalent effects: on the one hand, they can stimulate investment in research activities by reducing the tax burden on companies; on the other hand, in the absence of complementary measures to support technology transfer and the economic valorization of innovations, they can lead to reduced efficiency in commercializing research results.

A central role in this mechanism is played by the human resources involved in research, and from this perspective, the SDG_09_30 indicator – which measures the number of people engaged in R&D activities – is crucial for understanding the relationship between public policies and the efficiency of innovation processes. The quality, availability and mobility of researchers directly influence the ability of an economy to turn R&D investments into tangible innovations.

Therefore, for fiscal policies to be effective, they need to be coupled with strategies geared towards human capital development, continuous training and support for interregional and international mobility of research personnel.

In the absence of these components, the positive effects of fiscal incentives may be limited or even canceled out, a phenomenon reflected in the literature by the so-called “masking effects”, which occur when intermediate factors – such as the mobility of research personnel – mitigate or reverse the direct impact of public policies on innovation. Thus, the SDG_09_30 indicator should not be seen merely as a monitoring tool, but as a strategic benchmark in the definition of coherent public policies capable of supporting innovation performance at national and European level.

Equally important is that the innovation performance of European regions is shaped by the dominant type of knowledge base and the institutional structure of the R&D system, especially the balance between public and private components. Studies show that developed, knowledge-intensive regions with advanced science and technology have robust R&D systems, either dominated by the private sector or characterized by a relative balance between public and private research.

This institutional set-up favors a high capacity to convert knowledge into innovative solutions that are economically applicable. In contrast, less developed regions rely predominantly on synthetic knowledge bases – of a pragmatic, experience-oriented nature – and public sector research, which may limit the potential for competitive innovation. These findings support the need for European cohesion and innovation policies to be tailored to regional specificities, promoting not only increased investment in R&D, but also tailoring it to the typology of knowledge bases and institutional architecture of each region (Blažek & Kadlec, 2019; Meliciani et al., 2022).

It is crucial to emphasize that the economic performance and competitiveness of EU Member States are becoming increasingly dependent on the level of digitalization and their capacity to leverage human capital during the technological transition. Digitalization has emerged as a key driver of competitiveness, shaping and influencing all economic sectors.

Skilled human resources play a fundamental role in this equation, as the success of the digital transformation depends not only on infrastructure and technology, but also on workforce competencies. Therefore, policies to boost innovation and economic performance must include measures dedicated to skills development, lifelong learning and labor market mobility (Boikova et al., 2021; Marti & Puertas, 2023).

As highlighted by research findings, differences in the level of economic competitiveness between European countries are not only determined by the existing digital infrastructure, but also by the capacity of human resources to adapt and actively contribute to innovation processes. For example, countries such as Germany, Sweden and Denmark are characterized by a high share of R&D personnel and an education system that supports the development

of advanced technological skills, allowing them to effectively leverage investments in research and digital infrastructure.

In contrast, countries such as Romania, Malta or Slovakia face challenges related to a lack of skilled personnel and a limited capacity to turn research investment into applicable innovation, thus contributing to structural gaps in economic and technological performance.

In recent years, the number of patent applications filed annually at the European Patent Office (EPO) has increased significantly, highlighting not only the growing dynamism of innovative activity at European level, but also the need to develop efficient tools to manage and analyze this considerable volume of information. In this context, a key role is played by patent information retrieval, i.e., the process by which relevant documents are identified and extracted according to a specific subject matter or research need.

However, traditional search systems, similar to web search engines, often prove inefficient due to the complex legal and technical language used in patent documents. Their limited accuracy hinders the comprehensive retrieval of relevant information. To address this challenge, interactive tools developed in collaboration with patent experts are needed to facilitate more advanced and precise searching and analysis. These tools could also support related tasks, such as evaluating patent value, identifying legal risks, and designing licensing strategies (Shalaby & Zadrozny, 2019).

In this context, the *SDG_09_40* indicator, which monitors the evolution of the number of patent applications filed at the European Patent Office, provides not only a quantitative picture of innovation intensity in the EU Member States, but also a clear signal on the need to strengthen the digital and methodological infrastructure for patent information management. This is justified by the accelerating growth in the volume of data and the ever-expanding complexity of the technical and legal jargon specific to patent documents, which makes efficient retrieval of information from these databases a critical step in assessing the novelty and originality of inventions.

While recent advances in natural language processing and semantic search technologies have significantly improved the performance of information retrieval systems, these technologies are still limited by the specificity of patent documents and terminology variations between domains.

