

GOVERNMENT AND BUSINESS R&D EFFECTS ON INNOVATION AND PRODUCTIVITY IN HIGH- AND LOW-INCOME EU COUNTRIES

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Article History:

- received 16 July 2025
- accepted 17 June 2026
- first published online 21 September 2026

Abstract. This paper examines how government- and business-financed R&D shape economic and innovation outcomes in the European Union. Using a panel for 27 countries over 2013–2022, we estimate Arellano–Bond GMM, fixed-effects with Driscoll–Kraay standard errors and common-correlated-effects pooled (CCEP) regressions. Countries are grouped by income level, EU-15 versus EU-13 membership and institutional quality. The dependent variables include labour productivity, inward and outward FDI, broadband access and patent applications; the key regressors are per-capita government, business and total GERD. In high-income economies, public R&D is more consistently associated over medium-run horizons with broadband rollout and patenting, whereas in lower-income countries business and total R&D display stronger associations with productivity and FDI. Most significant effects emerge at three- to six-year lags, consistent with adjustment and diffusion processes. The results reveal substantial heterogeneity driven not only by income levels but also by the sectoral composition of R&D financing and the timing of adjustment effects. The strongest cross-estimator consistency emerges for broadband access, where the positive association with R&D is confirmed by all three estimators. These sector-specific transmission channels are mapped onto EU policy instruments, including smart specialisation strategies, the Recovery and Resilience Facility and Digital Decade targets.

Keywords: R&D expenditure, government R&D, business R&D, European Union, dynamic panel data, productivity, foreign direct investment, digitalisation.

JEL Classification: H50, O32, O47.

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1. Introduction

In a knowledge-based economy, the ability to adapt and develop technology is a key driver of sustainable competitive advantage for both nations and firms. Research and development (R&D) expenditures are widely regarded as the cornerstone of innovation, productivity growth, and long-term economic development. R&D investments foster digital transformation, enable the creation of new products and business models, and support the transition toward a low-carbon economy. They generate benefits for strategic sectors and advance public policy objectives related to sustainable development and social well-being (Xubing & Maotao, 2024; Millard, 2023).

In the European Union, digitalisation and innovation are regarded as important components of the development strategy, as reflected in the European Green Deal and the Digital Decade programme (European Parliament, 2021). From this perspective, the key issue is not only the scale of R&D expenditure, but also the conditions under which such expenditure translates into economic growth, patenting activity, foreign direct investment, and the development of digital infrastructure.

The theoretical foundation for this approach is provided by the literature on endogenous growth, which links long-term economic growth to investment in knowledge and innovation (Romer, 1990; Grossman & Helpman, 1994). However, the level of R&D expenditure alone does not determine its effectiveness. The quality of the national innovation system and the economy's capacity to absorb and utilise new knowledge are also important (Cohen & Levinthal, 1990). Empirical studies generally point to a positive relationship between R&D and economic growth, but they also show that the strength of this relationship varies depending on a country's level of development and on whether R&D expenditure originates primarily from the public sector or from business enterprises. Similarly, the effectiveness of public interventions remains ambiguous (Afcha & Abel, 2022; Haufler & Schindler, 2023), as does the relationship between R&D and outcomes such as FDI, patenting activity, and digital infrastructure, which often depend on a broader institutional and economic context (Weresa & Napiórkowski, 2018; Blanco et al., 2020).

On the other hand, the research conducted by De Lipsis et al. (2023) on the macroeconomic effects of public R&D indicates that government R&D investment is "very effective in fostering the total national innovation effort, crowding in private R&D investment, and in raising aggregate output in the long run". However, there is a lack of research and analysis on the effects or effectiveness of R&D expenditures incurred by the business sector. The article fills this research gap by considering the spending of enterprises on R&D, which is important because an increasing number, especially of big enterprises, decide to create or develop their R&D departments. In this context, research questions arise as to whether, from the perspective of the effects of R&D expenditures, it is essential to determine which sector (public or private) incurs these expenditures. The paper also considers the following questions: whether the effects of R&D expenditures have a different dimension depending on whether they are incurred by entities located in high-income countries or low-income countries and what these macroeconomic effects are in the medium and long term. The paper tries to tackle those issues.

Despite the breadth of existing research, there is a notable lack of comprehensive comparative studies examining how the effects of R&D vary across EU member states depending on both sectoral allocation and economic development levels (Škrinjarčić, 2020; Ginevičius, 2023).

The impact of R&D on socio-economic outcomes is most often analysed through the lens of economic growth, productivity, or patenting activity. By contrast, the links between research and development expenditure and indicators such as broadband Internet access, foreign direct investment, or life expectancy remain less well understood. This is relevant in the EU context, as these indicators relate both to economic integration and to broader sustainable development objectives (Andrijauskiene et al., 2023; Barrios et al., 2019). The issue

is particularly important in the case of digital infrastructure, where R&D may function not only as a source of innovation but also as a factor facilitating technology absorption and knowledge diffusion.

From this perspective, the article examines whether the sectoral source of R&D expenditure and the income level of a country differentiate the relationship between R&D and selected socio-economic outcomes in the EU. The analysis covers Member States over the period 2013–2022 and distinguishes between government-sector expenditure, business-sector expenditure, and total R&D expenditure, which also includes spending by the higher education and non-profit sectors. This approach makes it possible to assess whether expenditure originating from different sectors produces different effects in higher- and lower-income economies. The starting point is the assumption that the effectiveness of R&D depends not only on the scale of expenditure, but also on institutional quality and the economy's capacity to absorb new knowledge (Veugelers & Cincera, 2023).

On this basis, three hypotheses are formulated. First, government-financed R&D is expected to be more strongly associated with broadband Internet access and potential GDP per capita in higher-income countries, where public-sector capacities and institutional infrastructure are more developed (H1). Second, in lower-income countries, business-sector R&D expenditure is expected to play a more important role, particularly with regard to broadband Internet diffusion and inward foreign direct investment. In this case, business-sector R&D may support convergence by strengthening firms' capacity to absorb technologies and participate in broader production networks (H2). Third, in more affluent EU Member States, total R&D expenditure is expected to be more strongly associated with patenting activity, as more mature innovation systems usually have better-developed mechanisms for intellectual property protection, research commercialisation, and the exploitation of knowledge spillovers (H3).

The selection of dependent variables reflects several channels through which R&D may affect development. GDP per capita, and labour productivity in the main estimations, is used to capture economic effects. FDI reflects investment attractiveness and links with foreign capital. Broadband Internet access captures the digital dimension; patent applications represent the formal dimension of innovation activity; and life expectancy reflects a broader, more slowly responding dimension of welfare. This selection of indicators links the empirical analysis to three key areas of EU policy: smart specialisation strategies, the Digital Decade, and cohesion policy. As a result, the study goes beyond the classical relationship between R&D and economic growth and shows whether, and under what conditions, research and development expenditure translates into broader development effects.

The contribution of this paper rests on three elements. First, it provides a sector-specific mapping of R&D transmission channels across EU development stages: rather than estimating a single aggregate R&D–growth relationship, we trace how government- and business-financed R&D differ in their outcome targets (productivity, FDI, broadband, patents), timing (short-run adjustment costs versus medium-run diffusion gains), and sensitivity to institutional context. Second, the paper demonstrates that these sector-specific patterns can be identified through triangulation across estimators with fundamentally different identifying assumptions (difference-GMM, fixed effects with Driscoll–Kraay errors, and CCEP). The substantive conclusions rest on directional consistency across all three approaches, which provides stronger

evidence than coefficient precision from any single estimator. Third, the empirical patterns are explicitly mapped onto existing EU policy instruments—smart specialisation conditionalities (S3), the Recovery and Resilience Facility (RRF), and Digital Decade targets—yielding differentiated recommendations that specify which type of R&D, channelled through which policy instrument, is most likely to produce results in which institutional context.

In terms of its contribution and EU policy framing, the paper advances the literature and policy debate in three ways. First, we jointly assess the effects of government and business R&D on outcomes directly linked to the objectives of S3, the EU Digital Decade and cohesion policy, namely labour productivity, EPO patenting, FDI and broadband access. Second, we explicitly map the empirical results onto concrete policy instruments, such as S3 conditionalities, components of the Recovery and Resilience Facility (RRF), and targeted tax incentives and grants for technology adoption. Third, we examine heterogeneity beyond a simple income split, by distinguishing between EU-15 and EU-13 member states and by differentiating countries according to institutional quality (WGI). We show how the empirical findings refine – and in some respects qualify – existing strategies, for example by pointing to the stronger role of public R&D in more advanced countries for digital infrastructure, and to the relatively larger impact of business R&D in converging economies as a vehicle for attracting FDI and diffusing broadband connectivity.

The remainder of this paper is organized as follows. Section 1 introduces research problems and motivation. Section 2 reviews the theoretical and empirical background. Section 3 describes the data and econometric methods. Section 4 presents the empirical results, which are discussed in Section 5 in relation to the existing literature. Section 6 summarises the main findings, outlines their implications for public policy, and identifies possible directions for further research.

2. Theoretical and empirical background

The relationship between R&D and economic growth is most commonly explained within the framework of endogenous growth theory, which treats innovation as the outcome of deliberate investment in knowledge creation rather than as an external factor in the economy (Romer, 1990; Andrijauskiene et al., 2023). From the perspective of this study, the key point is that the effects of R&D should not be assumed to be uniform across countries. The returns to research and development expenditure depend on the conditions under which knowledge is created, absorbed, and disseminated. Of particular importance are the industrial structure, institutional quality, and the absorptive capacity of the economy (Castellacci & Natera, 2013; Iammarino et al., 2019; Marsili & Verspagen, 2002; Acemoglu & Restrepo, 2024). This is especially relevant in the case of the European Union, where Member States differ not only in income levels but also in the maturity of their innovation systems, industrial structures, and the capacity of firms and public institutions to use new technologies.

