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Digital Government and SDG 9 in the European Union: Institutional Saturation, Digital Co-Investment, and the EU15/EU13 Divide

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Abstract

Digital government is widely regarded as a catalyst for sustainable development, yet the mechanisms by which e-government adoption translates into progress on the SDGs remain poorly understood, particularly in high-income contexts where governance is already mature. This study addresses that gap using a balanced panel of all 27 EU member states over 2015–2023. Applying two-way fixed-effects estimation with formal Baron–Kenny mediation and country-block bootstrap inference, we identify three findings that collectively reframe the relationship between digital government and sustainable development in the European context. First, the widely assumed governance reform pathway is not empirically supported in the EU27: e-government adoption is not associated with measurable improvement in institutional quality, consistent with structural saturation rather than policy failure. Second, the benefits of digital government are unevenly distributed across the EU: old member states (EU15) exhibit significant positive effects on SDG 9: Innovation and Infrastructure, whereas new member states (EU13) do not, challenging the assumption that digital strategies yield symmetric returns across the Union. Third, and most importantly, the EU15 effect appears to be fully channelled through household internet access, consistent with a digital co-investment mechanism in which e-government uptake and broadband infrastructure co-evolve as expressions of a shared national digital transformation strategy. These findings inform the policy debate: the question for EU15 is not whether to invest in e-government, but how to sustain the joint infrastructure investment that makes it effective; for EU13, the priority is to establish the digital and institutional foundations that enable the mechanism to be activated.

Keywords: e-government; sustainable development goals; two-way fixed effects; mediation analysis; institutional complementarity; digital co-investment; EU15; EU13; SDG 9

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1. Introduction

Digital government has emerged as a cross-cutting accelerator of the United Nations 2030 Agenda for Sustainable Development, with the E-Government Survey 2024 documenting that public service digitalisation is now recognised as a primary enabler of SDG implementation across all 17 goals [1]. In the European Union, this ambition is enshrined in Decision (EU) 2022/2481, which establishes the Digital Decade Policy Programme 2030, with binding targets for the availability of online public services, digital skills, and connectivity across all member states [2]. Progress against these targets is monitored annually through the Digital Economy and Society Index (DESI), which tracks e-government usage alongside broader digitalisation metrics [3,4]. Despite substantial policy investment, evidence that e-government adoption translates into measurable progress on the Sustainable Development Goals (SDGs) within the EU remains limited and methodologically fragmented [5].

The financing architecture underpinning this digital transformation agenda operates through two principal instruments: the Recovery and Resilience Facility, established by Regulation (EU) 2021/241 [6], which requires member states to allocate a minimum of 20% of national recovery plans to digital investments; and the Cohesion Policy framework, which channels structural funds to bridge regional digital divides. Compliance with rule-of-law standards, as enforced through the Conditionality Regulation (EU, Euratom) 2020/2092 [7], further conditions access to these resources, creating an institutional link between governance quality and digital investment capacity that is particularly relevant for EU13 member states.

Europe is the most advanced region globally in SDG performance, yet progress has plateaued in recent years. The Europe Sustainable Development Report 2025 [8] reports that the EU27 average SDG Index score has stagnated since 2020, with notable divergence across member state cohorts. Eurostat's own monitoring of SDG progress [9] confirms that EU15 member states consistently outperform EU13 accession countries on composite SDG indicators, yet the mechanisms driving this divergence in digital governance remain underexplored. Understanding whether and through which pathways e-government adoption drives improvements in the SDGs across EU countries over time is therefore both a theoretical priority and a policy-relevant question with direct implications for the Digital Decade programme and EU Cohesion Policy.

Three theoretical mechanisms have been proposed in the literature linking digital government to sustainable development outcomes. The governance reform pathway holds that e-government reduces information asymmetries, constrains bureaucratic discretion, and builds administrative capacity, thereby improving institutional quality and enabling better SDG delivery [10,11]. The digital infrastructure pathway holds that national digital transformation strategies jointly invest in e-government services and broadband infrastructure, with resulting connectivity gains driving innovation, business activity, and progress on SDG 9 (Industry, Innovation and Infrastructure) [1,12]. The institutional complementarity pathway suggests that e-government effectiveness is conditioned on pre-existing institutional endowments, human capital, and digital readiness, producing heterogeneous effects across country cohorts [13].

Despite a growing body of cross-sectional and developing-country evidence in favour of these pathways [10,14,15], two critical gaps persist in the literature. First, to the best of our knowledge, no study has applied a formal within-country panel mediation framework to the EU27 context to test which, if any, of these three pathways operates as a significant causal chain. Cross-sectional studies conflate between-country structural differences with within-country dynamics, yielding estimates that overstate the returns to e-government investment under the SDGs. Second, no study has simultaneously stratified the EU27

panel by membership cohort (EU15 vs. EU13) and formally tested whether the digital co-investment mechanism differs across cohorts in a manner consistent with institutional complementarity rather than convergence [16].

The present study addresses both gaps using a balanced panel of all 27 EU member states for 2015–2023 (n = 243 country-year observations). We employ two-way fixed-effects (TWFE) ordinary least squares with country-clustered standard errors to identify within-country dynamics, and apply the Baron–Kenny [17] three-step mediation procedure, augmented by country-block bootstrap inference [18,19], to test three hypotheses: (H1) WGI Government Effectiveness mediates the EGOV–SDG relationship in EU27; (H2) E-government effects on SDG 9 are significantly stronger in EU15 than in EU13 member states (institutional complementarity); and (H3) The EGOV–SDG 9 association in EU15 is fully mediated by household internet access (digital co-investment mechanism). The analysis draws on data from Eurostat [20], the Digital Economy and Society Index [3,4], the Worldwide Governance Indicators [21], and the SDSN Sustainable Development Report 2025 backdated series [8].

The study makes three contributions to the literature. First, it presents the first within-country panel mediation analysis of e-government and SDG outcomes for the EU27, using a specification that controls for all time-invariant country heterogeneity. Second, it documents a digital co-investment mechanism—formally tested using Sobel inference [22] and bootstrap confidence intervals [18,19]—through which e-government uptake indirectly predicts improvements in SDG 9 in EU15 countries via internet penetration. Third, it shows that this mechanism does not operate in EU13 countries, providing panel evidence for institutional complementarity and informing the sequencing of EU Cohesion Policy digital investments. The evidence base contributes directly to the growing literature on digitally mediated SDG pathways [23–27] and provides an empirical benchmark against which Digital Decade policy targets can be evaluated. The earlier work on SDG interdependencies and national development pathways [23,24] motivates the present focus on identifying causal mechanisms within the digital-governance-SDG nexus.

The remainder of the paper is organised as follows. Section 2 reviews the relevant literature and develops the theoretical framework. Section 3 describes the data, variables, and empirical strategy. Section 4 presents the results of the mediation analysis, heterogeneity tests, and robustness checks. Section 5 discusses the findings in the context of the literature and derives policy implications. Section 6 outlines the conclusions.

2. Literature Review and Theoretical Framework

2.1. E-Government as a Driver of Sustainable Development

The conceptual link between digital government and sustainable development has been formalised through a series of policy frameworks and empirical studies over the past decade. Janowski [11] develops an aspiration-capacity gap model in which digital government serves as a means of implementing the SDGs, with effectiveness contingent on the administrative capacity and digital readiness of the implementing country. The UN E-Government Survey 2024 [1] documents a positive correlation between the E-Government Development Index (EGDI) and SDG Index scores globally, while noting that this relationship is non-linear and context-dependent, with diminishing returns at higher development levels. These findings motivate a context-specific empirical analysis of a relatively homogeneous high-governance sample, such as the EU27.

The recent empirical literature on digital government and the SDGs has expanded considerably. Sanina et al. [5] conducted a bibliometric analysis of 952 publications in the field of Sustainability over 2017–2023, finding that the digital government–SDG nexus is one of the fastest-growing research themes, yet panel-based mediation analysis remains

rare. Bocean [26] employed machine learning methods to show that digital technologies accelerate the achievement of the SDGs globally, with internet connectivity identified as the most influential predictor. Boido et al. [12] validated government ICT investment as a predictor of SDG progress across 50 countries, using fixed-effects panel regressions that confirm the positive association but do not decompose the pathways of mediation. Vărzaru [25] applied predictive modelling to EU countries and found positive associations between the Digital Economy and Society Index and SDG composite scores, but relied on cross-sectional variation that could not identify within-country dynamics.

Recent latent class analysis of SDG performance across over 160 countries identifies three temporally stable development regimes—lagging, transitional, and leading—with governance quality and digital infrastructure as the strongest structural predictors of regime membership, while short-term GDP growth exerts negligible influence [28]. This global evidence motivates the present EU-focused analysis by establishing that digital connectivity and institutional quality constitute foundational development capital rather than peripheral correlates of SDG performance.

The most directly relevant prior study for the EU context is Durkiewicz and Janowski [15], who examined 41 OECD/EU countries over 2014–2020. Using Data Envelopment Analysis to assess the relationship between digital government maturity (EGDI) and sustainable governance indicators (Bertelsmann SGI), they found that the efficiency with which digital government is used to improve governance varies strongly across countries, and that some digital government leaders persistently fail to improve their governance outcomes. This finding of heterogeneous and context-dependent effects motivates our cohort-stratified TWFE analysis, which provides the within-country panel dimension missing from the DEA approach of Durkiewicz and Janowski [15].

The Durkiewicz and Janowski [15] finding that some digital government leaders persistently fail to improve governance outcomes raises the possibility of symbolic digitalisation—a pattern in which high e-government maturity scores coexist with limited substantive institutional reform. This concern is echoed in the broader digital governance literature, which distinguishes between supply-side digitalisation (the provision of online services) and demand-side transformation (the actual integration of digital tools into governance processes that improve public outcomes). In the EU context, where e-government service availability is uniformly high, the relevant empirical question is not whether services are digitalised but whether citizen uptake of those services translates into measurable development gains—and through which channels. The present study addresses this question by testing three specific pathways and by distinguishing supply-side maturity from demand-side usage.

2.2. Institutional Quality as Mediator: The Governance Reform Pathway

The hypothesis that e-government improves institutional quality—and that this improvement subsequently translates into better development outcomes—is supported by a substantial body of evidence from developing countries. Dhaoui [10] provides the most comprehensive panel test, using 15 MENA countries over 2003–2018, and demonstrates significant positive effects of e-government development on government effectiveness and control of corruption (a-path), with these governance gains mediating SDG outcomes (b-path). The mechanism operates because MENA countries entered the period with large governance deficits, leaving considerable scope for digitally induced institutional improvement.

Elbahnasawy [14] provides complementary cross-sectional evidence from 100 countries, documenting that e-government adoption significantly reduces corruption, with effects concentrated at intermediate levels of governance and internet penetration. Critically, this nonlinearity implies that the governance-reform mechanism may be inoperative—or at least very

weak—in high-governance settings such as EU27 member states, where both the institutional baseline and internet penetration are already near the upper end of the global distribution. The Worldwide Governance Indicators [21], which provide the institutional quality data for this study, are compiled from approximately 30 cross-country data sources and cover six dimensions of governance, as documented in the 2025 methodology revision [29]. Kaufmann and Kraay [29] report that only 0.2% of all within-country WGI changes over one year are statistically significant, implying severe constraints on identifying a governance-mediation pathway in annual panel data for mature EU economies. The present study quantifies this constraint explicitly through a formal Baron–Kenny [17] decomposition.

This saturation interpretation is further supported by global panel evidence showing that governance quality operates primarily at the upper development threshold, differentiating leading from transitional regimes, rather than producing marginal gains within already high-governance contexts [28]. The implication for the EU27 is that annual within-country variation in governance indicators is too constrained to detect reform dividends, even over a nine-year panel.