Consequently, optimizing the search process requires a combination of advanced computational methods and specialized human expertise in a collaborative and interdisciplinary framework. Strengthening this technological framework is important not only for the efficiency of intellectual property systems, but also for supporting innovation ecosystems, reducing uncertainties related to invention protection and increasing economic competitiveness at European and global level (Ali et al., 2024; Tessema & Nicola-Gavrilă, 2023; Zhang et al., 2018).

In the European context, the *SDG_09_40* indicator should be interpreted not only quantitatively but also qualitatively, reflecting both the accessibility and effective use of patented information. An increase in applications filed at the European Patent Office is meaningful only when accompanied by measures that promote digitization, semantic indexing, and the intelligent management of patent documents.

Thus, this indicator becomes a strategic tool for strengthening European innovation ecosystems in line with the objectives of sustainable development and technological cohesion policies within the European Union (Hegde et al., 2023).

The analysis of the indicator “Share of buses and trains in total passenger transport” (SDG_09_50) provides a concrete and necessary framework for assessing the sustainability of urban mobility systems in Europe. In a context where cities are simultaneously facing challenges related to congestion, pollution and social exclusion, the transition to collective transport is no longer just an option for economic efficiency, but a strategic necessity for achieving sustainable development goals.

Individual transport, especially car-based travel, generates a disproportionate amount of emissions per capita and greatly contributes to the deterioration of air quality and urban life. By contrast, collective transport has the potential to reduce the carbon footprint and support social inclusion through increased accessibility. From this perspective, SDG_09_50 should not only be seen as a transport performance indicator, but as a barometer of European countries’ commitment to the green transition.

Rigorous monitoring of this indicator and its integration into local mobility strategies would enable a stronger alignment between transport policies, urban planning, and climate objectives. Moreover, this approach would support the transformation of cities into resilient, green and equitable urban spaces, where efficiency and sustainability are not contradictory but complementary.

It is also important to note that the SDG_09_50 indicator – Share of buses and trains in total passenger transport – provides a clear measure of the extent to which European countries are adopting collective, cleaner and more energy efficient mobility solutions. For example, the shift towards collective forms of transport is a key element in reducing the environmental impact of urban mobility, particularly in the context of increasing emissions from individual transport.

Public transport– such as buses, trains, and trolleybuses – has a much lower carbon footprint per passenger compared to private cars. This advantage is vital for cities striving to meet sustainable development goals by reducing pollution, congestion, and resource consumption. Countries that have consistently invested in modernizing public transport infrastructure and integrating sustainable urban logistics into planning strategies – such as Germany, France, and the Czech Republic – have consequently achieved a higher share of collective transport in total passenger trips (European Commission, 2020; EEA, 2022).

At the same time, optimizing connections between seaports and inland regions through the combined use of road, rail and inland waterways can contribute to more efficient logistics and reduce environmental impacts. Thus, the importance of an integrated multimodal approach, including solutions for the critical “last mile” segment, becomes essential to ensure a seamless transition of goods from the main infrastructures to the final delivery points. The intelligent integration of different modes of transport – in particular the promotion of inland waterways and rail transport – is seen as a key measure to reduce emissions, road congestion and logistics costs (Paulauskas et al., 2022).

The analysis also highlights the crucial role of digital technologies and coordinated planning in developing sustainable logistics chains that can respond effectively to the economic and environmental demands of European transport. Regions with well-developed multimodal port connections gain significant competitive advantages by reducing transport times, optimizing freight flows, and enhancing infrastructure resilience. Last-mile solutions, such as

urban logistics hubs or the use of electric vehicles for local distribution, are put forward as essential elements of a sustainable mobility strategy, aligned with European targets on reducing emissions and increasing energy efficiency (Andersson & Ivehammar, 2016; de Paula & Marins, 2018; Paulauskas et al., 2022).

The SDG_09_60 indicator – Share of freight transported by rail and inland waterways – expresses the proportion of freight transported by more sustainable modes of transport, compared to road transport, which remains predominant but with a significantly higher environmental impact. In this context, the development of inland waterway and rail transport can make a decisive contribution to the transition to a more sustainable and energy-efficient logistics system.

In order for these forms of transport to achieve their environmental and operational potential, inland waterway transport needs to be strategically harnessed through investment in navigation infrastructure, fleet modernization and integration into multimodal networks alongside rail transport. Despite the clear advantages of inland waterway transport, its use remains uneven across Europe, often constrained by factors such as outdated infrastructure, lack of interoperability and variable hydrological conditions. Therefore, the development of integrated logistics corridors linking river ports with rail and road networks becomes essential to provide efficient multimodal solutions in freight transport. Equally important is the digitization of supply chains and the use of intelligent river traffic management systems to increase the reliability and competitiveness of inland shipping (Bedoya-Maya et al., 2023; Sys et al., 2020).