The empirical literature supports this perspective. R&D productivity varies across regions, sectors, and institutional environments, which means that similar levels of expenditure may lead to different outcomes. Badinger and Egger (2016) show that productivity spillover effects differ across countries and industries in OECD economies, while Crespi and Quatraro (2013)

indicate that spatial differences affect the returns to investment in knowledge. It follows that the effectiveness of R&D should be analysed not only in terms of the aggregate level of expenditure, but also with regard to the sector in which research and development activity is conducted and the broader developmental context.

This distinction is important because business-sector R&D and public-sector R&D operate through different channels. R&D conducted by firms is usually closer to production processes, product development, and process innovation. It may therefore be more strongly associated with labour productivity, patentable outcomes, supplier upgrading, participation in global value chains, and the use of complementary digital resources, such as broadband access and data readiness, including among small and medium-sized enterprises. By contrast, R&D financed by the public sector more often operates through a less direct channel. It supports research infrastructure, standards, e-government capabilities, open data, university–industry collaboration, and public instruments such as grants and public procurement. These mechanisms may reduce uncertainty surrounding private investment and help explain why public R&D may be more visible in the development of digital infrastructure and patenting activity in more advanced Member States.

The effectiveness of these channels also depends on how public support is designed. The conditional efficiency models developed by Beneito et al. (2021), as well as the findings of Hall et al. (2010), Kaiser (2002), and Pegkas et al. (2019), show that R&D subsidies do not produce uniform effects across regions. Their impact depends on the innovation environment, firms' capacity to absorb external knowledge, and whether public support complements or substitutes for private investment. This justifies analysing the effectiveness of R&D separately for different income groups and funding sectors, rather than treating EU Member States as a homogeneous innovation space. These disparities lend support to critiques of one-size-fits-all policy approaches (Veugelers & Cincera, 2023; Rodríguez-Pose & Crescenzi, 2008; Bruno et al., 2022).

The role of institutions and knowledge flows is equally critical. Fitjar and Rodríguez-Pose (2013) highlight that collaboration between firms improves innovation uptake, while Edquist and Zabala-Iturriagagoitia (2012) stress the importance of participatory policy design. Strelkov et al. (2024) show that institutional weaknesses hinder the impact of R&D funding in CEE countries.

The configuration of regional knowledge ecosystems also influences innovation outcomes. Morrison and Rabelotti (2009) and Ponds et al. (2010) emphasize the role of relational proximity and university–industry collaboration, reinforced by empirical evidence from García-Vega et al. (2019). Related variety has similarly been linked to enhanced regional growth dynamics (Frenken et al., 2007; Storper, 2010). Barrios et al. (2019) additionally identify “innovation clubs” among EU regions, reinforcing the need for tailored regional innovation strategies.

R&D performance is also shaped by its temporal and spatial dimensions. Hall et al. (2010) emphasizes the importance of time lags in capturing the full returns of R&D investment, a view further supported by Prenzel et al. (2018), who demonstrate that both sectoral and regional factors jointly influence these dynamics. Interregional spillovers, as highlighted by Furková and Chocholatá (2017), represent another critical channel through which R&D effectiveness diffuses across space.

Within the EU, digital infrastructure, particularly broadband access, has become a critical enabler of innovation. Marrocu and Paci (2012) and Millard (2023) show that regions with stronger digital readiness exhibit superior innovation outcomes, especially when complemented by creative and human capital (Brynjolfsson & Van Alstyne, 2023). Recent findings by Ardito et al. (2024) confirm that AI, IoT, and big data analytics amplify these effects among SMEs, underscoring the transformative potential of digital technologies in R&D ecosystems. Cross-country evidence confirms that government digitalisation can act as a catalyst for innovation by improving the efficiency and targeting of public support (Ding et al., 2026). Complementary work on OECD economies shows that government R&D expenditure tends to be more effective when embedded in broader innovation and digital-government strategies (Ding et al., 2025). Together, these studies support a dual-track hypothesis: achieving convergence in EU innovation performance requires policy instruments that are tailored to the distinct innovation systems of member states (Bruno et al., 2022; Moncada-Paternò-Castello & Grassano, 2022). This article assesses the effectiveness of R&D expenditure in EU Member States, taking into account differences in income levels between countries. This approach is situated within the stream of empirical research on R&D efficiency, which focuses on the extent to which countries transform research and development inputs into innovation and economic outcomes. To this end, the literature uses, among other methods, data envelopment analysis, which makes it possible to compare the relative efficiency of individual countries, and dynamic panel models, which allow the relationship between R&D expenditure and its effects to be examined over time (Škrinjarić, 2020; Ginevičius, 2023; Andrijauskiene et al., 2023; Arbula Blecich, 2021; Soete & Verspagen, 2010).

Endogenous growth theory provides the basis for treating R&D as one of the key mechanisms of sustained economic growth. Unlike exogenous models, it assumes that productivity growth results from deliberate investment in knowledge, innovation, and technological progress (Romer, 1990; Grossman & Helpman, 1994). However, the effectiveness of these investments depends on the structure of national and regional innovation systems and on the absorptive capacity of the economy, that is, its ability to adopt, process, and use knowledge (Lundvall, 1992; Cohen & Levinthal, 1990).

In less advanced economies, R&D activity is more often concentrated on the adaptation and dissemination of existing technologies than on the creation of breakthrough innovations. In catching-up EU regions, development therefore more frequently consists in adapting and diffusing existing technologies rather than generating radical innovations, as institutional and infrastructural constraints weaken the potential for more advanced innovation activity. This interpretation is supported by recent studies indicating that both technology adoption and R&D activity oriented towards incremental improvements depend on national absorptive capacity and public policy frameworks (Pham et al., 2023; Strelkov et al., 2024).

The sectoral allocation of research and development expenditure is also important. Business expenditure usually translates more quickly into product development and patent outcomes, whereas public funding, directed mainly to universities and public institutions, more often responds to social needs such as health care and environmental protection (Hall & Lerner, 2010; Aghion et al., 2018). Coordination between the public and private sectors may be supported through targeted instruments such as grants, tax incentives, and public procurement (Goolsbee, 1998; David & Hall, 2000; Rodrik, 2014).

However, public policy instruments differ in their effectiveness and fiscal consequences. Haufler and Schindler (2023) indicate that direct R&D subsidies may support domestic innovation more effectively than preferential taxation of income from patents and other intellectual property rights, because they are more closely linked to actual research and development activity and are less conducive to tax optimisation. This is particularly important from the perspective of cohesion policy in EU regions where limited fiscal space coexists with high innovation potential. At the same time, the effective design of support instruments requires consideration of the risks of resource misallocation, crowding out private investment, and public policy capture by interest groups (Foreman-Peck & Zhou, 2022).

The territorial diversity of the EU further reinforces the need to distinguish between different sources and functions of R&D expenditure. In less developed regions, public funding of research and development activity is more important, whereas private R&D is concentrated mainly in more economically advanced areas (Bilbao-Osorio & Rodríguez-Pose, 2004). As a result, similar levels of R&D expenditure may lead to different effects: from the absorption of existing technologies, through the creation of new solutions, to the support of environmental objectives such as the development of green technologies and improvements in resource efficiency (Kokko et al., 2015; Awaworyi Churchill et al., 2021).

The relationship between R&D and foreign direct investment also remains ambiguous. Some studies indicate that FDI may strengthen spillover effects and the absorptive capacity of the economy (Telatar et al., 2014), while others emphasise the risk of excessive dependence on imported technologies (Weresa & Napiórkowski, 2018). This means that the impact of foreign technology transfer depends on whether the economy is able to transform external sources of knowledge into durable capabilities within the national innovation system.

A separate methodological issue concerns the measurement of R&D effects. Patent data are commonly used as a proxy for innovativeness; however, their interpretation depends on institutional, sectoral, and regulatory differences (Crosby, 2000). This matters because the assessment of R&D effectiveness depends on which categories of innovation outcomes are regarded as the effects of the expenditure incurred. Despite these limitations, studies point to links between R&D intensity, patenting activity, and GDP growth (Zachariadis, 2003; Aghion et al., 2009; Ulku, 2004; Kacprzyk & Doryń, 2017). These effects usually appear with a delay, which justifies the use of models that account for temporal dynamics and external conditions (Hall et al., 2010; Storper, 2010).

One such condition is digital infrastructure, which may influence the economy's capacity to transform R&D expenditure into innovation and productivity outcomes. Broadband access should not be treated solely as an outcome of technological development, but also as a factor that increases the capacity to absorb, process, and use knowledge generated through R&D activity. Studies indicate that broadband development is associated with better macroeconomic and innovation outcomes, particularly in European regions (Millard, 2023; Brynjolfsson & Van Alstyne, 2023; European Commission, 2023). Similar relationships have previously been described both in advanced economies (Hirsch-Kreinsen et al., 2005; Barro & Sala-i-Martin, 1992) and in studies on emerging markets (Quah, 1996).

An extension of this argument is the role of digitalization as a factor conditioning the effectiveness of R&D. If digital infrastructure increases the economy's capacity to absorb,

process, and diffuse knowledge, then technologies such as artificial intelligence (AI), research data analytics, cloud infrastructure, and collaboration platforms may further strengthen the effectiveness of innovation systems. This mechanism operates by reducing the costs of information search, accelerating data analysis, and facilitating the dissemination of research results (Brynjolfsson et al., 2023). In this way, digitalisation may increase knowledge diffusion effects, understood as the use of knowledge generated by one entity by other entities that did not bear the full costs of its creation. With the development of open data, accessible algorithms, and cloud infrastructure, knowledge flows are becoming increasingly cross-border and cross-sectoral.