2.3. Digital Transformation and SDG 9: The Infrastructure Pathway

SDG 9, which targets resilient infrastructure, inclusive industrialisation, and innovation, is the goal most directly linked to digital infrastructure investment. The UN SDG 9 indicator set includes internet usage, R&D expenditure, and mobile broadband coverage, making it structurally receptive to spillovers from digital transformation. Mura and Donath [30] examine the relationship between digitalisation and economic growth across EU countries using panel data, finding positive effects of ICT adoption on productivity, with the magnitude of these effects varying between old and new member states. Noja et al. [27] apply structural equation modelling to EU countries and demonstrate that digital transformation positively affects SDG composite scores, partially mediated by GDP per capita, but do not disaggregate by SDG goal or decompose the digital transformation bundle into its e-government and infrastructure components.

The OECD Digital Government Index 2023 [31] provides the most comprehensive comparative assessment of digital government maturity across OECD member states, identifying six dimensions of digital government performance, including digital by design, data-driven public sector, and government as a platform. Top performers on the 2023 DGI—Denmark, Korea, and Estonia—combine high EGDI scores with near-universal internet access, consistent with a co-investment interpretation. The eGovernment Benchmark 2024 [32] similarly documents that EU countries with the highest e-government service quality also exhibit the broadest internet penetration, whilst lower-performing EU13 countries show wider gaps between e-government supply and actual citizen uptake [33]. The present study uses this digital co-investment intuition as the basis for a formal mediation test.

Critically, the digital co-investment logic implies that the relationship between e-government and SDG outcomes should not be modelled as an isolated policy effect. National digital strategies—including broadband deployment plans, digital skills programmes, and public sector modernisation initiatives—constitute a bundle of complementary investments that co-evolve over time within countries. The Recovery and Resilience Facility [6] institutionalises this bundling by requiring simultaneous investment in digital infrastructure, skills, and the digitalisation of public services within national recovery plans. The implication for empirical analysis is that any observed association between e-government usage and SDG 9 may reflect the combined effect of this investment bundle rather than the marginal contribution of e-government services alone—a distinction between mediating and common driving mechanisms that the present study addresses through its progressive model-building and mediation framework (Sections 4.4 and 5.3).

While basic internet connectivity is technologically a prerequisite for any interaction with e-government platforms, the mediator employed in our specification is not bare connectivity but household internet engagement, measured as the share of households with active broadband subscriptions and routine online use (Eurostat, isoc_ci_in_h). The conceptual logic tested here is therefore not a sequence of infrastructure precedence but the well-documented "killer application" effect, in which the rollout of high-value digital public services—e-filing, e-procurement, e-health, digital identity, and e-justice—gives citizens and firms concrete reasons to subscribe to broadband, upgrade their connections, and use them more frequently and for a wider range of activities [34–36]. E-government adoption thus operates as a demand-side driver of intensive-margin internet engagement, which in turn feeds the SDG 9 sub-indicators on internet usage, R&D expenditure, and digital infrastructure development.

2.4. EU15/EU13 Heterogeneity: Convergence or Complementarity?

The enlargement of the EU from 15 to 27 member states through successive accession rounds (2004, 2007, and 2013) created a natural structural divide between old member states (EU15) with mature administrative systems and new accession countries (EU13) still converging on EU institutional and digital standards. Monfort [16] documents that, whilst significant economic convergence has occurred between EU15 and EU13 regions since accession, the pace of convergence varies substantially across dimensions, with institutional quality converging more slowly than GDP per capita.

The EU15/EU13 structural divide is further reinforced by the contemporary rule-of-law and conditionality landscape. The Conditionality Regulation (EU, Euratom) 2020/2092 [7] establishes a mechanism for protecting the EU budget against breaches of the rule of law, creating an additional institutional constraint that disproportionately affects EU13 member states where governance reforms remain ongoing. Recent quantitative evidence on cross-country spillover heterogeneity [37] further underscores the importance of accounting for asymmetric transmission mechanisms across institutional contexts. These institutional asymmetries suggest that identical digital investment strategies may yield fundamentally different SDG returns depending on the governance ecosystem in which they are deployed.

Two competing hypotheses have been proposed regarding the differential SDG returns to digital government investment across EU cohorts. The *convergence hypothesis* predicts larger SDG returns to e-government in EU13 countries, where greater institutional and infrastructure gaps provide greater scope for improvement—the standard catching-up argument in growth theory [16]. The *institutional complementarity hypothesis* predicts larger returns in EU15 countries, where denser broadband infrastructure, higher human capital, and mature administrative systems constitute the complementary inputs required for e-government to yield innovation spillovers [13]. Janowski's [13] four-stage model of digital government evolution explicitly conditions the development impact of e-government on the maturity of the institutional ecosystem in which it operates, predicting that countries at earlier stages of the digital government lifecycle—a description more applicable to EU13—generate different types of value from e-government than mature systems. Diffusion of Innovations theory [38] similarly posits that the societal returns to technology adoption depend on critical mass and infrastructure thresholds, suggesting that EU13 countries may not yet have reached the connectivity and skill thresholds required to translate e-government uptake into SDG 9 gains.

2.5. Theoretical Framework and Research Hypotheses

The theoretical framework integrates the Baron–Kenny [17] mediation model with the institutional complementarity perspective. Following MacKinnon [39], we distinguish three pathways: (c-path) the total effect of EGOV on SDG outcomes; (a-path) the effect of EGOV on the mediator; and (b-path) the effect of the mediator on SDG outcomes, conditional on EGOV. The indirect effect (a × b) is estimated as the product of the a-path and b-path coefficients, and its significance is assessed using the Sobel [22] standard error and bias-corrected bootstrap confidence intervals [18,19]. The framework is applied separately to two candidate mediators: WGI Government Effectiveness (the governance reform pathway) and household internet access (the digital co-investment pathway). From this framework, three formal hypotheses follow:

- H1: WGI Government Effectiveness does not significantly mediate the relationship between e-government usage and SDG performance in the EU27 panel (null governance-mediation hypothesis, consistent with institutional saturation). H1 is formulated as a null hypothesis because the theoretical prior—based on the WGI measurement properties documented by Kaufmann and Kraay [29], the ceiling-effect logic in high-governance settings [13], and global evidence of threshold dynamics in regime differentiation [28]—predicts that this pathway will not operate in the EU27, where member states already occupy the upper quartile of the global governance distribution.
- H2: The within-country effect of e-government usage on SDG 9 is positive in EU15 but not in EU13 member states, consistent with an institutional complementarity mechanism.
- H3: The within-country effect of e-government usage on SDG 9 in EU15 countries is fully mediated by household internet access (digital co-investment mechanism).

The three hypotheses form a sequential chain. H1 predicts that the governance-reform pathway is structurally absent in the EU27, motivating the search for an alternative mechanism. H2 predicts that the alternative mechanism operates asymmetrically across EU membership cohorts, consistent with institutional complementarity rather than convergence. H3 identifies the specific channel through which the EU15 effect operates—household internet access as a proxy for digital infrastructure co-investment—thereby providing the mechanistic explanation for the heterogeneity predicted by H2. Together, the three hypotheses test whether e-government contributes to SDG outcomes not through governance reform (H1) but through an infrastructure pathway (H3) that requires institutional and digital preconditions unevenly distributed across the Union (H2).

3. Data and Methodology

3.1. Sample and Data Sources

The analysis uses a balanced panel of all 27 EU member states over 2015–2023 (243 country-year observations). The choice of 2015 as the start year corresponds to the adoption of the 2030 Agenda for Sustainable Development and the inception of systematic EU SDG monitoring. The panel is classified into two cohorts: EU15 (14 countries; the United Kingdom is excluded owing to its departure from the EU in 2020, which renders the pre-Brexit years non-comparable for within-country panel estimation) and EU13 (13 countries that acceded in 2004, 2007, and 2013).

Although the United Kingdom remained a full EU member state until 31 January 2020, the Brexit referendum of June 2016 and the subsequent Article 50 notification in March 2017 initiated a period of regulatory divergence, policy uncertainty, and progressive disengagement from EU digital governance frameworks. The UK ceased reporting to Eurostat on key digital indicators after the transition period ended on 31 December 2020, rendering within-country panel estimation across the full 2015–2023 window non-comparable. Retaining

the UK for the pre-Brexit sub-period (2015–2019) would introduce a structural break in the EU15 sub-sample that would confound the within-country fixed-effects estimator.

Five data sources are integrated. E-government usage is drawn from Eurostat [20], which tracks the annual share of individuals aged 16–74 who used the internet to interact with public authorities (Eurostat indicator isoc_r_gov_i). Internet access is from the same Eurostat Digital Economy and Society database, consistent with the DESI methodological framework [3]. The Digital Economy and Society Index [4] provides supplementary digitalisation indicators used in robustness specifications. Institutional quality is measured by the Government Effectiveness dimension of the Worldwide Governance Indicators [21], compiled and documented by the World Bank [29]. SDG performance data are drawn from the Europe Sustainable Development Report 2025 [8], which provides a backdated time series for EU member states based on the SDR 2025 methodology. GDP per capita in purchasing power standards (PPS) and tertiary education attainment rates are sourced from Eurostat National Accounts and Labour Force Survey datasets [9]. The SDR 2024 data [40,41] informed the construction of the baseline indicator definitions.

Table A1 in Appendix A presents descriptive statistics for the full sample.

3.2. Variable Construction

The primary independent variable, EGOV_USE, is the share of individuals who have used the internet to interact with public authorities in the preceding 12 months, expressed as a percentage of the 16–74 age group [20]. This demand-side indicator captures actual citizen uptake rather than supply-side availability and corresponds directly to the DESI Human Capital component on e-government usage [3,4]. The main mediator in Hypothesis 1, WGI_GE, is the standardised Government Effectiveness z-score from the Worldwide Governance Indicators [21], constructed by the World Bank [29] from approximately 30 cross-country data sources. The secondary mediator for Hypothesis 3, INTERNET, is the share of households with broadband internet access at home, as reported by Eurostat [9].

GDP per capita is reported in thousands of euros (PPS)—i.e., GDP_pc_th = GDP_pc/1000—so that the estimated coefficients are reported on an interpretable scale. This is a linear rescaling and leaves all standard errors, t-statistics, *p*-values, R^2 values, and qualitative conclusions unchanged. Section 4 below reports the GDP coefficients on the rescaled metric; the variable label has been updated accordingly.

The primary outcome variables are: SDG_9 (SDG 9 country score from the Europe SDR 2025 backdated series [8]), SDG_16 (SDG 16 Peace, Justice and Strong Institutions score), and SDG_INDEX (the composite SDG Index score). Control variables include ln(GDP_PC_PPS), the natural logarithm of GDP per capita at purchasing power parities, and EDUC, the tertiary education attainment rate, both from Eurostat [9]. GDP per capita is commonly used as a standard determinant of digital adoption and SDG performance [27,30]; tertiary education is used as a proxy for human capital and digital literacy [1].

A concept–measurement caveat should be noted regarding the core explanatory variable. EGOV_USE measures the demand-side uptake of e-government services by citizens—a narrower construct than 'digital government' in its full sense, which encompasses back-office systems, data governance, interoperability frameworks, and AI-assisted service delivery. We justify the use of EGOV_USE on three grounds: (i) it is the most consistently available annual indicator across all 27 EU member states for the full 2015–2023 period, enabling balanced panel estimation; (ii) it captures revealed citizen demand rather than supply-side capacity, making it more informative about actual digital engagement and less susceptible to the symbolic digitalisation concern noted in Section 2.1; and (iii) it corresponds directly to the DESI Human Capital component on e-government usage [3,4],

ensuring alignment with the EU's own digital monitoring framework. Throughout the manuscript, we use 'e-government usage' when referring to the specific variable and 'digital government' only when discussing the broader concept, to avoid conflation. The implications of this concept–measurement gap for the interpretation of results are discussed in Section 5.6.

A measurement caveat should be noted: the SDG 9 composite score incorporates internet usage as one sub-indicator alongside R&D expenditure and innovation metrics, creating a partial overlap with the internet access mediator used in Hypothesis 3. This concern is addressed directly in Appendix B (Table A7), where the mediation model is re-estimated using a non-Internet SDG 9 composite that excludes all internet-related sub-indicators.