To support the transition towards a truly sustainable and competitive logistics system in Europe, one of the innovative directions is the integration of advanced automation and digitization technologies in rail and inland waterway transport. For example, the development of intelligent and autonomous logistics corridors based on Autonomous Inland Vessels (AIVs) and automated freight trains could radically transform the efficiency and flexibility of supply chains in the European Union. These solutions would enable continuous operation without downtime, reduce energy consumption through real-time route optimization, and increase transport safety and predictability (Cassetta et al., 2017; Gkoumas et al., 2022).

In addition, the use of artificial intelligence in the management of multimodal flows, together with the implementation of “digital twins” for transnational logistics corridors, can allow the simulation and optimization of transport scenarios before actual implementation, thus reducing operational risks and environmental impacts. These technologies, already in pilot phases in European projects (e.g., AUTOFLEX or IW-NET), can support a true green revolution in logistics, transforming the SDG_09_60 indicator from a simple monitoring tool into a real catalyst for the structural transformation of freight transport in Europe (Gkoumas et al., 2022; Specht et al., 2022).

Achieving the targets of the SDG_09_60 indicator is therefore directly dependent on the ability of EU Member States to integrate rail and inland waterway transport into national logistics corridors. Countries such as Germany, the Netherlands or Belgium demonstrate that through targeted investments in multimodal infrastructure and operational support policies, these modes can become viable and competitive alternatives to road transport.

Increasing the share of freight transport by rail and inland waterways not only reduces emissions and energy consumption, but also contributes to smoother supply chains, strengthening economic resilience and logistical sustainability. In this way, the SDG_09_60 indicator becomes a concrete tool for assessing progress towards greener and more efficient freight mobility in Europe (Krmac & Djordjevic, 2024).

The SDG_09_70 indicator – Industrial Air Emissions Intensity – measures the amount of air pollutant emissions produced by the industrial sector in relation to Gross Value Added (GVA). This indicator reflects the environmental efficiency of industrial processes and the ability of the economy to decouple increased production from increased pollution. The lower the intensity of emissions, the more eco-efficient the industry, indicating real progress towards sustainable industrialization.

In the European Union, this indicator is essential for monitoring the impact of industrial processes on air quality and for assessing the compatibility between economic performance and environmental protection. Reducing emission intensity implies the adoption of clean technologies, increased energy efficiency, the transition to renewable sources and the application of circular economy principles in industrial activities. Recent studies show that significant reductions in emissions of fine particulate matter (PM_{2.5}), SO₂ and NO_x from industry are possible through a combination of source control technologies and modernization of production processes, particularly in sectors such as the steel industry (Wang & Luo, 2023; Yuan et al., 2024).

Another relevant example is the oil refining industry, which is a core sector of the energy industry. It has a significant impact on the value of the SDG_09_70 indicator - Emissions intensity of industry, measuring air emissions relative to gross value added. By its carbon and energy intensive nature, crude oil refining contributes to both global greenhouse gas emissions and local air pollution (Griffiths et al., 2022; Kim et al., 2022).

In this context, industrial restructuring has become a strategic tool for reducing air pollutant and greenhouse gas emissions, especially in energy-intensive sectors. Input-output model analyses indicate that transitioning to a more energy-efficient industrial structure can generate significant decarbonization effects; however, these effects are uneven over time and follow a non-linear trajectory.

Overall, restructuring has a greater impact on lowering greenhouse gas emissions than on reducing traditional air pollutants. The effectiveness of these measures is most evident when combined with structural reforms in the energy sector and policies that promote technological modernization.

Decarbonizing the sector is both a technological necessity and a strategic priority for improving the environmental performance of industry. Measures such as electrification of processes, use of renewable energy sources, integration of carbon capture and storage technologies and reorganization of production flows can directly contribute to reducing emissions intensity. Linking these initiatives with policies on green transition and industrial innovation is essential for the SDG_09_70 indicator to reflect real progress towards sustainable and low-emission industrialization.

The results of this research highlight the complex and uneven trajectory of EU Member States in achieving SDG 9 objectives, emphasizing the dual challenge of fostering innovation while strengthening infrastructure resilience. The upward trends in R&D expenditure

and human capital development observed in countries such as Belgium, Germany, and Sweden confirm the effectiveness of long-term policy commitments and stable innovation ecosystems. These findings align with previous research that links sustained investment in research and innovation to higher competitiveness and resilience (Blažek & Kadlec, 2019; Urbano et al., 2020). However, the persistent disparities among Member States, particularly in sustainable mobility and industrial decarbonization, reveal a growing divergence between innovation leaders and lagging economies. This divergence mirrors the “core-periphery” dynamic described in European cohesion studies, suggesting that current policy mechanisms are insufficient to ensure territorial convergence. Furthermore, the forecasted decline in the share of public transport and rail freight underscores systemic barriers to decarbonizing mobility systems, highlighting the urgent need for integrated policies that combine infrastructure modernization with behavioral and regulatory interventions.