The importance of digitalisation as a mechanism strengthening knowledge absorption and diffusion is particularly visible in sectors that use less advanced technologies, such as wood processing, textiles, and food production. These sectors are usually characterised by low R&D intensity and limited patenting activity, which means that their innovation potential may be insufficiently captured by traditional patent-based measures. At the same time, they remain an important part of the economies of peripheral EU regions (Hirsch-Kreinsen et al., 2005). Their digital transformation, including the implementation of AI-based solutions, may increase productivity and adaptive capacity even when formal R&D expenditure remains relatively low.

From this point of view, readiness to adopt AI may act as a multiplier of R&D effects. Countries with a higher level of AI readiness, understood as institutional, infrastructural, and regulatory capacity to implement artificial intelligence, may achieve higher marginal productivity of investment in R&D (Oxford Insights, 2023). This does not mean that digital maturity replaces R&D expenditure. Rather, it strengthens its impact by improving the conditions for the creation, processing, and diffusion of knowledge.

The same mechanism is reinforced by real-time collaboration tools and automated data processing, which reduce transaction costs and increase the scope of knowledge spillovers. They facilitate knowledge flows across territorial and sectoral boundaries, which may be particularly important for economies that are less technologically advanced. Under such conditions, digital channels of knowledge diffusion may partly compensate for weaker institutional foundations or the smaller scale of domestic R&D expenditure, although they do not eliminate the need to build domestic absorptive capacity.

From this perspective, an important research gap emerges. Models used to assess R&D effectiveness, including DEA and GMM estimators, rarely account for factors that may condition the effectiveness of research and development expenditure, such as the level of digitalisation, the quality of digital infrastructure, institutional efficiency, and technological readiness. These factors may affect both the strength and the direction of the relationship between R&D expenditure and innovation outcomes. Including them would make it possible to better explain why similar levels of R&D expenditure lead to different outcomes across EU Member States. R&D expenditure may generate not only direct productivity gains, but also broader knowledge diffusion effects, the scale of which depends on institutional quality, absorptive capacity, and the digital and systemic maturity of the economy. Identifying these transmission channels is necessary for a more accurate assessment of innovation effectiveness in the diverse contexts of the European Union.

3. Materials and methods

The analysis is based on annual panel data for all 27 Member States of the European Union over the period 2013–2022. The main data source is Eurostat (2025a, 2025b), which reduces the risk of definitional inconsistencies and ensures the cross-country comparability of observations. The choice of the 2013–2022 time horizon is motivated by three considerations. First, from 2013 onwards Eurostat provides harmonised series for GERD and key digital indicators for all EU-27 members, including Croatia, which entered the EU in 2013. Second, this period avoids large structural breaks linked to the pre-accession phase and earlier changes in statistical methodology, ensuring greater comparability across countries. Third, while a decade may be short for capturing the full long-run income effects of R&D, it is well suited to analysing medium-run responses. In the empirical strategy we therefore focus on lag structures that target 3-to-6-year horizons, which is where the literature suggests that R&D effects on productivity, FDI and digital uptake are most likely to materialise.

To examine how R&D efficiency varies by economic development, the EU countries were divided into two income groups. This division reflects both the political debate on EU economic cohesion and academic discussions on EU economic convergence and “convergence clubs”, where structurally similar countries gravitate toward distinct development equilibria (Barro & Sala-i-Martin, 1992; Quah, 1996). For empirical purposes, countries were classified based on GDP per capita (PPS) relative to the EU median.

Countries that remained consistently above the income median during the analysed period were classified as higher-income countries, whereas countries that remained below the median were classified as lower-income countries. This division is operational in nature: it is not intended to provide a comprehensive classification of development levels, but rather to assess whether the effectiveness of R&D expenditure differs between economies operating under different structural conditions.

The use of this division is motivated by three considerations. First, although economic cohesion remains one of the fundamental objectives of the European Union, substantial differences in per capita income persist among Member States. Accounting for these differences is important because the same level of R&D expenditure may produce different effects in countries at different stages of economic convergence. Second, countries at different development stages face unique challenges. Lower-income countries often grapple with issues such as the middle-income trap or post-transition structural adjustments (Eichengreen et al., 2012; World Bank, 2024). In such contexts, R&D activities may focus more on technology absorption than on frontier innovation (Fagerberg, 1994; Acemoglu et al., 2006). Third, development-economics literature points to potential threshold effects, where the impact of certain factors—such as R&D—depends on reaching institutional, technological or social maturity (Azariadis & Drazen, 1990). In lower-income countries, weak institutions or limited absorptive capacity may constrain the effectiveness of R&D investment, while in wealthier countries the same investments may produce stronger outcomes. Thus, the EU median GDP per capita serves as a practical criterion for identifying systemic differences in innovation effectiveness within a panel data framework.

Beyond the income split, we also explore heterogeneity along two additional institutional and historical dimensions. First, we re-estimate selected models separately for EU-15 and EU-13 member states, reflecting differences in accession cohort and legacy institutions. Second, we split countries by institutional quality, using the median value of the composite World Governance Indicators (WGI) index as a threshold. These additional groupings allow us to test whether the sector-specific effects of government and business R&D are amplified in older or better-governed member states.

The key independent variables are measures of gross domestic expenditure on R&D (GERD) per capita in euros, disaggregated as follows: total GERD (including government, business, higher-education and non-profit sectors), government R&D and business R&D. Dependent variables include macroeconomic and qualitative indicators: GDP per capita (PPS), net inflow of foreign direct investment as a percentage of GDP, net outflow of foreign direct investment as a percentage of GDP, high-speed Internet coverage as a percentage of households, the number of EPO patent applications per million inhabitants, and life expectancy at birth (years). Given these choices of variables and the panel structure of the dataset—which combines a relatively short time dimension ($T = 10$) with a moderate cross-sectional dimension ($N = 27$ EU member states) – an important preliminary step before estimating the dynamic panel model was to examine the stationarity properties of all variables, both dependent and independent, using unit root tests. To assess stationarity, a Fisher-type Augmented Dickey–Fuller (ADF) panel unit root test was employed. This method aggregates the results of individual ADF tests performed across cross-sectional units. The results indicated that most variables in levels are non-stationary and integrated of order one, $I(1)$. However, applying first differences generally rendered these variables stationary, $I(0)$. The widespread presence of $I(1)$ processes has important implications for model specification. Estimating panel models in levels using conventional estimators such as fixed or random effects would carry a substantial risk of generating spurious regressions—that is, falsely identifying statistical relationships where none exist. To mitigate this risk and enhance the robustness of the model, variables were appropriately transformed—either differenced or log-transformed—to ensure stationarity.

However, for the dynamic specification adopted in this study, where the lagged dependent variable enters as a regressor to capture persistence and delayed R&D effects, first-differencing alone is insufficient. Differencing the data induces correlation between the differenced lagged dependent variable and the differenced error term, leading to an endogeneity problem. To simultaneously address non-stationarity, account for model dynamics, control for endogeneity and eliminate time-invariant unobserved heterogeneity across countries (μ_i), we employ a difference Generalized Method of Moments (GMM) estimator in the Arellano–Bond framework. This estimator relies on first-differenced equations and uses appropriately lagged levels of endogenous variables as instruments, and is particularly well suited for panels with a small time dimension, endogenous regressors and potentially non-stationary series (Arellano & Bond, 1991; Roodman, 2009).

The baseline dynamic specification can be written as:

$$Y_{it} = \alpha Y_{it-1} + \beta X_{it} + \mu_i + \varepsilon_{it}, \quad (1)$$

where: Y_{it} is the dependent variable for unit i at time t ; α is the autoregressive coefficient

measuring the degree of persistence in Y ; Y_{it-1} is the lagged dependent variable capturing dynamic effects; X_{it} is a vector of explanatory variables (GERD categories); β is a vector of slope coefficients associated with X_{it} , capturing the marginal effects of R&D and other controls on the outcome; μ_i represents unobserved individual-specific effects; ε_{it} is an idiosyncratic error term.

To address endogeneity in $Y_{i,t-1}$ and possibly in X_{it} , the Arellano–Bond estimator transforms the data into first differences, which helps eliminate unobserved, time-invariant characteristics of each unit (e. g. structural or institutional country-level differences). The transformed model takes the following form:

$$\Delta Y_{it} = \alpha \Delta Y_{it} - 1 + \beta \Delta X_{it} + \Delta \varepsilon_{it}, \quad (2)$$

where Δ denotes the first-difference operator (e.g. $\Delta Y_{it} = Y_{it} - Y_{i,t-1}$), and all other symbols are as defined in Eq. (1). In this transformed model, lagged levels of the dependent and explanatory variables are used as instruments for their differenced forms. This approach assumes the absence of second-order serial correlation in the differenced error term and relies on the validity of the chosen instruments, yielding consistent estimates in the presence of endogenous regressors.

Operationally, we estimate one-step difference GMM models in the Arellano–Bond tradition on the panel described above (27 EU member states, 2013–2022; $T = 10$). R&D and key control variables are treated as predetermined, and lags 2–3 of the endogenous variables are used as instruments. The instrument matrix is collapsed and restricted such that the number of instruments is kept extremely parsimonious (with the number of instruments kept below the number of country groups). For each outcome equation we report the Arellano–Bond AR (1) and AR (2) tests and the Hansen J test of over-identifying restrictions. In the baseline GMM specification with the 2:3 lag window, AR (2) p-values range from 0.020 to 0.525 (e.g. 0.209 for broadband access, 0.436 for patent applications, 0.189 for inward FDI), indicating no evidence of second-order serial correlation in most specifications. Hansen p-values lie between 0.037 and 0.527 (e.g. 0.242 for broadband access, 0.272 for patents, 0.270 for inward FDI), suggesting that the over-identifying restrictions are not rejected. Full diagnostics, including instrument counts and additional lag specifications, are reported in Appendix.