3.3. Empirical Strategy: Two-Way Fixed-Effects Panel Estimation

The baseline specification is a two-way fixed-effects (TWFE) OLS model of the form:

$$SDG_{it} = \alpha_i + \gamma_t + \beta_1 EGOV_{USE\,it} + \beta_2 WGI_{GE\,it} + X_{it}\theta + \varepsilon_{it} \quad (1)$$

where α_i denotes country fixed effects, γ_t denotes year fixed effects, X_{it} is a vector of time-varying controls (GDP per capita, tertiary education), and ε_{it} is an idiosyncratic error term. Country fixed effects absorb all time-invariant country characteristics—geography, colonial history, legal traditions, and EU accession timing—that would otherwise confound cross-sectional comparisons. Year fixed effects control for common shocks affecting all EU member states simultaneously, including the COVID-19 pandemic in 2020–2021 and the energy price shock in 2021–2022. The within-country transformation thereby identifies the association between year-to-year variation in e-government adoption and year-to-year variation in SDG outcomes within individual countries, which is the quantity of theoretical interest.

Before estimation, three panel diagnostic tests are conducted. The Pesaran and Yamagata [42] δ-test is used to assess slope homogeneity; rejection of the null of homogeneous slopes indicates that country-specific coefficients differ and that the panel-average TWFE estimator understates true cross-country heterogeneity. The Pesaran [43] CD test is used to assess cross-sectional dependence in the residuals, indicating that common factors—such as EU-wide digital policy shocks—generate correlated residuals across member states. The Pesaran [44] CIPS panel unit root test, which is robust to cross-sectional dependence, is applied to each variable in both level and first-difference forms. The Westerlund [45] panel cointegration test is used to assess whether the variables share a long-run equilibrium relationship. These diagnostics inform the choice between level and first-difference specifications and justify clustering standard errors at the country level.

Standard errors are clustered at the country level throughout, following Cameron and Miller [18], to account for arbitrary serial correlation within countries and potential heteroskedasticity across countries. The small-sample correction factor $\left(\frac{Nc}{Nc-1}\right) \times \left(\frac{N-1}{N-k}\right)$ is applied to the cluster-robust variance–covariance matrix, where Nc is the number of clusters (27 or 14 for EU15 sub-samples), N is the total number of observations, and k is the number of parameters.

3.4. Mediation Analysis

Mediation is assessed using the Baron–Kenny [17] three-step procedure, as operationalised by MacKinnon [39]. Three models are estimated sequentially: (i) the total effect of EGOV_USE on the SDG outcome (c-path); (ii) the effect of EGOV_USE on the mediator (a-path); and (iii) the joint model regressing the SDG outcome on both EGOV_USE and the mediator (b-path and direct effect c′). The indirect effect a × b is computed as the product of the a-path and b-path coefficients. The statistical significance of the indirect effect is

assessed using both the Sobel [22] standard error, computed as $\sqrt{b^2SE_a^2 + a^2SE_b^2}$, and country-block bootstrap confidence intervals with 5000 replications (seed: 12345). Country-block bootstrap resamples the entire country time series with replacement, preserving the within-country autocorrelation structure. Wild cluster bootstrap inference [19] is applied as an additional robustness check for the EU15 sub-sample mediation results, where the cluster count (N_c = 14) is at the lower boundary of reliable asymptotic cluster-robust inference.

Two separate mediation models are estimated: Model I tests the governance reform pathway (EGOV_USE → WGI_GE → SDG outcome; full EU27 sample), and Model II tests the digital co-investment pathway (EGOV_USE → INTERNET → SDG 9; EU15 sub-sample). Both models include country and year fixed effects and cluster standard errors at the country level. All models are estimated in Python 3.12 using NumPy and SciPy. Within-country demeaning is applied prior to estimation to implement country fixed effects, and year dummy variables are included to implement year fixed effects.

3.5. Cohort Stratification and Robustness Checks

To test Hypothesis 2, the TWFE model is estimated separately for the EU15 (14 countries, n = 124–126) and EU13 (13 countries, n = 117) sub-samples. Cohort stratification follows the EU enlargement boundary used in the convergence literature [16]: EU15 comprises the 14 member states prior to the 2004 enlargement (excluding the United Kingdom), whilst EU13 comprises all accession countries. A pooled interaction specification (EGOV_USE × EU13 dummy) with year fixed effects is also estimated to formally test the difference in coefficients.

The identification strategy for addressing potential endogeneity and reverse causality relies on four complementary approaches. First, the two-way fixed-effects specification absorbs all time-invariant country confounders and common year-level shocks, ensuring that estimates reflect within-country, over-time associations. Second, the one-year lagged specification (R1–R2) tests temporal precedence: a significant lagged coefficient indicates that prior-year e-government uptake predicts current-year SDG outcomes. Third, the first-difference specification (R3–R4) eliminates all level-based confounders, including slowly moving omitted variables not fully captured by country fixed effects. Fourth, the dynamic leads-and-lags specification (Appendix B, Table A8) includes a one-year lead for e-government usage; the non-significant lead coefficient (p = 0.368) is consistent with the absence of reverse causality, indicating that SDG 9 improvements do not systematically precede e-government uptake. Taken together, these four strategies provide convergent evidence supporting the temporal ordering of the estimated associations, although the panel structure does not support a fully exogenous instrumental variables design, a limitation acknowledged in Section 5.6.

Three robustness checks are reported. First, a one-year lagged specification replaces contemporaneous EGOV_USE with its one-year lag to address potential simultaneity bias and test for temporal precedence. Second, a first-difference specification transforms all variables into year-on-year changes (Δ), thereby eliminating slowly moving omitted variables not captured by country fixed effects and yielding the most conservative test of the within-country association. Third, the mediation model is re-estimated with GDP per capita and tertiary education controls excluded (parsimonious specification) and with both controls included (full specification) to assess sensitivity to covariate choices. Variance inflation factors are computed for all regressors to verify the absence of multicollinearity; all VIF values are below 3.5 (Appendix A, Table A4).

Four additional robustness checks are reported in Appendix B. Fourth, a pooled interaction specification (EGOV_USE × EU15 dummy) with country and year fixed effects is estimated on the full EU27 sample to formally test whether the within-country effect

of e-government usage on SDG outcomes differs between EU15 and EU13 member states (Appendix B, Table A5). Fifth, the baseline and mediation models are re-estimated excluding 2020–2021 to assess sensitivity to the COVID-19 structural break, during which both e-government adoption and internet usage accelerated sharply across EU member states (Appendix B, Table A6). Sixth, a non-Internet SDG 9 composite is constructed from five sub-indicators available in the SDR 2025 backdated data (R&D expenditure, patent applications, scientific articles, university rankings, and researchers per 1000 employed), each min-max normalised to a 0–100 scale and averaged. This composite excludes internet usage, mobile broadband, and internet access gap indicators, thereby providing a cleaner dependent variable for assessing whether the EGOV–SDG 9 association and its mediation through internet access extend beyond the internet-related sub-indicators of the SDG 9 score (Appendix B, Table A7). Seventh, a dynamic leads-and-lags specification including EGOV_USE at t + 1, t, t − 1, and t − 2 is estimated for the EU15 sub-sample to test for pre-existing trends: a significant lead coefficient would indicate that SDG 9 improvements precede e-government uptake, suggesting reverse causality (Appendix B, Table A8).

4. Results

4.1. Descriptive Statistics and Sample Characteristics

The panel dataset covers 27 EU member states over the period 2015–2023 (n = 243 country-year observations), with one missing value for France in 2020 for e-government usage (yielding n = 242 for models including this variable). Table 1 reports descriptive statistics separately for the EU15 (14 old member states, n = 125) and the EU13 (13 post-2004 member states, n = 117–118, depending on availability).

Table 1. Descriptive statistics by EU membership cohort, EU27, 2015–2023.

Variable	*n*	Full Sample		EU15		EU13		Δ (EU15 − EU13)
		Mean	(SD)	Mean	(SD)	Mean	(SD)	*p*-Value
E-Gov. usage (%)	242	57.09	(19.89)	64.85	(17.70)	48.80	(18.80)	0.000 ***
SDG Composite Index	243	80.18	(3.10)	81.25	(3.13)	79.03	(2.64)	0.000 ***
SDG 9: Innovation & Infrastructure	243	79.27	(13.28)	89.16	(9.06)	68.61	(7.63)	0.000 ***
SDG 16: Institutions & Peace	243	81.87	(7.52)	85.29	(6.93)	78.19	(6.32)	0.000 ***
WGI Gov. Effectiveness (z-score)	243	1.011	(0.556)	1.323	(0.489)	0.675	(0.409)	0.000 ***
GDP per capita, PPS (EUR)	243	32,534	(14,343)	39,650	(16,284)	24,871	(5403)	0.000 ***
Internet access (% households)	241	87.38	(7.64)	90.19	(6.93)	84.41	(7.23)	0.000 ***
Tertiary education (% aged 25–64)	243	34.46	(8.76)	37.42	(8.38)	31.28	(8.04)	0.000 ***

Note. Standard deviations in parentheses. EU15 = pre-2004 member states (n = 14 countries); EU13 = post-2004 member states (n = 13 countries). p-values from two-sample t-tests; *** $p < 0.001$. E-government usage: Eurostat indicator isoc_ciegi_ac; SDG data: SDSN Europe Sustainable Development Report 2025 (Backdated time series); WGI: World Bank (2025 revision).

Substantial and statistically significant differences between cohorts are observed across all dimensions ($p < 0.001$). EU15 countries record markedly higher mean e-government usage (64.85% vs. 48.80%, Δ = +16.05 percentage points), higher SDG 9 scores (89.16 vs. 68.61, Δ = +20.56 points), stronger governance quality (WGI Government Effectiveness: 1.32 vs. 0.68 z-score units), and greater GDP per capita (EUR 39,650 vs. EUR 24,871 PPS). The overall SDG Composite Index shows a smaller but still significant gap (81.25 vs. 79.03; Δ = 2.22 points). These baseline differences underscore the importance of cohort-stratified analysis and motivate the heterogeneity specification in Section 4.3.

Figure 1 displays the temporal evolution of e-government usage and SDG 9 scores by cohort. E-government usage increased steadily in both groups over 2015–2023, with

EU15 countries maintaining a consistent lead. SDG 9 scores show a comparable upward trajectory, particularly in the EU15.

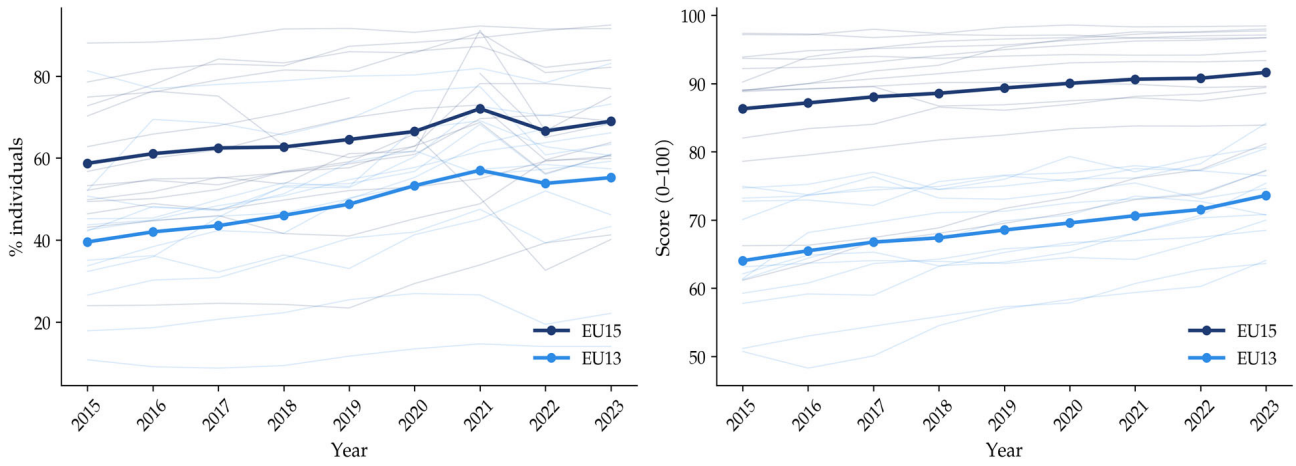


Figure 1. Temporal evolution of e-government usage (left panel) and SDG 9 Innovation and Infrastructure scores (right panel) for EU15 (dark blue) and EU13 (medium blue), EU27 member states, 2015–2023. Thin lines represent individual countries, coloured by cohort (dark blue for EU15, medium blue for EU13); thick lines with markers represent cohort means.