These findings have significant implications for European policy frameworks. First, they point to the necessity of strengthening financial and technical support for lagging Member States to bridge innovation and infrastructure gaps. Second, they underline the importance of cross-border collaboration and knowledge transfer to accelerate convergence, particularly in areas such as green technologies and sustainable logistics. Finally, the uneven pace of industrial emissions reduction suggests that climate objectives cannot be met through market mechanisms alone; rather, coordinated interventions at the EU level are essential to harmonize standards and promote systemic resilience. By linking innovation and infrastructure development to broader societal outcomes, the study reinforces the strategic role of SDG 9 as a driver of sustainable and inclusive growth within the European Union.

7. Conclusions

Strengthening technological innovation and infrastructural resilience are fundamental elements in achieving sustainable economic development in the European Union. In the context of the implementation of Sustainable Development Goal 9 (SDG 9), this research provided an empirical analysis of key structural indicators – R&D expenditure, patent applications, low-emission transport infrastructure and industrial emissions intensity – to assess the degree of convergence of Member States towards a resilient, innovative and climate neutral economy.

The results show important progress in strengthening innovation capacity. Increasing gross R&D expenditure, particularly in countries such as Belgium, Austria and Germany, suggests a positive trend towards exceeding the 3% of GDP threshold by 2030, thus aligning with the targets set in the Europe 2020 Strategy. Also, the expansion of the R&D workforce in countries such as Poland, Hungary and Croatia points to an inclusive industrialization orientation and increased potential for technology transfer. Developments in patent applications in countries such as Portugal, Lithuania and Ireland suggest a strengthening of research capitalization systems and better protection of intellectual property in emerging economies.

However, the analysis also reveals persistent regional and sectoral disparities. The declining share of rail and inland waterway transport in total freight transport, as well as the declining use of public transport in passenger mobility, signal a deviation from the trajectories set out in European sustainable infrastructure policies. In addition, the uneven reduction in the intensity of industrial emissions – with examples of stagnation or regression in countries

such as Portugal and Hungary – highlights structural vulnerabilities that require differentiated interventions tailored to national and regional specificities.

The results emphasize the necessity for an integrated and adaptive policy framework designed to stimulate innovation while mitigating regional inequalities and responding to environmental pressures. Strengthening cross-border cooperation, enhancing financial mechanisms for lagging economies, and prioritizing sustainable infrastructure investment are critical steps to accelerate progress. By explicitly connecting innovation and infrastructure to long-term competitiveness and climate neutrality, this research contributes valuable empirical evidence to inform European strategies for sustainable development. Future studies should expand on this work by exploring causal relationships and evaluating the effectiveness of specific policy interventions, thereby deepening the understanding of how SDG 9 objectives can be fully realized across the European Union.

While the findings provide valuable insights, several limitations should be acknowledged. Variations in data availability and quality across Member States pose challenges to ensuring full comparability and may limit the overall comprehensiveness of the analysis. Moreover, although quantitative indicators are effective for identifying general trends, they cannot fully capture the underlying socio-economic dynamics, such as institutional structures, policy coherence, and the functioning of innovation ecosystems. These constraints underscore the importance of incorporating qualitative methodologies and interdisciplinary perspectives in future research to achieve a more nuanced and holistic understanding of the factors driving sustainable development.

From a future research perspective, it is recommended to deepen the interlinkages between SDG 9 indicators and other 2030 Agenda goals – in particular SDG 7 (Clean and affordable energy), SDG 11 (Sustainable cities and communities) and SDG 13 (Climate action). There is also a need to develop interdisciplinary analytical tools that integrate quantitative and qualitative data to better understand institutional contexts, innovation ecosystems and policy implementation mechanisms.

Strategically, it is imperative that European policies support sustainable digitization and the transition to smart industry. Emerging technologies such as artificial intelligence, industrial automation, smart infrastructure and digital solutions for decarbonization need to be promoted as levers for the structural transformation of the European economy. In this respect, particular emphasis should be put on strengthening institutional capacity, supporting regional innovation ecosystems and fostering transnational partnerships in programmes such as Horizon Europe or the Recovery and Resilience Facility.

In conclusion, only through an integrated policy approach – capitalizing on the complementarity between technological innovation and infrastructural resilience – can the European Union move sustainably towards a fair, competitive and adaptable economy capable of meeting the challenges of the 21st century.

Author contributions

The authors contributed equally to this paper.

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