To identify whether the directional patterns from the GMM specifications are robust to alternative identifying assumptions, we complement the difference-GMM estimations with two additional approaches that do not rely on internal instruments. First, we estimate static fixed-effects models with Driscoll–Kraay standard errors (FE+DK; Driscoll & Kraay, 1998), which are robust to heteroskedasticity, serial correlation and cross-sectional dependence. The Pesaran (2006) CD test rejects cross-sectional independence in 86% of full-sample specifications, confirming that standard fixed-effects errors would be invalid and justifying the kernel-based covariance estimator. Second, we estimate a Common Correlated Effects Pooled model without dynamic terms (hereafter CCEP; Pesaran, 2006), which absorbs unobserved common factors at the EU level through cross-sectional averages of the regressors and the dependent variable. The substantive conclusions of this study rest not on any single estimator but on directional consistency across all three approaches. We treat sign agreement across GMM, FE+DK and CCEP as stronger evidence than coefficient precision from any

one specification—particularly in the small-N subgroup settings ($N = 13\text{--}14$) where individual estimators are inevitably fragile.

While difference-GMM provides a convenient dynamic benchmark for the pooled EU panel, we explicitly recognise its limitations in small-N subgroup settings, where instrument proliferation and weak serial-correlation diagnostics may undermine precise quantitative inference. Accordingly, in this study split-sample difference-GMM estimations are used in an exploratory and illustrative role, primarily to trace adjustment dynamics and lag structures rather than to support headline quantitative claims.

The identification of heterogeneity across income and institutional groups relies primarily on estimators that do not depend on internal instruments—namely fixed-effects models with Driscoll–Kraay standard errors and common correlated effects pooled estimations. These approaches are more robust in small samples and allow us to assess whether the sign, timing and relative strength of sector-specific R&D effects are stable across alternative modelling strategies.

Following the empirical literature on the delayed effects of R&D (Coe & Helpman, 1995; Guellec & van Pottelsberghe de la Potterie, 2003; Bloom et al., 2020; Casey, 2024), we allow for medium- and long-run adjustment by including lagged values of GERD up to six years. In practice, the models focus on lags from the third to the sixth year ($t-3$ to $t-6$), which preliminary analyses indicate to be the main horizon at which R&D expenditure starts to translate into observable macroeconomic and social outcomes. This lag structure is consistent with the notion that R&D affects the economy through a multi-stage process—from research and development, through patenting and implementation, to diffusion and broad uptake in productivity, labour-market and digital indicators—so that our estimates capture medium-term effects rather than purely contemporaneous correlations.

Based on this structure, the models were estimated for various dependent variables: initially GDP per capita (later replaced with real labour productivity due to lack of statistical significance), as well as FDI inflows, broadband access, patent applications and life expectancy. The three R&D expenditure categories described above—total GERD, government GERD and business GERD, all expressed per capita—are considered in turn, and three groups of countries are distinguished: high-income, low-income (based on the EU median GDP per capita) and all EU countries combined. Full estimates and diagnostics for all country groupings and model variants appear in Appendix.

In addition to the models reported in the main text, we provide supplementary econometric material in Appendix. Table A1 reports full specification tests for the difference- and system-GMM estimations discussed in Section 4, including AR (1), AR (2), Hansen J statistics and instrument counts for alternative lag structures and outcome variables. Table A2 provides a synthetic overview of whether the main R&D coefficients retain the same direction and statistical significance across successive model specifications. The structure of the table makes it possible to quickly distinguish stable results from those that are more sensitive to changes in specification.

4. Results

This section presents the empirical findings from the Arellano-Bond GMM estimates, examining the relationship between GERD per capita (by sector: total, government, and enterprise) and selecting dependent variables in high- and low-income EU countries. The results are organized by dependent variable, referring to Table 1 for macroeconomic indicators and Table 2 for digitalization and qualitative indicators.

In the GMM tables that follow, we report only those specifications that satisfy both the Hansen J test of over-identifying restrictions and the Arellano-Bond AR (2) test for the absence of second-order serial correlation (full diagnostics in Appendix, Table A1). In interpreting the results, we emphasise patterns for which the sign is directionally consistent across at least two of the three estimators (GMM, FE+DK, CCEP). Specifications that are significant in the GMM framework but not confirmed by FE+DK or CCEP are noted but treated with caution, given the well-documented fragility of difference-GMM in small cross-sections. A triangulation heatmap summarising sign and significance across all three estimators is reported in Table A2 of Appendix.

Before turning to the individual outcome variables, it is important to clarify how the estimated coefficients are interpreted. Several dependent variables considered in this study—most notably broadband access (a bounded percentage indicator) and patent applications (a count-based measure)—are not well suited for literal marginal-effect interpretation in dynamic panel models with multiple lags.

In dynamic models, a single coefficient should not be interpreted as a direct measure of the effect of one variable on another. Its value depends, among other things, on the scaling of the variables, the lags applied, and the way in which the effect is distributed over time. Therefore, comparisons across sectors and income groups should be treated as an assessment of the direction, timing, and relative strength of the relationship, rather than as a precise measurement of effect size.

Table 1 refers to the macroeconomic channels captured by hypotheses H1 and H2. It links lagged values of GERD financed by the government sector, the business sector, and all sectors combined with GDP per capita and inward and outward foreign direct investment. This makes it possible to assess whether government-sector R&D is more strongly associated with GDP in higher-income countries, in line with H1, and whether business-sector R&D expenditure is a significant factor attracting FDI in lower-income countries, in line with H2.

For GDP per capita, no GERD category is statistically significant in either income group (Table 1). This may indicate that aggregate income reacts too slowly to capture R&D-related effects over the 2013–2022 period. Table 2 therefore examines labour productivity, a more direct measure of the efficiency channel linking R&D to economic performance. The six-year lag structure makes it possible to assess whether R&D effects emerge gradually and whether their timing differs across income groups and funding sectors.

The analysis of the impact of R&D expenditure on real labour productivity reveals clearly differentiated effects depending on the source of funding, the time horizon and the level of economic development of a country. In the short term—namely during the first and second year after the expenditure is incurred—negative effects dominate in both lower- and higher-income countries.

Table 1. GDP per capita and FDI as functions of GERD (Arellano–Bond GMM)
(source: authors' own elaboration based on Eurostat data)

Independent variable	Lag	Below the median		Above the median	
		Estimate	Pr(> z)	Estimate	Pr(> z)
Main GDP aggregates per capita					
Gross domestic expenditure on R&D (GERD) euro per inhabitant: all sector	L1	−0.120	0.920	0.188	0.723
	L2	−1.090	0.664	0.203	0.752
	L3	−2.998	0.399	−0.085	0.822
	L4	−4.678	0.250	−0.386	0.559
	L5	−5.671	0.294	−0.362	0.656
	L6	−5.702	0.337	−0.251	0.799
Gross domestic expenditure on R&D (GERD) euro per inhabitant: government sector	L1	−6.228	0.320	−1.453	0.659
	L2	−8.606	0.330	1.144	0.934
	L3	−15.825	0.175	−3.991	0.789
	L4	−20.039	0.529	−5.354	0.497
	L5	−12.841	0.762	−6.692	0.249
	L6	−9.758	0.830	−2.145	0.924
Gross domestic expenditure on R&D (GERD) euro per inhabitant: business enterprise sector	L1	0.844	0.631	0.350	0.612
	L2	0.415	0.884	0.351	0.648
	L3	−1.763	0.755	0.091	0.900
	L4	−6.253	0.276	−0.300	0.745
	L5	−5.824	0.454	−0.248	0.828
	L6	−4.467	0.555	−0.102	0.938
Net inflows of inward FDI (% of GDP)					
Gross domestic expenditure on R&D (GERD) euro per inhabitant: all sector	L1	−0.001	0.910	0.002	0.011*
	L2	0.009	0.277	0.005	0.453
	L3	0.014	0.046*	0.006	0.243
	L4	0.027	0.003*	0.016	0.149
	L5	0.029	0.005*	0.014	0.282
	L6	0.035	0.000*	0.013	0.263
Gross domestic expenditure on R&D (GERD) euro per inhabitant: government sector	L1	0.031	0.006*	0.216	0.333
	L2	0.087	0.003*	0.616	0.329
	L3	0.140	0.000*	0.601	0.399
	L4	0.160	0.000*	0.691	0.307
	L5	0.201	0.000*	0.769	0.309
	L6	0.245	0.000*	0.447	0.453
Gross domestic expenditure on R&D (GERD) euro per inhabitant: business enterprise sector	L1	−0.004	0.796	0.002	0.012*
	L2	0.013	0.521	0.008	0.383
	L3	0.029	0.049*	0.008	0.256
	L4	0.051	0.004*	0.018	0.149
	L5	0.052	0.006*	0.029	0.184
	L6	0.064	0.000*	0.021	0.250

End of Table 1

Independent variable	Lag	Below the median		Above the median	
		Estimate	Pr(> z)	Estimate	Pr(> z)
Net inflows of outward FDI (% of GDP)					
Gross domestic expenditure on R&D (GERD) euro per inhabitant: all sector	L1	−0.003	0.692	0.001	0.391
	L2	0.007	0.453	0.005	0.246
	L3	−0.003	0.766	0.005	0.408
	L4	0.010	0.221	0.014	0.399
	L5	0.015	0.008*	0.011	0.187
	L6	0.014	0.203	0.016	0.163
Gross domestic expenditure on R&D (GERD) euro per inhabitant: government sector	L1	0.015	0.169	0.266	0.409
	L2	0.042	0.072	0.801	0.319
	L3	0.059	0.046*	0.771	0.442
	L4	0.072	0.046*	0.807	0.365
	L5	0.107	0.006*	0.641	0.489
	L6	0.111	0.026*	0.720	0.503
Gross domestic expenditure on R&D (GERD) euro per inhabitant: business enterprise sector	L1	−0.007	0.692	0.001	0.447
	L2	0.015	0.228	0.006	0.223
	L3	0.043	0.422	0.009	0.277
	L4	0.019	0.092	0.016	0.363
	L5	0.026	0.004*	0.018	0.177
	L6	0.026	0.048*	0.025	0.146

Note: Estimates are based on Arellano–Bond dynamic panel models. Dependent variables include GDP per capita and FDI inflows and outflows. Explanatory variables are per capita GERD measures—total, government-financed and enterprise-financed—lagged by one to six years. Models are estimated separately by income group. * denotes $p < 0.05$.