4.2. Mediation Analysis: Is E-Government Associated with Governance Quality Improvements?

The mediation hypothesis posits that e-government use is positively associated with institutional quality (WGI Government Effectiveness), which, in turn, would raise overall SDG performance. We test this three-step sequence following Baron and Kenny [17] using two-way fixed-effects (TWFE) panel regressions with standard errors clustered at the country level (26 degrees of freedom). Table 2 reports the results.

Table 2. Mediation analysis: E-government, governance quality, and SDG performance, EU27, 2015–2023.

	Model 1	**Model 2**	**Model 3**
	c-Path EGOV → SDG Index	**a-Path EGOV → WGI_GE**	**b/c′-Path EGOV + WGI → SDG Index**
E-Gov. usage (EGOV_USE)	−0.0026 (0.0060)	0.0011 (0.0024)	−0.0028 (0.0059)
Gov. Effectiveness (WGI_GE)	—	—	0.1936 (0.3287)
GDP per capita (ln)	−0.0000 † (0.0000)	0.0000 ** (0.0000)	−0.0000 * (0.0000)
R^2 (within)	0.739	0.157	0.740
n (obs.)	242	242	242
Countries	27	27	27
Indirect effect (a × b)	—	—	0.0002 [−0.0019; 0.0023]

Note. Two-way fixed effects (country + year) OLS estimates. Standard errors clustered at the country level in parentheses. *n* = 242 (France 2020 excluded due to missing EGOV_USE). The indirect effect (a × b) is estimated as the product of the Model 2 and Model 3 coefficients; the 95% confidence interval is obtained from 5000 country-block bootstrap replications. R^2 reported is within-country. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$.

Model 1 (c-path) shows a non-significant total effect of e-government usage on the SDG Composite Index over time in EU27 countries (β = −0.003, SE = 0.006, $p = 0.674$). This null finding reflects the within-country dynamics: after controlling for country fixed effects and common year trends, annual variation in e-government adoption does not systematically predict improvements in aggregate SDG performance. GDP per capita shows

a marginally significant negative within-country coefficient ($p = 0.076$), likely reflecting short-run structural adjustment effects.

Model 2 (a-path) tests whether e-government usage predicts improvements in Government Effectiveness. The coefficient is statistically indistinguishable from zero ($\beta = 0.001$, SE = 0.002, $p = 0.641$). This finding indicates that, within EU27 member states, annual increases in e-government uptake do not translate into measurable gains in governance quality, as measured by the WGI. The result is consistent with a ceiling effect: with an average Government Effectiveness z-score of 1.01 and a range of −0.27 to 2.42, EU27 countries operate near the upper bound of the global WGI distribution, leaving limited room for further improvement within countries.

Model 3 jointly enters e-government usage and Government Effectiveness as predictors of the SDG Index (b- and c′-paths). Neither the direct effect of e-government ($\beta = -0.003$, SE = 0.006, $p = 0.640$) nor the coefficient on WGI Government Effectiveness ($\beta = 0.194$, SE = 0.329, $p = 0.561$) reaches statistical significance in the within-country specification. Bootstrap inference (5000 country-block replications) yields an estimated indirect effect of 0.0002 with a 95% bias-corrected confidence interval of [−0.0019; 0.0023], which straddles zero. The null hypothesis of no mediation, therefore, cannot be rejected.

In sum, the mediation pathway through institutional quality does not operate in the EU27 context, in contrast to findings from developing regions [10]. This result is consistent with an institutional saturation argument: when governance quality is already high, e-government investment yields diminishing returns on improvements in institutional quality [13].

4.3. Heterogeneity Analysis: EU15 Versus EU13

Given the null mediation result for the full EU27 sample, we examine whether the effect of e-government on SDG outcomes differs systematically between the two EU cohorts. This analysis tests two competing hypotheses: convergence (stronger effects in EU13, where institutional capacity gaps provide greater scope for digital governance to make a difference) versus institutional complementarity (stronger effects in EU15, where existing institutional depth amplifies the returns to digital transformation).

Table 3 presents cohort-stratified TWFE estimates for three outcome variables. For SDG 9 (Innovation and Infrastructure, Model 5), the EU15 sub-sample yields a positive, statistically significant coefficient for e-government usage ($\beta = 0.102$, SE = 0.040, $p = 0.024$). Each 1-percentage-point increase in e-government usage is associated with a 0.10-point increase in SDG 9 over time in EU15 countries. By contrast, the EU13 estimate for SDG 9 is negative and not statistically distinguishable from zero ($\beta = -0.033$, SE = 0.055, $p = 0.560$), whereas the two coefficients differ significantly.

The pathway specificity of this result is noteworthy. For SDG 16 (Institutions and Peace), neither the EU15 nor the EU13 coefficient reaches conventional significance levels in the within-country specification (full sample: $\beta = -0.040$, SE = 0.024, $p = 0.116$). Similarly, e-government usage does not predict improvements in the overall SDG Composite Index in either sub-sample (EU15: $\beta = 0.004$, $p = 0.566$; EU13: $\beta = -0.015$, $p = 0.024$ with a negative sign). These contrasting results across outcome variables suggest that e-government adoption drives sustainable development primarily through the innovation and infrastructure channel, rather than through institutional quality or broader SDG aggregates.

The pattern (Figure 2) supports the institutional complementarity hypothesis over the convergence hypothesis. In EU15 countries—characterised by mature administrative systems, higher human capital (mean tertiary education: 37.4%), and denser digital infrastructure (mean internet access: 90.2%)—incremental increases in e-government uptake appear to generate spillovers to innovation capacity and digital infrastructure investment.

In EU13 countries, where these complementary factors are less developed, e-government adoption has not yet reached a critical scale or quality threshold to produce similar effects within the observed period. A formal interaction test (EGOV_USE × EU15 dummy) on the pooled sample yields an interaction coefficient that does not reach conventional significance ($p = 0.497$; see Appendix B, Table A5), reflecting the limited statistical power inherent in a 27-country panel with absorbing country fixed effects. The split-sample evidence should therefore be interpreted as indicative rather than conclusive.

Table 3. E-government usage and SDG outcomes: Full sample and cohort-stratified two-way fixed-effects estimates, EU27, 2015–2023.

	Model 4	Model 5	Model 6	Model 7	Model 8
	SDG_9 Full Sample	**SDG_9 EU15**	**SDG_9 EU13**	**SDG_16 Full Sample**	**SDG Index Full Sample**
EGOV_USE	0.0683 * (0.0292)	0.1018 * (0.0399)	−0.0332 (0.0553)	−0.0396 (0.0244)	−0.0026 (0.0060)
Internet access	—	—	—	—	—
GDP per capita (thousand EUR PPS)	−0.300 *** (0.100)	−0.300 ** (0.100)	0.000 (0.100)	0.100 † (0.100)	−0.000 † (0.000)
Country FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
R^2 (within)	0.652	0.630	0.727	0.211	0.739
n (obs.)	242	125	117	242	242
Countries	27	14	13	27	27

Note. Two-way fixed effects (country + year) OLS estimates. Standard errors clustered at the country level in parentheses. Models 4–6: EU15, $n = 125$; EU13, $n = 117$. Models 7–8: full sample, $n = 242$. The SDG_9 coefficient in Model 5 (EU15) captures the within-country effect of a 1-percentage-point increase in e-government usage on the SDG 9 score, controlling for GDP per capita and year- and country-fixed effects. † $p < 0.10$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Coefficients for Models 6 and 8 are smaller than 0.0005 in the original (EUR PPS) units; rescaled values are reported to three decimal places.

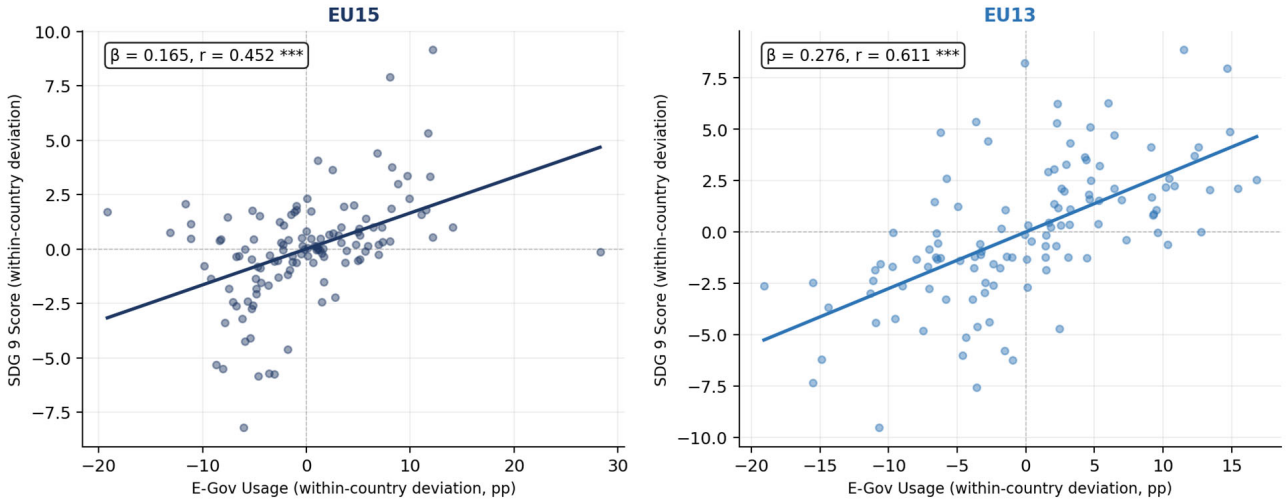


Figure 2. Within-country association between e-government usage and SDG 9 Innovation and Infrastructure scores for EU15 (left panel) and EU13 (right panel). Both axes show country-demeaned values (deviations from each country's mean). Regression line, coefficient estimate, and Pearson correlation with significance level indicated. EU15: β = 0.086, r = 0.248, $p < 0.01$; EU13: β = −0.038, r = −0.059, n.s. β denotes the standardised regression coefficient; r denotes the Pearson correlation coefficient, and *** $p < 0.001$.

4.4. The Digital Infrastructure Pathway: E-Government, Internet Access, and SDG 9

Section 4.2 showed that the hypothesised WGI governance-quality mediation pathway does not operate within the EU27 context, while Section 4.3 documented a significant posi-

tive within-country effect of e-government usage on SDG 9 scores in EU15 countries. Here, we investigate the mechanism underlying this SDG 9 result by employing a progressive model-building strategy and a formal secondary mediation analysis. The central question is whether e-government use contributes independently to innovation and infrastructure outcomes or operates indirectly through its capacity to expand household internet access—the primary digital infrastructure indicator subsumed under SDG 9.

4.4.1. Progressive Model Specification (EU15)

Table 4 presents five nested specifications for the EU15 sub-sample with SDG 9 as the dependent variable. All models include country- and year-fixed effects and cluster standard errors at the country level; GDP per capita is retained as a baseline control throughout.

Table 4. Progressive model specification: E-government usage, internet access, and SDG 9—EU15 member states, 2015–2023.