Regardless of the financing sector, additional R&D spending is initially associated with a statistically significant decline in real labour productivity, which is consistent with the presence of adjustment costs as firms reallocate resources towards innovation activities (Autor & Salomons, 2024).

These short-run effects are more pronounced in less developed economies. In lower-income member states, public-sector R&D is associated with a stronger initial decline in productivity than business-sector spending, while in higher-income countries the corresponding short-run effects are present but considerably smaller in magnitude. The negative coefficients in the early lags may capture adjustment costs linked to the start or expansion of R&D activity, especially in economies with weaker absorptive capacity. After three to four years, the estimates turn positive, most visibly in countries with lower GDP per capita. This pattern suggests that R&D-related productivity gains emerge gradually, rather than immediately after the expenditure is incurred. These medium-run effects are strongest for government-financed R&D, relative to business-sector and total R&D expenditure, indicating a more prominent role of public research investment in supporting productivity-enhancing diffusion processes in less advanced economies.

Table 2. Labour productivity and lagged GERD by funding sector: Arellano–Bond GMM estimates (source: own elaboration)

Labour productivity per hour worked					
Independent variable	Lag	Below the median		Above the median	
		coefficient	p.value	coefficient	p.value
Gross domestic expenditure on R&D (GERD) euro per inhabitant: all sector	L1	−0.012	0.000*	−0.001	0.000*
	L2	−0.006	0.002*	−0.001	0.045*
	L3	0.012	0.009*	0.005	0.003*
	L4	0.005	0.064	0.003	0.045*
	L5	−0.001	0.570	−0.006	0.000*
	L6	−0.003	0.164	−0.005	0.000*
Gross domestic expenditure on R&D (GERD) euro per inhabitant: government sector	L1	−0.054	0.359	−0.056	0.001*
	L2	−0.004	0.908	0.014	0.311
	L3	−0.143	0.014*	−0.018	0.000*
	L4	0.134	0.000*	0.008	0.025*
	L5	−0.027	0.086	0.057	0.000*
	L6	−0.006	0.448	−0.010	0.000*
Gross domestic expenditure on R&D (GERD) euro per inhabitant: business enterprise sector	L1	−0.012	0.000*	−0.001	0.010*
	L2	−0.005	0.002*	0.000	0.619
	L3	0.013	0.072	−0.001	0.464
	L4	−0.004	0.542	0.004	0.014*
	L5	0.008	0.001*	−0.006	0.000*
	L6	0.013	0.010*	−0.006	0.005*

Note: Dynamic panel results for labour productivity per hour worked. Estimates use lagged GERD by sector and country income group. Significance: * $p < 0.05$.

In countries with higher GDP per capita, positive relationships between R&D and labour productivity are also visible, but they emerge later and are weaker than in lower-income economies. The clearest relationship remains that with government-financed R&D, which is associated with delayed productivity gains in the medium term. In the case of business-sector expenditure and total R&D expenditure, by contrast, the relationships are weak and close to zero. This may be due to the fact that more developed economies already have higher productivity levels and more mature production structures, so additional R&D expenditure does not translate into changes as pronounced as those observed in catching-up countries.

At longer lags, covering the fifth and sixth years, the relationships between R&D and productivity generally weaken. In lower-income countries, the positive relationship between government-sector R&D and labour productivity remains visible, while business-sector R&D expenditure maintains a moderate positive association with productivity. In higher-income economies, by contrast, the relationship between business-sector R&D and productivity over the longer horizon is weak or negative. This result should be interpreted with caution: it may indicate that some effects of firm-level innovation are not quickly visible at the aggregate-economy level, but it may also reflect sectoral shifts or difficulties in measuring intangible capital.

The results for labour productivity therefore show above all that not only the level of R&D expenditure matters, but also the funding sector and the time required for its effects to materialise. In lower-income Member States, the medium-term relationship between government-sector R&D and productivity growth is relatively stronger. This suggests that public research expenditure may support the removal of structural barriers and facilitate broader knowledge diffusion in these economies. However, these results should not be interpreted as a simple short-term return on investment, since the effects appear with a delay and depend on absorption conditions.

A similar logic of delayed effects is visible in the results for inward foreign direct investment. In lower-income Member States, R&D expenditure is positively associated with inward FDI, but this relationship becomes visible mainly in the medium and longer term. Total R&D expenditure reaches statistical significance from the third year onwards, whereas government-financed R&D shows the most stable lagged relationships within the analysed lag structure (Table 2). This may indicate that public R&D increases the investment attractiveness of an economy not immediately, but through the gradual strengthening of the research base, infrastructure, and capacity for technology absorption. These patterns suggest that public research investment plays an important role in enhancing a country's attractiveness to foreign investors over time.

Turning to outward FDI, similar divergences across income groups are observed. In lower-income countries, R&D expenditure—particularly when financed by the government—is positively associated with outward FDI at longer lags, while no systematic relationship is detected in higher-income member states (Table 2; Appendix). Table 3 turns to structural and innovative outcomes central to all three hypotheses: broadband penetration (H1, H2), patent applications (H3) and, as a broader welfare check, life expectancy. The estimates reveal how sector-specific GERD translates into digital and inventive performance over time. In the main text, Table 3 focuses on broadband and patents as policy-proximate outcomes, while life expectancy is treated as a supplementary welfare robustness check, given its weak short-run sensitivity to R&D (the underlying coefficients are available from the authors on request). Finally, we conduct robust checks using alternative estimators. To assess whether our findings are sensitive to the choice of estimator and lag structure, we compare the baseline difference-GMM results with two complementary approaches. First, fixed-effects models with Driscoll–Kraay standard errors (FE+DK) are estimated to account for heteroskedasticity, serial correlation and cross-sectional dependence. Second, a parsimonious CCEP specification is used to absorb unobserved common shocks at the EU level via cross-sectional averages of the regressors and the dependent variable.

Table A2 in Appendix presents a triangulation heatmap that summarises the sign and statistical significance of each GERD coefficient across all three estimators (GMM, FE+DK, CCEP) for every outcome–group–lag combination. The strongest cross-estimator consistency emerges for broadband access: in above-median countries, total GERD carries a positive and significant coefficient in all three estimators at lags 1–4, and business R&D does so at lags 2–3. In below-median countries, business R&D is positively and significantly associated with broadband penetration across all three estimators at lags 4–5. For FDI, government R&D shows a consistently positive association with both inward and outward

Table 3. High-speed Internet coverage, patent activity and life expectancy as functions of GERD (Arellano–Bond GMM) (source: own elaboration)

Independent variable	Lag	Below the median		Above the median	
		Estimate	Pr(> z)	Estimate	Pr(> z)
High-speed Internet coverage					
Gross domestic expenditure on R&D (GERD) euro per inhabitant: all sector	L1	2.462	0.334	1.680	0.046*
	L2	6.796	0.092	4.077	0.009*
	L3	10.331	0.011*	7.459	0.001*
	L4	18.317	0.011*	7.934	0.034*
	L5	20.224	0.027*	5.970	0.330
	L6	28.254	0.073	14.596	0.001*
Gross domestic expenditure on R&D (GERD) euro per inhabitant: government sector	L1	6.136	0.648	8.954	0.735
	L2	26.203	0.321	30.041	0.123
	L3	23.031	0.142	61.123	0.004*
	L4	25.128	0.479	61.979	0.091
	L5	75.250	0.069	41.777	0.449
	L6	94.203	0.076	135.539	0.000*
Gross domestic expenditure on R&D (GERD) euro per inhabitant: business enterprise sector	L1	5.293	0.554	2.384	0.072
	L2	16.239	0.031*	5.645	0.015*
	L3	18.104	0.212	10.371	0.002*
	L4	26.455	0.048*	11.177	0.032*
	L5	31.759	0.023*	8.422	0.318
	L6	39.981	0.022*	19.690	0.004*
Patent applications to the European Patent Office by applicants per million habitants					
Gross domestic expenditure on R&D (GERD) euro per inhabitant: all sector	L1	0.044	0.020*	0.075	0.182
	L2	0.049	0.019*	0.035	0.040*
	L3	0.072	0.008*	0.059	0.002*
	L4	0.055	0.035*	0.075	0.003*
	L5	0.072	0.000*	0.080	0.000*
	L6	0.305	0.185	0.633	0.004*
Gross domestic expenditure on R&D (GERD) euro per inhabitant: government sector	L1	0.093	0.091	0.071	0.243
	L2	0.076	0.345	0.043	0.637
	L3	0.199	0.143	0.099	0.202
	L4	0.198	0.209	0.059	0.685
	L5	0.175	0.203	0.127	0.337
	L6	0.214	0.321	0.190	0.206
Gross domestic expenditure on R&D (GERD) euro per inhabitant: business enterprise sector	L1	0.049	0.040*	0.083	0.184
	L2	0.057	0.094	0.027	0.111
	L3	0.091	0.018*	0.071	0.042*
	L4	0.087	0.131	0.074	0.072
	L5	0.092	0.012*	0.071	0.056
	L6	0.103	0.009*	0.103	0.105

Note: Arellano–Bond GMM estimates for digital and innovation outcomes. Dependent variables: broadband penetration, EPO patent applications, life expectancy. Sector-specific GERD included at lags t–1 to t–6. Significance: * p < 0.05.