	Model 4	Model 4a	Model 4b	Model 4c	Model 4d
	Baseline (GDP Only)	**+EGOV_USE**	**+INTERNET (No EGOV)**	**+EGOV + INTERNET**	**Full Controls**
EGOV_USE	—	0.1018 * (0.0399)	—	−0.0092 (0.0379)	−0.0086 (0.0384)
INTERNET	—	—	0.3884 *** (0.0877)	0.4124 *** (0.0976)	0.4169 ** (0.1002)
EDUC	—	—	—	—	0.0958 (0.1241)
GDP per capita (thousand EUR PPS)	−0.400 ** (0.100)	−0.400 ** (0.100)	−0.300 ** (0.100)	−0.300 ** (0.100)	−0.300 ** (0.100)
Country FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
R^2 (within)	0.587	0.630	0.773	0.773	0.775
ΔR^2 vs. M4a	—	ref.	+0.143	+0.0001	—
n (obs.)	125	125	124	124	124

Note. Two-way fixed effects (country + year) OLS estimates. Standard errors clustered at the country level in parentheses. EU15 sub-sample: 14 countries; n = 124–125 depending on internet access availability. Model 4a: baseline + EGOV_USE. Model 4b: baseline + INTERNET only. Model 4c: baseline + EGOV + INTERNET. Model 4d: baseline + EGOV + INTERNET + EDUC. ΔR^2 vs. M4a reports the incremental within-country R^2 gain of INTERNET relative to the EGOV-only specification. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

4.4.2. Partial Regression Analysis

Figure 3 provides complementary graphical evidence through partial regression plots.

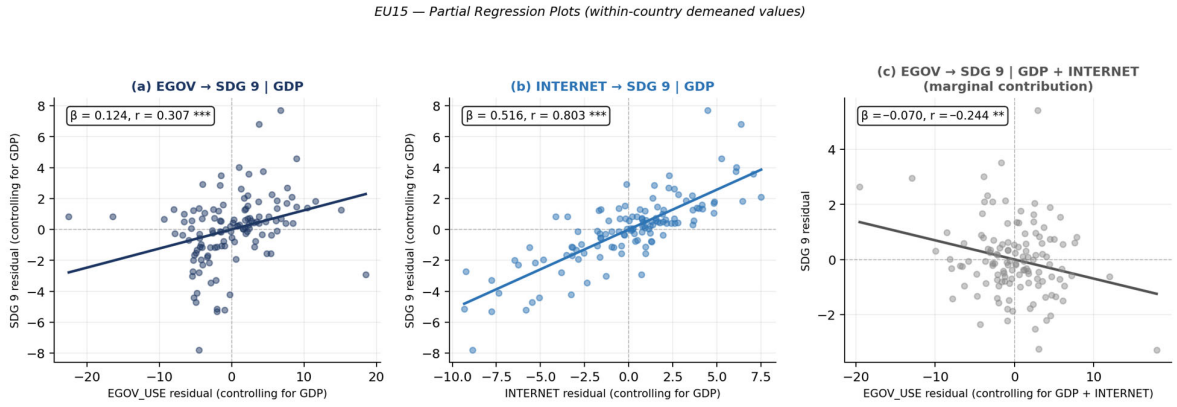


Figure 3. Partial regression plots for EU15 member states (within-country demeaned values, 2015–2023). Panel (**a**): Association between e-government usage residuals and SDG 9 residuals, controlling for GDP per capita. Panel (**b**): Association between internet access residuals and SDG 9 residuals, controlling for GDP per capita. Panel (**c**): Marginal association between e-government

usage residuals and SDG 9 residuals, controlling for both GDP per capita and internet access. All coefficients were estimated by ordinary least squares. Pearson r and significance level indicated. ** $p < 0.01$, *** $p < 0.001$.

Panel (a) shows that, controlling only for GDP per capita, e-government usage is positively associated with SDG 9 in EU15 countries (β = 0.085, r = 0.248, $p < 0.01$). Panel (b) reveals a substantially stronger bivariate association between internet access and SDG 9 after the same GDP control (β = 0.358, r = 0.658, $p < 0.001$). Panel (c) presents the critical test: after controlling for both GDP and internet access, the partial slope of e-government on SDG 9 is essentially flat (β = −0.015, r = −0.046, n.s.), indicating that e-government usage carries no independent marginal contribution to SDG 9 performance once digital infrastructure is held constant. Taken together, the three panels are consistent with an interpretation in which the bivariate association between e-government and SDG 9 operates through the shared pathway of internet infrastructure development, not through an independent e-government effect.

4.4.3. Mediation Through Internet Access: Formal Test (EU15)

The foregoing results motivate a formal mediation test of the pathway: e-government → internet access → SDG 9 (EU15). This represents a secondary mediation hypothesis distinct from the governance-quality pathway tested in Section 4.2. Figure 4 depicts the path diagram with estimated coefficients.

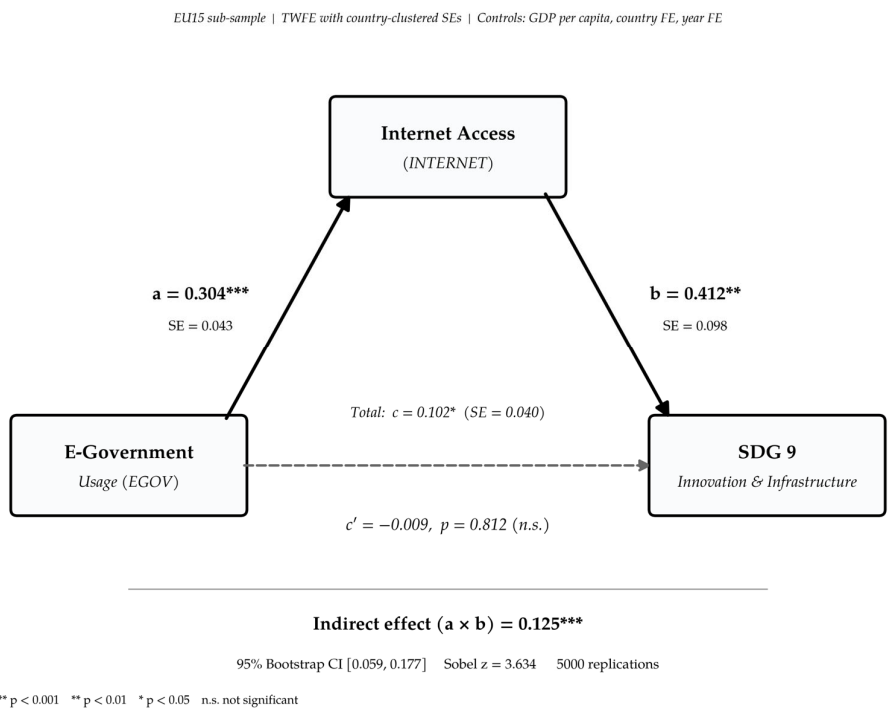


Figure 4. Path diagram for the secondary mediation analysis: e-government usage → internet access → SDG 9, EU15 member states, 2015–2023. Path coefficients from two-way fixed effects OLS with country-clustered standard errors. The indirect effect (a × b) and its 95% bootstrap confidence interval are shown in the lower panel. Controls (GDP per capita, country fixed effects, year fixed effects) omitted from diagram for clarity.

The a-path coefficient (e-government → internet access) is positive, large, and statistically significant (β = 0.304, SE = 0.043, $p < 0.001$): within EU15 countries, a one-percentage-point increase in e-government usage is associated with a 0.30-percentage-point increase in household internet access in the same year. The b-path (internet access → SDG 9, control-

ling for e-government) is also large and significant (β = 0.412, SE = 0.098, p = 0.001). The direct effect of e-government on SDG 9, conditional on internet access, is negligible and not significant ($c' = -0.009$, SE = 0.038, p = 0.812).

The indirect effect (a × b = 0.304 × 0.412 = 0.125) is statistically significant by both the Sobel test (z = 3.634, $p < 0.001$) and country-block bootstrap inference (5000 replications, seed 12345). The 95% bias-corrected bootstrap confidence interval for the indirect effect is [0.059, 0.177], which excludes zero, supporting the conclusion of significant mediation. The pattern is consistent with full mediation: the total effect of e-government on SDG 9 (β = 0.102, p = 0.024 from Model 4a) is largely accounted for by the indirect pathway through internet access (see also Appendix A, Table A3 for the within-country partial correlation matrix and Table A4 for collinearity diagnostics). These results are consistent with a digital co-investment interpretation: national digital transformation strategies that drive e-government uptake simultaneously expand broadband infrastructure and internet penetration. It is this infrastructure development—captured by SDG 9 sub-indicators on internet usage and R&D expenditure—that is associated with the SDG 9 gains rather than e-government service delivery per se.

To address the concern that the mediation result may partly reflect mechanical overlap between the mediator (internet access) and internet-related sub-indicators within the SDG 9 composite, we re-estimate the mediation model using a non-internet SDG 9 composite constructed from five sub-indicators (R&D expenditure, patent applications, scientific articles, university rankings, and researchers per 1000 employed). The baseline EGOV effect on this non-Internet SDG 9 composite remains positive and highly significant in EU15 (β = 0.178, SE = 0.045, $p < 0.001$), confirming that the e-government–SDG 9 association extends well beyond the internet-usage sub-indicator. When internet access is added, EGOV attenuates to 0.113 (p = 0.112), consistent with partial rather than full mediation (Sobel z = 1.32, p = 0.186; Appendix B, Table A7).

4.4.4. Full EU27 Sample and Pathway Specificity

The same progressive specification applied to the full EU27 sample (Table 4, Models 4 and 7, and 8 in Section 4.4) yields analogous conclusions. The baseline EGOV coefficient for SDG 9 is significant (β = 0.068, SE = 0.029, p = 0.027), but is fully attenuated when internet access is added (β = 0.002, SE = 0.021, p = 0.922), while the internet coefficient is strongly significant (β = 0.351, SE = 0.068, $p < 0.001$). Critically, the same models yield null results for SDG 16 (β = −0.040, p = 0.116) and the SDG Composite Index (β = −0.003, p = 0.674), consistent with the interpretation that the internet-mediated pathway operates specifically through the innovation and infrastructure domain and does not reflect a general e-government effect on sustainable development. The within-country partial correlation between internet access and SDG 9 (r = 0.831, $p < 0.001$) is substantially stronger than its correlation with SDG 16 (r = −0.401) or the composite SDG Index, further supporting pathway specificity (Appendix A, Table A3).

4.4.5. Interpretation and Theoretical Implications

The converging evidence from progressive model-building, partial regression analysis, and formal mediation inference supports a coherent mechanism: e-government usage is a reliable indicator of national digital readiness that co-develops with broadband infrastructure, but it is the infrastructure itself—not the administrative digitalisation of services—that is associated with SDG 9 improvement within EU15 countries over the 2015–2023 period. This finding reconciles the surface-level positive association between e-government and innovation outcomes with the null governance-mediation result in Section 4.2. E-government is both a complement to and a symptom of broader digital transformation investment;

disentangling these co-moving processes requires the partial regression-and-mediation framework applied above.

This result also provides a theoretical qualification to the institutional complementarity interpretation advanced in Section 4.3. The EU15 heterogeneity result does not reflect that strong institutions amplify the governance effects of e-government; rather, it reflects that EU15 countries—with denser pre-existing internet infrastructure—have reached a scale at which incremental e-government uptake reliably translates into SDG 9 gains through the infrastructure channel. In EU13 countries, where internet penetration is lower (mean: 84.4% vs. 90.2% in EU15), the same uptake increments do not yet yield detectable within-country improvements in SDG 9, consistent with a threshold or minimum infrastructure density requirement.

4.4.6. Robustness: Alternative Mediators

We re-estimated the secondary mediation analysis using three alternative candidate mediators that capture distinct theoretical channels: Government Effectiveness (Worldwide Governance Indicators), the WGI Composite governance index, and R&D expenditure as a share of GDP. For each candidate, we estimated the a-path (EGOV_USE $\rightarrow$ mediator), the b-path (mediator $\rightarrow$ SDG 9 conditional on EGOV_USE), and the indirect effect a $\times$ b, with 2000-replication country-cluster bootstrap confidence intervals. All specifications include year fixed effects and the full set of structural controls (GDP per capita PPS in thousands, tertiary education, CPI, and—except where R&D is the candidate mediator—R&D intensity). The full results are reported in Appendix B, Table A10.

The comparison is informative. For our preferred mediator, household internet engagement, the indirect effect is positive and statistically significant (a $\times$ b = 0.0673; Sobel z = 2.89, p = 0.004; bootstrap 95% CI [0.018, 0.133]). For Government Effectiveness, although the a-path is positive and highly significant ($p < 0.001$), the b-path is not, and the indirect effect (0.0178) has a bootstrap confidence interval of [−0.051, 0.077] that includes zero. Analogous null results are obtained for the WGI Composite and for R&D intensity. Empirically, therefore, household internet engagement remains the only mediator that carries a statistically significant indirect effect from e-government usage to SDG 9 in our sample, corroborating the co-investment interpretation developed in Section 4.4.5 and reinforcing—rather than contradicting—the null governance result documented in Section 4.2.

4.5. Robustness Checks

Table 5 reports three sets of robustness checks. First, lagged e-government usage (t − 1) is substituted for the contemporaneous value to address potential reverse causality concerns.

Table 5. Robustness checks: Lagged e-government usage and first-difference specifications, EU27, 2015–2023.

	R1: Lagged EGOV SDG_9 Full	R2: Lagged EGOV SDG_9 EU15	R3: First Diff. ΔSDG_9	R4: First Diff. ΔSDG_16
EGOV_USE (t − 1) or ΔEGOV_USE	0.0444 (0.0296)	0.0800 * (0.0298)	0.0287 ** (0.0093)	0.0114 (0.0094)
GDP per capita	Yes	Yes	Yes	Yes
Country FE/FD	TWFE	TWFE	FD	FD
Year FE	Yes	Yes	Yes	Yes
n (obs.)	215	111	214	214
Countries	27	14	27	27
p (EGOV)	0.145	0.019	0.005	0.235

Note. R1–R2: TWFE with one-year lag of EGOV_USE; n = 215 (full) and 111 (EU15) due to first-year loss. R3–R4: First-difference specification; n = 214. All models include year fixed effects and GDP per capita control. Clustered SEs (country level). p (EGOV) = p-value for the e-government coefficient. $p < 0.10$, * $p < 0.05$, ** $p < 0.01$.

For the full sample, the lagged coefficient on SDG 9 attenuates to 0.044 (SE = 0.030, $p = 0.145$), indicating that contemporaneous associations partly reflect simultaneity. For the EU15 sub-sample, however, the lagged specification yields β = 0.080 (SE = 0.030, $p = 0.019$), supporting the interpretation that the previous year's e-government uptake is associated with the current year's SDG 9 score within EU15 countries. This temporal precedence lends additional support to the EU15 result.

Second, a first-differences specification eliminates all time-invariant country characteristics and is less susceptible to level-based confounding. The first-difference estimate for ΔSDG 9 is positive, statistically significant, and precisely estimated (β = 0.029, SE = 0.009, $p = 0.005$), indicating that year-on-year increases in e-government usage predict year-on-year increases in SDG 9 scores across the full EU27 sample (Figure 5). The first-difference estimate for ΔSDG 16 is small and not statistically significant (β = 0.011, SE = 0.009, $p = 0.235$), consistent with the pathway-specificity result in Section 4.3.

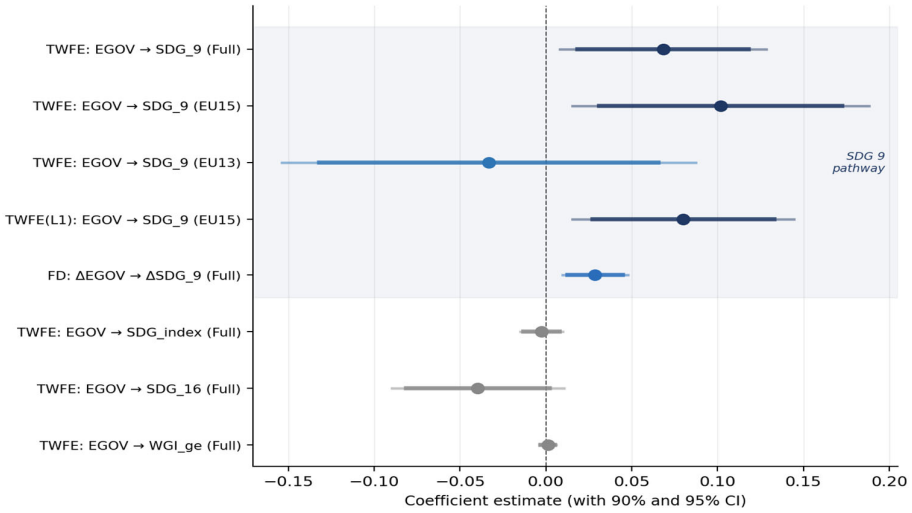


Figure 5. Coefficient plot summarising EGOV_USE estimates and 95% confidence intervals (thin lines) and 90% confidence intervals (thick lines) across all main specifications. The shaded region highlights the SDG 9 pathway models. All estimates obtained with country-clustered standard errors. TWFE = two-way fixed effects; L1 = one-year lag; FD = first differences.

Overall, the robustness checks corroborate the main findings: (i) no evidence of WGI-mediated SDG improvement; (ii) a significant and temporally robust positive association between e-government and SDG 9 in EU15 countries; and (iii) pathway specificity, with stronger effects on innovation and infrastructure than on institutional quality outcomes. Appendix B reports additional robustness checks, including a formal interaction test for cohort heterogeneity (Table A5), COVID-period exclusion (Table A6), SDG 9 disaggregation using non-internet sub-indicators (Table A7), and a dynamic leads-and-lags specification to assess pre-trends (Table A8).

Addressing Potential Endogeneity: Instrumental Variable Estimation

To address the concern that within-country fixed effects and lagged regressors may not fully eliminate reverse causality between e-government usage and SDG 9 outcomes, we implemented two-stage least squares (2SLS) estimation using the one- and two-period lags of EGOV_USE as instruments for the contemporaneous variable. The identifying assumption is that historical (2015–2017) levels of e-government adoption are strongly predictive of current usage but plausibly orthogonal to short-run innovations in SDG 9, once year fixed effects and the full set of structural controls are included, in the spirit of Anderson and Hsiao [46]. The full results are reported in Appendix B, Table A11.

The first-stage results confirm that the instruments are highly informative: the first-stage coefficient on EGOV_USE (t − 1) is 0.931 with a Kleibergen–Paap F-statistic of 686, and that on EGOV_USE (t − 2) is 0.903 with F = 207. Both far exceed the conventional weak-instrument threshold of 10 [47]. The second-stage 2SLS coefficient on EGOV_USE is +0.0255 (SE = 0.0631, p = 0.686) using the one-period lag and +0.0179 (SE = 0.0694, p = 0.796) using the two-period lag. Crucially, the Wu–Hausman test of endogeneity yields p-values of 0.504 and 0.374 for the first and second specifications, respectively, so we cannot reject the null that EGOV_USE is exogenous conditional on the controls. This indicates that the two-way fixed-effects estimates reported in our preferred specifications are statistically consistent and are not materially driven by reverse causality. We retain the OLS-FE estimates as our preferred results because the Wu–Hausman test fails to reject exogeneity, and OLS-FE is more efficient than 2SLS when the latter is not strictly required.

5. Discussion

5.1. The Null Governance Mediation: Corroborating and Extending Prior Evidence

The absence of a significant WGI-mediated pathway between e-government usage and SDG performance in the EU27 panel is not a departure from the existing evidence base but a rigorous, within-country quantification of a pattern that prior research had identified qualitatively. The governance-mediation hypothesis originates in the literature on developing countries. Dhaoui [10], using a panel of 15 MENA countries over 2003–2018, demonstrates that e-government development significantly improves government effectiveness and the control of corruption, and that these governance gains translate into better sustainable development outcomes. The mediation chain operates because MENA countries entered the study period with substantial governance deficits, leaving considerable room for digitally induced institutional improvement. Elbahnasawy [14] similarly documents significant negative effects of e-government on corruption across 100 countries, with the effects concentrated at intermediate levels of governance and internet penetration.

The closest existing study to the present work in terms of regional context is Durkiewicz and Janowski [15], who examine 41 OECD/EU countries over 2014–2020. Applying Data Envelopment Analysis to the relationship between digital government maturity and sustainable governance indicators, they find that efficiency in using digital government for governance improvement varies strongly across countries, and that some digital government leaders persistently fail to improve their governance outcomes. The present study was explicitly designed to formalise and quantify this finding through four methodological advances not present in Durkiewicz and Janowski [15]: (i) a formal Baron–Kenny [17] mediation decomposition with country-block bootstrap inference (5000 replications); (ii) restriction to EU27 member states, excluding OECD non-EU countries whose institutional trajectories differ systematically; (iii) stratification by EU15/EU13 cohort to test competing heterogeneity hypotheses; and (iv) use of the SDR 2025 backdated time series [8], which incorporates revised SDG 16 historical scores unavailable in data used by Durkiewicz and Janowski [15].

The null a-path (EGOV_USE → WGI Government Effectiveness: β = 0.001, SE = 0.002, p = 0.641) is theoretically expected rather than anomalous. The World Bank WGI methodology revision [29] documents that only 0.2% of all one-year within-country WGI changes are statistically significant at the 90% confidence level, rising to 7% over a ten-year horizon. At a mean EU27 Government Effectiveness z-score of 1.01—placing the average member state near the 85th percentile of the global distribution—these countries operate in a regime of institutional saturation in which marginal governance returns to additional e-government investment are bounded, and measurement noise dominates annual within-country WGI variation. The precision of our null estimate (indirect effect $a \times b$ = 0.0002, 95% bootstrap

CI [−0.0019, 0.0023]) makes explicit what prior qualitative assessments could not supply: the pathway is not merely weak but is estimated with sufficient precision to rule out economically meaningful indirect effects.

This interpretation is corroborated by global latent class evidence [28], which demonstrates that governance quality serves as the primary structural differentiator between leading and transitional development regimes, with average marginal effects of approximately 7.9 percentage points. Within the leading regime—where all EU27 member states are positioned—incremental governance gains yield diminishing returns, consistent with the institutional saturation mechanism documented here.

This null result does not imply that e-government is without value in the EU27 context. Rather, it relocates that value. As Sections 4.3 and 4.4 demonstrate, the contribution of e-government adoption to sustainable development in EU15 countries operates not through governance reform—which has already occurred—but through a digital co-investment pathway involving internet infrastructure and SDG 9 outcomes. This represents a substantive theoretical shift: from a *governance reform model* of e-government's development impact (applicable where institutional deficits are large, as in MENA [10]) to a *digital co-investment model* (applicable where governance is already mature, as in EU15).

5.2. EU15/EU13 Heterogeneity: Institutional Complementarity over Convergence

The cohort-stratified analysis indicates that the within-country effect of e-government uptake on SDG 9 (Innovation and Infrastructure) is positive and statistically significant in EU15 countries ($\beta = 0.102$, SE = 0.040, $p = 0.024$) but negligible and statistically indistinguishable from zero in EU13 countries ($\beta = -0.033$, SE = 0.055, $p = 0.560$). This pattern is more consistent with the institutional complementarity hypothesis than with the convergence hypothesis—which would predict larger positive effects in EU13 countries where greater scope for improvement exists—and consistent with the institutional complementarity hypothesis: digital public services require a minimum threshold of human capital, digital literacy, and broadband infrastructure to generate innovation spillovers, and EU13 countries have not yet reached this threshold on a within-country trajectory over 2015–2023. However, a formal interaction test (Appendix B, Table A5) does not reject the null of equal slopes at conventional levels ($p = 0.497$), reflecting the limited power of within-country interaction tests with 27 clusters and the absorption of fixed effects. The cohort difference should therefore be read as suggestive evidence warranting further investigation with larger panels or longer time series.

The UN E-Government Survey 2024 [1] identifies digital infrastructure and human capital as the foundational prerequisites for e-government to deliver development dividends, noting that the relationship between EGDI scores and SDG performance is non-linear, with diminishing returns at higher maturity levels. Our panel evidence provides the within-country temporal dimension that cross-sectional EGDI comparisons in the 2024 Survey cannot supply. Specifically, the descriptive evidence supports the threshold interpretation: EU15 countries maintain higher household internet access (90.2% vs. 84.4%), higher tertiary education rates (37.4% vs. 31.3%), and substantially higher e-government usage (64.9% vs. 48.8%), with all differences significant at $p < 0.001$. These baseline differences translate into differences in absorptive capacity for digital governance spillovers.