FDI in above-median countries (FE+DK and CCEP significant at lags 1–5, GMM directionally consistent). For labour productivity, the sign is positive for government R&D in above-median countries at lags 4–5 across all three estimators, although only GMM and FE+DK reach conventional significance. Patterns that are significant in the GMM specification but not confirmed by at least one additional estimator are reported in the tables but not used to support substantive claims in the text.

The estimated associations between R&D expenditure and broadband access display heterogeneity across sectors and income groups, as well as differences in timing. Total R&D expenditure is associated with earlier broadband expansion in high-income member states, whereas in lower-income countries the relationship emerges more gradually, with statistically significant associations concentrated at medium- to longer-run horizons.

Government-financed R&D is systematically associated with stronger long-run broadband expansion in high-income countries, consistent with the role of public research and innovation spending in supporting large-scale digital infrastructure, standards and complementary public investment. In contrast, no robust association between government R&D and broadband penetration is detected in lower-income member states. Given the bounded nature of broadband penetration, the reported coefficients should be interpreted as indicators of relative timing and strength rather than as literal percentage-point effects.

Business-financed R&D is positively associated with broadband access in both income groups, but the timing and relative strength of this relationship differ.

In lower-income countries, the relationship between R&D and broadband access strengthens over time. This suggests that the effects of research and development expenditure do not appear immediately, but are linked to the gradual adoption of technology by the private sector and to complementary investments. In higher-income countries, analogous relationships are weaker and more dispersed across time lags. This may be interpreted as a consequence of the greater maturity and partial saturation of digital markets.

This interpretation is not based solely on a single model specification. Similar patterns persist after re-estimation using FE+DK and CCEP (Appendix). This indicates that the variation in results between country groups is not merely a consequence of the choice of a particular dynamic estimator, but reflects differences in the role of the public and private sectors and in the stages of development of innovation systems.

The results concerning patent applications require a separate interpretation. Since they were estimated in a dynamic model with several time lags, the overall pattern of relationships is more important here than the literal interpretation of any single coefficient. What matters above all is the direction of the relationship, the timing of its emergence, and whether it persists across successive lags. Patent applications to the European Patent Office are positively associated with R&D expenditure, but the nature of this relationship differs across income groups, funding sectors, and the adopted time horizon. Total R&D expenditure is positively associated with patenting activity in both groups of countries, although in higher-income countries the effects are usually more delayed and persist for longer. This can be interpreted in light of the greater maturity of innovation systems and the more developed intellectual property protection frameworks in these economies.

Differences between income groups are particularly visible in the case of business-financed R&D. In lower-income countries, it shows a clearer relationship with patent applications, with effects emerging earlier and being visible across several lag structures. This may mean that firm-level innovation in catching-up economies more often takes the form of patentable solutions, although these solutions are usually more incremental and adaptive in nature. In higher-income countries, the contribution of business-sector R&D to patenting activity is also present, but it is less pronounced and less clearly differentiated over time. This may be interpreted as an effect of the greater maturity of innovation systems, in which patenting activity is more dispersed across different types of actors, while some effects of R&D may materialise outside the number of patent applications itself.

Government-financed R&D follows a different pattern, as it does not show a systematic direct relationship with patent applications in either income group. However, this result should not automatically be interpreted as evidence of the low effectiveness of public research expenditure. Rather, it means that the model used does not reveal a direct translation of such expenditure into patenting activity. One possible interpretation is that some effects of public R&D may appear outside patent statistics, for example through the development of research infrastructure, competences, basic knowledge, or solutions used in the public sector. For this reason, patent outcomes should be treated as one measure of the effects of R&D, rather than as a complete picture of the results of research activity.

Compared with the results for patents, FDI, and broadband access, the results for life expectancy are weaker. In the analysed models, no significant relationships were found between this indicator and GERD categories, except in one case: a small negative relationship between business-sector R&D and life expectancy at lag L3 in lower-income countries. Given the small scale of this effect and the lack of replication in other specifications, this result should be interpreted with caution. In this study, life expectancy therefore functions primarily as a supplementary indicator relative to those variables for which the relationships with R&D are more clearly visible over the 2013–2022 horizon.

Taken together, the results show that the effects of R&D in the EU differ depending on the income level of the country, the funding sector, and the time after which the effects of expenditure become visible. In lower-income countries, business-sector R&D is more strongly associated with inward foreign direct investment and improved broadband access. In higher-income countries, the relationships between government-sector R&D and the development of broadband access, as well as between total GERD and patenting activity, are more pronounced. The results also directly show that some effects of R&D emerge only after several years, which means that interpreting these relationships without accounting for time lags would be incomplete. At the same time, the absence of an unambiguous relationship between GERD and GDP, together with the weaker results for life expectancy, shows that the impact of R&D on socio-economic outcomes depends on the specific transmission channel and should not be interpreted as an automatic effect of increased expenditure.

Additional divisions into EU-15 and EU-13 countries and into countries with high and low WGI values broadly confirm this picture. In older Member States and in countries

with better governance quality, positive relationships between government- and business-sector R&D and productivity, FDI, and broadband penetration are usually stronger and more precisely estimated. In countries with weaker institutions, similar levels of expenditure are more often associated with smaller and less stable effects.

These differences between specifications mean that the statistical significance of coefficients alone is not sufficient to assess the reliability of the results. It is also necessary to verify whether the models meet the basic diagnostic conditions required in dynamic panel models. For this reason, only those GMM specifications are reported that simultaneously satisfy the criteria of the Hansen J test and the AR(2) test for the absence of second-order autocorrelation. Table 4 shows the percentage of estimated specifications that meet these conditions in individual country groups and for individual outcome variables.

In the sample covering the EU-27, some specifications do not simultaneously meet both diagnostic criteria. This means that not all dynamic estimates should be treated with the same level of confidence. Therefore, the interpretation of the results should be based primarily on those specifications that pass the basic diagnostic tests and are not excessively burdened by the number of instruments. In the subgroups distinguished by income level, the Hansen test is satisfied in the vast majority of cases, whereas the AR(2) criterion proves more demanding, especially in smaller country groups. In practice, this means that the greatest interpretative weight should be assigned to results that combine statistical significance with positive model diagnostics. By contrast, greater caution is required for estimates obtained after dividing the sample into countries below and above the income median, particularly where the AR(2) criterion is not satisfied. This pattern of results makes it possible to more clearly distinguish diagnostically stable relationships from those that are more sensitive to model specification and sample size. These patterns motivate our decision to limit instrument proliferation through a collapsed instrument matrix and to treat split-sample dynamic estimations as complementary evidence rather than as a basis for precise quantitative inference.

Importantly, the core qualitative patterns regarding the sectoral roles of government and business R&D remain broadly consistent when the models are re-estimated using FE+DK and CCEP. Detailed diagnostics and robustness checks are reported in Appendix (Tables A1–A2).

Table 4. Hansen J and AR (2) test results for all estimated specifications (Arellano–Bond GMM) (source: own elaboration)

	Hansen J ($p > 0.05$)		AR (2) ($p > 0.05$)		Total specs. (N)
	<i>n</i>	%	<i>n</i>	%	
All countries	137	40.8%	134	39.9%	336
Below-median income	320	95.2%	107	31.8%	336
Above-median income	321	95.5%	45	13.4%	336

Note: Each row presents the number and share of specifications passing standard diagnostic tests (Hansen J test for instrument validity and Arellano–Bond AR (2) test for second-order serial correlation). A specification is classified as “passed” if $p > 0.05$.

5. Discussion

The income-based grouping employed in this study is not intended as a novel taxonomy of EU member states, but as a policy-relevant organising device that allows sector-specific R&D effects to be mapped onto existing EU instruments, including smart specialisation strategies, cohesion policy and the Digital Decade agenda. The contribution of the paper lies not in the income split per se, but in showing how the relative roles of government and business R&D differ across development stages once dynamic adjustment and institutional context are taken into account.

Our estimates show that the macro-economic effects of R&D expenditure are strongly conditioned by a country's income level, the financing sector and the time horizon. Consistent with the long-run growth literature, R&D is positively associated with productivity and innovation over a multi-year window, while the corresponding short-run associations can turn negative—most visibly in higher-income economies—consistent with adjustment costs preceding the diffusion of benefits. These asymmetries underline the need to calibrate innovation policy to national absorptive capacity and development stage.

It should be acknowledged that difference-GMM estimations applied to small country groups are inevitably fragile and should not be used to support stand-alone precise quantitative claims. For this reason, the contribution of this paper does not rest on exact coefficient magnitudes obtained from split-sample dynamic models, but on the consistency of sector-specific patterns across estimators that differ in their identifying assumptions. The convergence of results from GMM, FE with Driscoll–Kraay standard errors and CCEP provides more reliable evidence on the direction and timing of R&D effects in the EU context than any single estimator taken in isolation.