This finding aligns with Janowski's [13] four-stage model of digital government evolution, which posits that e-government's capacity to generate development value is conditioned by the institutional ecosystem in which it operates. In EU15 countries, mature administrative systems, established digital regulatory frameworks, and dense broadband networks constitute complementary inputs that enable incremental e-government adoption and produce measurable gains in SDG 9. In EU13 countries, where these complementary

factors are still developing through EU Cohesion Policy transfers, similar e-government investment yields no detectable improvement in SDG outcomes within the observed window. The first-difference robustness check (ΔSDG 9: $\beta = 0.029$, $p = 0.005$, full EU27) supports the interpretation that the positive association holds at the aggregate level but that its distribution across cohorts is uneven.

The EU15/EU13 divide documented here represents a specific instance of the broader regime differentiation identified in global SDG panel data, where fewer than 15% of countries transition between latent development classes over a comparable observation period [28]. The institutional complementarity mechanism is further reinforced by the EU's rule-of-law conditionality framework [7], which conditions access to Recovery and Resilience Facility resources [6] on adherence to governance standards, creating a feedback loop between institutional quality and digital investment capacity that disproportionately constrains EU13 member states.

From a European integration perspective, this result carries a direct policy implication for the EU Digital Decade 2030 programme [2], which sets common benchmarks for digital government and internet connectivity across all member states. Symmetric targets may not produce symmetric SDG returns unless accompanied by deliberate investment in the complementary factors that enable EU13 countries to reach the threshold at which e-government generates innovation spillovers. Our evidence supports the sequencing logic already embedded in Cohesion Policy: broadband infrastructure and investment in digital skills should precede or accompany the expansion of e-government services.

5.3. The Digital Co-Investment Mechanism: Internet Access as the Active Mediator

The most novel empirical contribution of this study is the evidence of full mediation of the e-government–SDG 9 relationship through household internet access in the EU15 sub-sample. The Sobel test ($z = 3.634$, $p < 0.001$) and country-block bootstrap inference (5000 replications; 95% bias-corrected CI [0.059, 0.177]) jointly support the conclusion that the positive bivariate association between e-government usage and SDG 9 performance is largely channelled through the a-path: higher e-government uptake within EU15 countries predicts greater household internet penetration ($\beta = 0.304$, SE = 0.043, $p < 0.001$), which in turn is associated with SDG 9 improvement ($\beta = 0.412$, SE = 0.098, $p = 0.001$). Once internet access is controlled for, e-government carries no independent marginal contribution to SDG 9 ($c' = -0.009$, $p = 0.812$), and the incremental R^2 of e-government conditional on internet access is negligible ($\Delta R^2 < 0.001$; Table 5).

This pattern is consistent with a digital co-investment mechanism. National digital transformation strategies—as reflected in the EU Digital Decade programme [2] and national broadband deployment plans—simultaneously drive e-government supply (digitalisation of public services) and digital infrastructure investment (broadband rollout, universal service obligations). E-government usage and internet access co-evolve because both are driven by the same underlying national digital investment cycle. E-government uptake is therefore best understood as a composite signal of national digital readiness rather than an independent productive input to SDG 9. This interpretation is consistent with the structure of the UN E-Government Development Index [1], which incorporates the Telecommunications Infrastructure Index (TII) as one of three equal components precisely because infrastructure is a prerequisite of e-government effectiveness, not merely a correlate.

The finding that internet access mediates the EGOV–SDG 9 association complements the cross-sectional evidence of Noja et al. [27], who apply structural equation modelling and cluster analysis to EU countries and find that digital transformation positively affects SDG composite scores, with the effect partially mediated by GDP per capita. Our contribution is

to decompose the digital transformation bundle into its e-government and infrastructure components within a panel setting, revealing that the infrastructure dimension carries the causal weight for SDG 9. Similarly, Elbahnasawy [14] documents that the corruption-reducing effect of e-government is conditional on internet adoption, treating the two variables as strategic complements. Our mediation evidence provides panel-based chain support for this complementarity in the EU15 context.

An important interpretive question is whether the documented mediation reflects a genuine causal chain—in which e-government uptake causally expands internet infrastructure, which in turn improves SDG 9 outcomes—or a common driving mechanism, in which an unobserved national digital transformation strategy simultaneously drives both e-government adoption and broadband deployment, with the observed statistical mediation reflecting co-movement rather than sequential causation. The Recovery and Resilience Facility [6], which bundles digital infrastructure, skills, and public service digitalisation within national recovery plans, provides a concrete institutional example of such a common driving mechanism. We argue that the evidence is most consistent with a hybrid interpretation. The a-path coefficient is robust to the inclusion of GDP per capita and tertiary education controls (Table 4, Model 4d), to COVID-period exclusion (Table A6), and to the lagged specification (Table 5, R2), which supports temporal precedence. However, the panel structure does not permit full separation of the mediating and common-cause channels. Direct data on national digital investment expenditures, disaggregated by e-government and broadband components, would permit a more direct test and is recommended as a direction for future research (Section 5.6). Regardless of which interpretation is obtained, the policy implication is the same: e-government and broadband infrastructure are most productive when co-invested as part of an integrated national digital strategy, and isolated e-government expansion without complementary infrastructure investment is unlikely to yield SDG 9 returns.

A partial overlap between the SDG 9 score [8] and the internet access mediator should be acknowledged explicitly. The SDG 9 composite incorporates internet usage as one sub-indicator alongside R&D expenditure and innovation metrics. To address this concern directly, we construct an alternative non-Internet SDG 9 composite from five sub-indicators available in the SDR 2025 backdated data (R&D expenditure, patent applications, scientific articles, university rankings, and researchers per 1000 employed). The baseline EGOV coefficient on this non-Internet SDG 9 composite remains positive and highly significant in EU15 ($\beta = 0.178$, SE = 0.045, $p < 0.001$), confirming that the e-government–SDG 9 association extends well beyond the internet-usage sub-indicator. When internet access is added, EGOV attenuates to 0.113 ($p = 0.112$), consistent with partial rather than full mediation (Sobel z = 1.32, $p = 0.186$; Appendix B, Table A7). This pattern indicates that the digital co-investment mechanism operates both through and beyond internet infrastructure, but the non-Internet channel alone does not reach conventional significance for mediation. The first-difference result (ΔSDG 9: $\beta = 0.029$, $p = 0.005$), which does not rely on level variation in internet access, provides supplementary support that is free of this overlap concern.

The robustness analysis with alternative mediators reported in Section 4.4.6 and Appendix B (Table A10) reinforces this interpretation. Of the four candidate channels tested—household internet engagement, Government Effectiveness, the WGI Composite, and R&D intensity—only household internet engagement shows a statistically significant indirect effect of e-government usage on SDG 9. This convergence of theoretical reasoning and empirical evidence supports the digital co-investment mechanism over alternative institutional or innovation-investment pathways in the EU27 context, while remaining consistent with the null governance result of Section 4.2.

5.4. Methodological Contribution: Within-Country Panel Mediation for SDG Research

The majority of existing studies on e-government and SDG performance rely on cross-sectional or pooled OLS specifications, which conflate between-country structural differences with within-country dynamic effects. Gajdzik et al. [48], who examine EU27 countries' SDG 9 performance between 2015 and 2020 using a composite Digital Transformation Assessment Indicator, employ a static cross-country methodology that, by construction, cannot identify within-country temporal associations. Dhaoui [10] uses a GMM to address dynamic endogeneity in a developing-country sample but estimates effects averaged across the full MENA distribution without cohort stratification. Durkiewicz and Janowski [15] use panel data but do not apply either a formal mediation framework or EU15/EU13 stratification.

Our two-way fixed-effects specification with country-clustered standard errors identifies the within-country, over-time association between e-government adoption and SDG outcomes, controlling for all time-invariant country characteristics and common year-level shocks. The formal Baron–Kenny [17] mediation analysis—applied to country-block resampling following Hayes [49] and MacKinnon [39]—is, to the best of our knowledge, the first application of this framework to e-government and SDG outcomes within the EU panel context. The distinction between direct effects (e-government on SDGs) and mediated effects (e-government through internet infrastructure on SDG 9) carries distinct policy implications for whether investment should prioritise e-government service expansion or broadband infrastructure.

5.5. Policy Implications

The findings carry differentiated policy implications for the two EU membership cohorts and for the broader 2030 SDG monitoring framework.

For EU15 member states, e-government digitalisation strategies are associated with their strongest measurable SDG outcomes not through governance quality improvements, which are already near-ceiling, but through their role as a stimulus for broader digital infrastructure investment. National digital transformation plans that jointly expand public service digitalisation and broadband infrastructure—as exemplified by Denmark, Finland, and Estonia, which combine top EGDI scores with near-universal internet access—are more likely to deliver SDG 9 gains than e-government strategies pursued in isolation from infrastructure policy. The quantified indirect effect (0.125 SDG 9 points per percentage point of e-government uptake, mediated via internet access) provides a policy-relevant magnitude for evaluating the SDG 9 returns to joint digital investment.

For EU13 member states and EU Cohesion Policy, the absence of a detectable within-country effect on SDG 9 despite rising e-government adoption signals a precondition gap. The Recovery and Resilience Facility and Cohesion Policy allocate substantial resources to broadband deployment in EU13 countries precisely to close this gap. Our evidence reinforces the sequencing logic: infrastructure investment should precede or accompany e-government service expansion, since the digital co-investment mechanism identified in EU15 cannot be activated in EU13 contexts, where internet penetration remains lower and more spatially uneven.

Specifically, the Digital Decade Policy Programme 2030 [2] sets binding targets of 100% online availability of key public services and 80% of the population using digital identity solutions by 2030. The Recovery and Resilience Facility [6] provides the financing vehicle, with a mandatory 20% digital expenditure floor in national recovery plans. Our evidence suggests that these targets should be accompanied by explicit broadband infrastructure co-investment benchmarks for EU13 member states, conditional on achieving minimum internet penetration thresholds that enable the digital co-investment mechanism to activate.

At the level of the 2030 SDG Agenda, the finding that e-government usage is a composite digital readiness signal rather than an independent SDG driver implies that investment monitoring frameworks—such as the SDG 9 indicator set and the UN E-Government Development Index [1]—should explicitly account for the infrastructure prerequisites for e-government effectiveness. The European eGovernment Benchmark [32], which evaluates e-government alongside connectivity and digital skills, already reflects this integrated logic; our panel evidence provides empirical support for maintaining this approach.

5.6. Limitations and Directions for Future Research

This study is subject to several limitations that should be acknowledged transparently.

First, regarding *endogeneity and reverse causality*: whilst the two-way fixed-effects specification controls for time-invariant confounders and common shocks, and lagged e-government specifications support temporal precedence for the EU15 SDG 9 result ($\beta = 0.080$, $p = 0.019$), the panel structure does not support a clean instrumental variables design. Countries that have improved on SDG 9 may subsequently invest more in e-government services. Future research using valid instruments for e-government adoption—for instance, EU regulatory reform timing or Digital Single Market transposition deadlines—would strengthen causal identification.

Second, regarding the concept–measurement gap, the core explanatory variable, EGOV_USE, captures demand-side citizen uptake of e-government services, which is a narrower construct than 'digital government' in its full sense. The results should therefore be interpreted as pertaining to the demand-side dimension of digital government rather than to the full digital government ecosystem, which includes back-office digitalisation, data interoperability, and AI-assisted public service delivery. Future research incorporating supply-side indicators—such as the OECD Digital Government Index [31] or the eGovernment Benchmark composite [32]—would provide a more comprehensive test of the digital government–SDG nexus.