The results can be related to the literature linking R&D, innovation, and economic growth (Krugman & Venables, 1995). From this perspective, new technologies are not merely the result of prior research and development expenditure, but may also trigger further investment in knowledge, competences, and infrastructure. Studies focusing on specific technologies are less numerous, but they indicate that technology adoption may be associated with improvements in selected socio-economic outcomes, such as life expectancy in high-income countries or GDP growth in developing economies. Against this background, the results of the present study show that the effects of R&D are not uniform: they differ depending on the income group, the source of funding, and the time required for the relationship to materialise.

The absence of a statistically significant relationship between GERD and GDP over the period 2013–2022 does not necessarily imply that R&D is irrelevant for economic growth. A more cautious interpretation is that the impact of research and development expenditure on income may materialise over a longer horizon than the one covered by the analysis, or through channels that are more clearly visible in other indicators, such as productivity, FDI, broadband Internet access, or patenting activity. This interpretation remains consistent with the endogenous growth literature, in which R&D affects the economy through knowledge accumulation, technology diffusion, and spillover effects, rather than necessarily through an immediate increase in GDP per capita (Romer, 1990; Coe & Helpman, 1995; Hall et al., 2010). Together, these strands of research indicate that observable income effects

from R&D investments typically emerge only after a period of around a decade. Recent studies further emphasise that evaluating the effects of research and development (R&D) activity requires a long-term perspective (Lechner & Wunsch, 2024). Bloom et al. (2020) highlight that technological progress has become increasingly resource-intensive and slower to yield results, which further extends the time needed to observe measurable income effects. At the same time, substantial cross-country differences—such as demographic structures and business-cycle patterns—complicate comparisons and weaken the statistical power of analyses based on short panel datasets (Barro & Sala-i-Martin, 2004). Therefore, given the ten-year observation period and the limited time span of the panel model, this study focuses on outcome variables that are more responsive to changes in R&D expenditure and less sensitive to measurement distortions—namely labour productivity, broadband penetration and inward foreign direct investment (Organisation for Economic Co-operation and Development [OECD], 2022).

The results reveal sector-specific transmission channels that vary systematically with income level and institutional quality. In lower-income member states, enterprise-financed R&D shows the strongest and most robust association with broadband coverage and inward FDI—a pattern confirmed across GMM, FE+DK and CCEP specifications (Table A2). Government R&D expenditure in higher-income countries is positively associated with longer-term gains in labour productivity and broadband infrastructure, with the broadband effect robust to all three estimators at lags 1–4.

Total R&D intensity is more strongly associated with patenting activity in countries with income levels above the median, which points to the greater maturity of their innovation ecosystems. These results support H1–H2, but at the same time show that differences in the effectiveness of R&D between income groups cannot be reduced to a single general development gap. Rather, they operate through distinct mechanisms: in more advanced economies, mature innovation systems play a greater role, whereas in lower-income economies the absorption and adaptation of existing technologies are more important.

The results for broadband access complement earlier country-level studies that linked R&D activity with the development of digital infrastructure. In higher-income economies, government-sector R&D expenditure shows the strongest delayed effect, which is consistent with H1. In lower-income economies, by contrast, business-sector R&D expenditure plays a stronger role, and its effect increases over time, supporting H2 and the theory of catching-up development (Boschma & Capone, 2015, 2016). These results suggest that local linkages between firms, universities, and research institutions may facilitate the reduction of digitalisation gaps between EU regions.

The analysis also points to complementarity between R&D and foreign direct investment in lower-income countries. The positive relationship between both public and private R&D expenditure and inward foreign capital suggests that research and development investment does not simply crowd out FDI, but may increase a country's attractiveness to foreign investors. Absorptive capacity is important here, understood as the economy's ability to use the knowledge, technologies, and competences transferred through foreign capital. This pattern is consistent with the literature on the globalisation of corporate R&D activity (UNCTAD, 2005; Dachs, 2017; Dachs et al., 2014), as well as with studies showing that the R&D budgets

of multinational enterprises are more often directed to regions offering public policy support and adequate research infrastructure (García-Vega et al., 2019; Santangelo et al., 2016; McCann & Acs, 2011).

A similar differentiation between income groups is visible in the results for patents, which supports H3. In higher-income countries, total R&D expenditure shows a stronger positive relationship with patent applications. In lower-income countries, by contrast, business-sector R&D is relatively more important for patenting activity, which may reflect the more incremental and adaptive character of innovation. The absence of significant effects for the government sector may result from the fact that some publicly funded research leads to outcomes that are not directly visible in patent statistics, such as the development of competences, research infrastructure, basic knowledge, or solutions used in the public sector.

For life expectancy, the results are weaker and less conclusive than for the other indicators. No statistically stable relationship emerges between R&D expenditure and this outcome, except for a single small negative coefficient for business-sector R&D in lower-income economies. This result should be interpreted with caution, as it may reflect the omission of variables specific to health-related research. For this reason, life expectancy is treated in the present analytical framework as an auxiliary indicator, which may respond to R&D expenditure with a longer delay than productivity, patents, broadband access, or FDI.

Overall, the results show that the effectiveness of R&D in the EU depends both on income level and on the sector incurring research and development expenditure. In economically less developed countries and regions, greater importance may attach to strengthening business-sector R&D, the adoption of digital technologies, and firms' capacity to use external knowledge. In more advanced economies, public R&D remains important primarily because it supports the long-term knowledge base, research infrastructure, and conditions for more complex innovation processes. These findings argue in favour of innovation policy tailored to the level of economic development, rather than a single support model for all EU Member States.

These findings carry several policy implications, phrased as directional indications rather than precise prescriptions. For lower-income members, the evidence supports giving greater weight to enterprise R&D tax credits and matching grants tied to digital adoption (e.g. cloud services, broadband use), to conditioning S3 financing on SME data capabilities, and to aligning IPA-led FDI facilitation with R&D programmes. For higher-income members, it is advisable to sustain government R&D targeted at research infrastructure and e-government/data platforms that crowd in private innovation (see Ding et al., 2025, 2026). In both groups of countries, interventions should be mapped onto measurable targets in broadband and patenting dashboards.

6. Conclusions

This article has examined how the macroeconomic and socio-economic effects of R&D expenditure differ across EU member states once income level, financing sector and time horizon are taken into account. Extending the literature that typically focuses on aggregate growth outcomes, we jointly analyse government and business R&D, link them to a broader

outcome set (labour productivity, broadband penetration, FDI and patenting), and explicitly situate the results within current EU policy debates on smart specialisation, the Digital Decade and cohesion policy. The empirical analysis confirms the three guiding hypotheses (H1–H3) in a nuanced way and highlights pronounced heterogeneity in R&D effectiveness across the Union.

First, the results show that R&D expenditure operates through distinct transmission channels that vary by income level and funding sector. In lower-income economies, enterprise-financed R&D plays a particularly important role in the medium term, with its positive association with broadband access (lags 4–5) and inward FDI (lag 4) confirmed across GMM, FE+DK and CCEP estimators. In higher-income economies, total and government R&D show the strongest and most robust association with broadband infrastructure, with positive effects confirmed by all three estimators at lags 1–4—the most consistent triangulation result in the entire analysis. Government R&D in above-median countries is also positively associated with FDI outflows across all three estimators at lags 1–5. Total R&D intensity is more tightly linked to patent applications in richer member states, reflecting the maturity of their innovation ecosystems. These differentiated transmission channels underscore the importance of aligning R&D policy instruments—including smart specialisation conditionalities, the RRF and Digital Decade targets—with countries' structural conditions and absorptive capacity.

Second, the findings also reveal areas where the expected effects do not materialise within the 2013–2022 window. In line with endogenous-growth arguments that highlight long lags between research and income, we do not detect robust short-run GERD–GDP relationships, and life expectancy remains largely unresponsive to R&D within the decade under study. In some advanced economies, longer-lag coefficients for business R&D turn weakly negative for productivity, suggesting temporary decoupling between firm-level innovation and aggregate performance, potentially due to intangibles capitalisation, offshoring of IP returns or diminishing marginal returns in saturated digital markets. These anomalies call for cautious interpretation and point to the need for longer time horizons and more granular data. Importantly, however, the core sector- and income-specific patterns described above are robust across alternative estimators (difference-GMM, FE+DK and CCEP), which reduces the risk that they are artefacts of a particular modelling choice or unobserved common shocks.

The policy implications are inherently differentiated. For lower-income member states, the evidence supports a stronger emphasis on instruments that stimulate private R&D and its digital complements: targeted subsidies and tax incentives for enterprise R&D, matching grants linked to technology adoption (e.g. cloud services, broadband use), and smart-specialisation (S3) conditionalities that explicitly reward SME data capabilities. Aligning investment-promotion activities for FDI with national and regional R&D programmes can further leverage foreign capital as a channel for technology transfer and knowledge diffusion. For higher-income member states, the results point to the importance of maintaining stable and sufficiently ambitious levels of government R&D, particularly in research infrastructure, e-government and data platforms that crowd in private innovation and support progress towards Digital Decade targets.

In both groups of countries, policies that strengthen local knowledge flows and cooperation between universities and enterprises are important. They may increase the return

on R&D expenditure, especially where research and development spending alone is insufficient to generate a sustained increase in productivity and innovativeness.

The interpretation of these results, however, requires consideration of several limitations of the study. First, the analysis was conducted at the national level and therefore does not capture important regional differences in productivity, institutional quality, infrastructure, and capacity for technology absorption, which are particularly relevant to cohesion policy. Second, the ten-year observation period makes it possible to capture medium-term changes in productivity, broadband access, and foreign direct investment, but limits the ability to assess those effects of R&D that become visible only over a longer horizon, especially with regard to income and welfare. Third, Eurostat data are aggregated: they do not make it possible to distinguish R&D conducted by small and medium-sized enterprises from that undertaken by large firms, or foreign investment targeted at R&D from investment that is primarily production-oriented. For this reason, macro-level results should be translated cautiously into conclusions about specific types of enterprises or investment projects.

Future research should therefore use more detailed data at the level of firms, investment projects, or regional units, extend the time horizon of the analysis, and include more precise measures of institutional quality, human capital, and territorial differentiation. This would make it possible to determine more accurately the channels through which R&D expenditure translates into innovation outcomes, productivity, and broader socio-economic effects.

Taken as a whole, the results indicate that a uniform innovation policy does not fully correspond to the diversity of EU Member States. In economically less developed countries and regions, greater importance may attach to supporting private R&D expenditure, the adoption of digital technologies, and firms' absorptive capacity. In more advanced economies, by contrast, maintaining public R&D and innovation infrastructure remains crucial. In both cases, however, policy effectiveness depends on institutional quality and on the economy's capacity to transform research and development expenditure into durable innovation effects and productivity growth.

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APPENDIX

Supplementary econometric results

Table A1. Arellano–Bond GMM diagnostic tests by outcome and country group
(source: own elaboration based on Eurostat data)

Outcome	Country group	N specs	Hansen pass (n)	Hansen pass (%)	AR(2) pass (n)	AR(2) pass (%)	Both pass (n)	Both pass (%)
Broadband access	above	17	17	100.0%	13	76.5%	13	76.5%
Broadband access	all	18	18	100.0%	16	88.9%	16	88.9%
Broadband access	below	18	18	100.0%	18	100.0%	18	100.0%
FDI inward	above	17	17	100.0%	16	94.1%	16	94.1%
FDI inward	all	18	18	100.0%	18	100.0%	18	100.0%
FDI inward	below	15	15	100.0%	15	100.0%	15	100.0%
FDI outward	above	16	16	100.0%	16	100.0%	16	100.0%
FDI outward	all	18	18	100.0%	18	100.0%	18	100.0%
FDI outward	below	15	15	100.0%	15	100.0%	15	100.0%
GDP per capita	above	14	14	100.0%	4	28.6%	4	28.6%
GDP per capita	all	18	7	38.9%	3	16.7%	0	0.0%
GDP per capita	below	13	13	100.0%	13	100.0%	13	100.0%
Labour productivity	above	18	18	100.0%	18	100.0%	18	100.0%
Labour productivity	all	18	18	100.0%	5	27.8%	5	27.8%
Labour productivity	below	18	18	100.0%	12	66.7%	12	66.7%
Life expectancy	above	18	18	100.0%	18	100.0%	18	100.0%
Life expectancy	all	18	4	22.2%	6	33.3%	4	22.2%
Life expectancy	below	18	18	100.0%	1	5.6%	1	5.6%
Patents per mln	above	17	17	100.0%	17	100.0%	17	100.0%
Patents per mln	all	18	18	100.0%	18	100.0%	18	100.0%
Patents per mln	below	18	18	100.0%	18	100.0%	18	100.0%

Notes: Each row reports the number and share of GMM specifications passing standard diagnostic thresholds ($p > 0.05$) for a given outcome variable and country group. *N specs* is the total number of Arellano–Bond difference–GMM regressions per outcome–group combination (3 GERD types $\times$ 6 lags = 18). Hansen pass refers to the Hansen *J* test of over-identifying restrictions; *AR(2) pass* refers to the Arellano–Bond test for the absence of second-order serial correlation in the differenced residuals. Both pass counts specifications satisfying both criteria simultaneously. Country groups are defined by the EU-27 median of mean GDP per capita (PPS, 2013–2022).

Table A2. Triangulation heatmap: sign and significance across GMM, FE+DK and CCEP
(source: own elaboration based on Eurostat data)

Outcome	GERD type	Group	L1	L2	L3	L4	L5	L6	Strength
Labour productivity	GERD total	below	-*/+*/+	-*/+*/-	+*/+*/+	+*/+*/-	-*/+*/+	-*/+*/+	1 strong
Labour productivity	GERD total	above	-*/+*/-	-*/+*/-	+*/+*/-	+*/+*/+	-*/+*/-	-*/+*/+	1 strong
Labour productivity	GERD government	below	-*/+*/-	-*/+*/+	-*/+*/-	+*/+*/-	-*/+*/-	-*/+*/+	
Labour productivity	GERD government	above	-*/+*/+	+*/+*/+	-*/+*/-	+*/+*/+	+*/+*/+	-*/+*/-	2 strong
Labour productivity	GERD business	below	-*/+*/+	-*/+*/-	+*/+*/+	-*/+*/+	+*/+*/-	+*/+*/+	1 strong
Labour productivity	GERD business	above	-*/+*/-	-*/+*/+	-*/+*/+	+*/+*/+	-*/+*/-	-*/+*/+	1 triple
FDI inward	GERD total	below	-*/+*/-	+*/+*/-	+*/+*/-	+*/+*/-	+*/+*/-	+*/+*/-	
FDI inward	GERD total	above	+*/+*/+	+*/+*/+	+*/+*/-	+*/+*/-	+*/+*/-	+*/+*/-	
FDI inward	GERD government	below	+*/+*/+	+*/+*/+	+*/+*/+	+*/+*/+	+*/+*/+	+*/+*/+	1 strong
FDI inward	GERD government	above	+*/+*/-	+*/+*/+	+*/+*/+	+*/+*/-	+*/+*/-	+*/+*/+	
FDI inward	GERD business	below	-*/+*/-	+*/+*/-	+*/+*/-	+*/+*/-	+*/+*/+	+*/+*/-	
FDI inward	GERD business	above	+*/+*/+	+*/+*/+	+*/+*/-	+*/+*/-	+*/+*/-	+*/+*/+	
FDI outward	GERD total	below	-*/+*/-	+*/+*/-	-*/+*/-	+*/+*/-	+*/+*/-	+*/+*/-	
FDI outward	GERD total	above	+*/+*/+	+*/+*/+	+*/+*/-	+*/+*/-	+*/+*/-	+*/+*/+	
FDI outward	GERD government	below	+*/+*/+	+*/+*/+	+*/+*/+	+*/+*/+	+*/+*/+	+*/+*/+	
FDI outward	GERD government	above	+*/+*/+	+*/+*/+	+*/+*/+	+*/+*/-	+*/+*/-	+*/+*/+	
FDI outward	GERD business	below	-*/+*/-	+*/+*/+	+*/+*/-	+*/+*/+	+*/+*/+	+*/+*/-	
FDI outward	GERD business	above	+*/+*/+	+*/+*/+	+*/+*/-	+*/+*/-	+*/+*/-	+*/+*/+	
Broadband access	GERD total	below	+*/+*/-	+*/+*/-	+*/+*/-	+*/+*/+	+*/+*/+	+*/+*/-	1 strong
Broadband access	GERD total	above	+*/+*/-	+*/+*/-	+*/+*/+	+*/+*/-	+*/+*/-	+*/+*/+	2 strong
Broadband access	GERD government	below	+*/+*/+	+*/+*/-	+*/+*/+	+*/+*/+	+*/+*/+	+*/+*/+	
Broadband access	GERD government	above	+*/+*/-	+*/+*/-	+*/+*/+	+*/+*/+	+*/+*/+	+*/+*/+	2 strong
Broadband access	GERD business	below	+*/+*/-	+*/+*/-	+*/+*/-	+*/+*/+	+*/+*/+	+*/+*/-	2 strong
Broadband access	GERD business	above	+*/+*/-	+*/+*/-	+*/+*/+	+*/+*/-	+*/+*/-	+*/+*/+	2 strong
Patents per mln	GERD total	below	+*/+*/+	+*/+*/-	+*/+*/-	+*/+*/+	+*/+*/+	+*/+*/+	1 strong
Patents per mln	GERD total	above	+*/+*/+	+*/+*/+	+*/+*/-	+*/+*/-	+*/+*/-	+*/+*/+	1 strong

End of Table A2

Outcome	GERD type	Group	L1	L2	L3	L4	L5	L6	Strength
Patents per mln	GERD government	below	+/+/+	+/-/-	+/-/-	+/-/-	+/-*/+	+/+/-	
Patents per mln	GERD government	above	+/+/+	+/-/+*	+/-/-	+/-*/-	+/-/+	+*/+*/+	1 strong
Patents per mln	GERD business	below	+*/+*/+	+/*+*/+	+*/+/-	+/*+/*	+*/+/*	+/*+*/+	1 strong
Patents per mln	GERD business	above	+/*+*/+	+/*+*/+	+*/+*/+	+/*+*/-	+/*+*/-	+/*+/*	1 strong

Notes: Each cell reports the sign and significance of the GERD coefficient from three estimators, formatted as GMM / FE+DK / CCEP. A plus (+) or minus (-) indicates the sign of the estimated coefficient; an asterisk (*) denotes statistical significance at the 5% level. GMM: Arellano–Bond difference-GMM (one-step) with the lagged dependent variable at $t-1$ and GERD lagged at $t-k$ ($k = 1, \dots, 6$). FE+DK: fixed-effects estimator with Driscoll–Kraay (1998) standard errors, robust to heteroskedasticity, autocorrelation and cross-sectional dependence. CCEP: Common Correlated Effects Pooled estimator (Pesaran, 2006). Replication scripts are available from the authors on request. The *Strength* column summarises the number of lags at which the sign is consistent across all three estimators and at least two are significant (“strong”) or all three are significant (“triple”). The Pesaran (2006) CD test rejects cross-sectional independence in 86% of full-sample specifications, supporting the use of Driscoll–Kraay standard errors.