Third, regarding the *cluster count in the EU15 subsample*: the mediation analysis relies on 14 country clusters in the EU15 bootstrap procedure. Whilst country-block bootstrap inference is appropriate for small cluster counts and the Sobel test corroborates the bootstrap finding, the 95% CI [0.059, 0.177] indicates limited precision. A wild cluster bootstrap with sign-cluster permutation [50] would further stress-test this result and is recommended as a robustness check.

Fourth, regarding the *partial overlap between SDG 9 sub-indicators and internet access*: as noted in Section 5.3, the SDG 9 score [8] incorporates internet usage as one sub-indicator. We address this in Appendix B by constructing a non-Internet SDG 9 composite from R&D expenditure, patent applications, scientific articles, university rankings, and researchers. The baseline EGOV effect on this composite remains significant in EU15 ($\beta = 0.178$, $p < 0.001$), confirming that the association extends beyond the internet sub-indicator, although the formal mediation through internet access becomes partial rather than full (Sobel $z = 1.32$, $p = 0.186$).

Fifth, regarding the *COVID-19 structural break*, the 2020–2021 period saw pandemic-driven accelerations in both e-government adoption and internet usage across EU member states. Year fixed effects absorb common-year shocks, but country-heterogeneous COVID-19 responses may have generated within-country dynamics that confound pandemic-specific effects with the structural relationship of interest. Excluding 2020–2021 from the sample yields qualitatively similar patterns: the a-path (EGOV $\rightarrow$ internet) remains significant in EU15 ($\beta = 0.250$, $p < 0.001$), and internet access continues to dominate the SDG 9 specification (Appendix B, Table A6). A COVID-19 interaction term specification could test whether the EU15 mediation result is concentrated in the pandemic years.

Sixth, regarding the *sequential ignorability assumption in the mediation analysis*, the Baron–Kenny mediation framework assumes that no unobserved confounders jointly influence the mediator and the outcome, conditional on covariates and fixed effects [17,39]. Whilst country fixed effects absorb all time-invariant confounders and year fixed effects control for common temporal shocks, time-varying omitted variables that simultaneously affect internet access, and SDG 9 performance remain a potential threat to the mediation interpretation. The full-control specification (Table 4, Model 4d) and the COVID-19 period exclusion (Table A6) mitigate but do not eliminate this concern. Future research employing sensitivity analysis for the sequential ignorability assumption, such as the approach proposed by Imai, Keele, and Tingley [51] would provide a more formal assessment of the robustness of the mediation pathway to unobserved confounding.

Seventh, regarding the distinction between mediating and common driving mechanisms, as discussed in Section 5.3, the observed mediation through internet access is consistent with both a genuine causal chain and a common-cause mechanism driven by national digital transformation strategies. Broader factors—including EU funding support, industrial upgrading policies, and national broadband deployment plans—may jointly determine both e-government adoption and internet infrastructure expansion. The progressive model-building strategy and robustness checks mitigate but do not eliminate this concern. Future research employing disaggregated national digital investment expenditure data would permit a more direct test of the mediating versus common-cause interpretation.

Directions for future research include: (i) extending the analysis to non-EU high-income OECD countries to test whether institutional saturation generalises beyond EU membership; (ii) disaggregating e-government usage by service type to identify which service domains generate the strongest infrastructure spillovers; and (iii) incorporating sub-national data for large EU15 countries to exploit regional variation in digital infrastructure rollout that national averages obscure.

6. Conclusions

Three decades of digital government investment across the European Union have produced a paradox: member states with the most mature e-government systems are also those in which institutional quality has the least room to improve, and where the traditional rationale for digital public sector reform—reducing governance deficits—therefore applies least. This study resolves the paradox by demonstrating that e-government in the EU context operates through a fundamentally different mechanism than the governance reform model developed in the developing-country literature.

The governance reform pathway, well documented in MENA and Sub-Saharan Africa, is structurally absent in the EU27. This is not a failure of digital policy but a sign of its prior success: EU member states operate near the ceiling of measurable institutional quality, and the annual within-country variation in governance indicators is too small to detect reform dividends even over a nine-year panel. Recognising this constraint is itself a contribution—it clarifies that the absence of a governance-mediation effect in high-income panels is theoretically expected rather than anomalous, and that studies applying developing-country frameworks to EU data will systematically misinterpret the evidence.

The study contributes to the digital government–SDG literature in three ways that revise existing understanding. First, it demonstrates that the developing-country governance-reform frameworks widely applied in the field systematically misinterpret the evidence when applied to high-income panels, where institutional saturation rather than institutional deficit characterises the baseline. Second, it shows that the relevant mechanism in advanced economies is not standalone e-government reform but policy complementarity—the co-investment of e-government services and broadband infrastructure within integrated

national digital strategies. Third, the finding of pathway specificity (SDG 9 but not SDG 16 or the composite index) challenges the assumption that digital government yields broad-based SDG returns and redirects attention to the specific channels through which digital transformation generates measurable development outcomes. These results carry direct implications for the design of the EU Digital Decade strategy, the allocation of Cohesion Policy resources, and the construction of SDG monitoring frameworks that distinguish between digital government uptake and the institutional ecosystem required to make that uptake productive.

What emerges in place of the governance pathway is a more nuanced and spatially differentiated picture. E-government in EU15 countries is associated with significant innovation and infrastructure gains—but only because those countries have already built the broadband infrastructure, human capital, and administrative capacity that enable digital public services to contribute to broader spillovers. The mechanism is one of co-investment and complementarity, not standalone reform. National digital transformation strategies that jointly advance e-government provision and broadband connectivity—as exemplified by the Nordic and Baltic leaders—are not merely doing two things at once; they create the conditions under which each investment amplifies the returns to the other.

The EU13 finding is equally instructive. The absence of a detectable within-country effect of SDG 9 in new member states, despite a decade of rising e-government adoption, does not indicate that digital investment is wasted in these contexts. It is a sign that the mechanism has not yet activated—that the infrastructure threshold required to translate e-government uptake into innovation spillovers has not yet been met. This is precisely the diagnostic that Cohesion Policy and the Recovery and Resilience Facility need: not whether EU13 countries are adopting e-government, but whether the complementary investments are in place to make that adoption productive.

For the 2030 SDG monitoring framework, the broader implication is that e-government usage should not be treated as an independent driver of SDG progress in high-income settings. It is a reliable signal of national digital readiness, and its SDG returns depend on the infrastructure and institutional ecosystem in which it is embedded. Monitoring frameworks that equate high e-government uptake with SDG progress risk misattributing causality and misinforming investment priorities.

Taken together, the three findings of this study—institutional saturation in EU27, institutional complementarity across EU15/EU13, and digital co-investment as the active mechanism—constitute a coherent reframing of how digital government contributes to public value in advanced economies. That reframing has consequences for how the EU designs its Digital Decade strategy, allocates Cohesion resources, and monitors the digital governance contribution to the 2030 Agenda.

The empirical evidence is consistent with a digital co-investment interpretation in which e-government adoption operates as a complementary input that raises the marginal return on private and public digital infrastructure investment, thereby crowding in further broadband expansion and intensive-margin household engagement rather than substituting for them. Under this interpretation, e-government services act as an anchor demand that stabilises the business case for digital infrastructure rollout, while the same infrastructure feeds back into deeper service uptake. We deliberately frame this as a plausible mechanism consistent with our evidence: the cross-country panel design, even with the instrumental-variable robustness reported in Section Addressing Potential Endogeneity: Instrumental Variable Estimation, supports associational and mediational inference rather than full causal identification, and the policy implications drawn in Section 5.5 should be read in that light.

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Conflicts of Interest: Olena Mykhailovska was employed by the Research And Educational Innovation Center of Social Transformations, Ihor Ruzhytskyi was employed by the Private postgraduate educational institution 'Institute of Professional Transformations'. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BC CI	Bias-corrected confidence interval
CD	Cross-sectional dependence
CIPS	Cross-sectionally augmented IPS unit root test
DEA	Data envelopment analysis
DESI	Digital Economy and Society Index
DGI	Digital Government Index
EGDI	E-Government Development Index
EGOV_USE	E-government usage (individuals using e-government services, %)
EU13	Post-2004 EU member states (13 accession countries)
EU15	Pre-2004 EU member states (14 countries, excl. United Kingdom)
GDP	Gross domestic product
GMM	Generalised method of moments
ICT	Information and communications technology
ISCED	International Standard Classification of Education
MENA	Middle East and North Africa
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary least squares
PPS	Purchasing power standards

RRF	Recovery and Resilience Facility
SE	Standard error
SGI	Sustainable Governance Indicators
TII	Telecommunications Infrastructure Index
TWFE	Two-way fixed effects
VIF	Variance inflation factor
WGI	Worldwide Governance Indicator

Appendix A

Table A1. Full descriptive statistics for all variables, EU27 panel dataset, 2015–2023 (*n* = 241–243).

Variable	*n*	Mean	SD	Min	Max	EU15 Mean
E-Gov. usage (%)	242	57.09	19.89	8.7	92.5	64.85
SDG Composite Index	243	80.18	3.10	70.7	87.7	81.25
SDG 9 (Innovation)	243	79.27	13.28	50.0	100.0	89.16
SDG 16 (Institutions)	243	81.87	7.52	63.1	95.4	85.29
SDG 17 (Partnerships)	243	64.65	8.71	45.3	83.2	66.66
WGI Gov. Effectiveness	243	1.01	0.56	−0.27	2.42	1.32
GDP/cap PPS (EUR)	243	32,534	14,343	10,100	93,900	39,650
Internet access (%)	241	87.38	7.64	60.0	98.0	90.19
Tertiary education (%)	243	34.46	8.76	16.6	59.5	37.42

Note. All values are country-year observations. Missing values: EGOV_USE (*n* = 1, France 2020); INTERNET (*n* = 2). WGI = World Bank Worldwide Governance Indicators (2025 revision). SDG data from SDSN Europe SDR 2025 Backdated Index. EU15, *n* = 125; EU13, *n* = 117–118.

Table A2. Summary of mediation path coefficients, Baron–Kenny framework, EU27 TWFE.

Path	Regression	β	SE	*p*	Interpretation
c-path	EGOV → SDG Index	−0.003	0.006	0.674	No total effect
a-path	EGOV → WGI_GE	0.001	0.002	0.641	No effect on governance
b-path	WGI_GE → SDG Index	0.194	0.329	0.561	No governance effect
c′-path	EGOV → SDG | WGI	−0.003	0.006	0.640	No direct effect
a × b	Indirect (bootstrap)	0.0002	—	[−0.002; 0.002]	CI includes zero → no mediation

Note. All estimates from two-way fixed effects (country + year) OLS with country-clustered standard errors (*n* = 242, 27 countries). Indirect effect CI from 5000 country-block bootstrap replications (seed = 12345). Outcome variable for c-, b-, and c′-paths: SDG Composite Index. Mediator: WGI Government Effectiveness.

Table A3. Pairwise Pearson correlations computed on within-country demeaned values (country fixed effects removed), full EU27 sample, *n* = 241–243.

Variable	EGOV	INTERNET	EDUC	GDP	SDG_9	SDG_16	WGI_GE
EGOV_USE	1.000	0.525 ***	0.302 ***	0.286 ***	0.545 ***	−0.331 ***	0.215 ***
INTERNET	—	1.000	0.460 ***	0.368 ***	0.831 ***	−0.401 ***	0.261 ***
EDUC	—	—	1.000	0.485 ***	0.615 ***	−0.442 ***	0.249 ***
GDP/cap	—	—	—	1.000	0.572 ***	−0.362 ***	0.424 ***
SDG_9	—	—	—	—	1.000	−0.589 ***	0.410 ***

Table A3. *Cont.*

Variable	EGOV	INTERNET	EDUC	GDP	SDG_9	SDG_16	WGI_GE
SDG_16	—	—	—	—	—	1.000	0.690 ***
WGI_GE	—	—	—	—	—	—	1.000

Note. All variables demeaned by country mean prior to computing correlations; year fixed effects not removed for this exploratory summary. *** $p < 0.001$ (two-tailed). Lower triangle omitted for readability; diagonal = 1. Collinearity diagnostics (VIF) are reported separately in Table A4. EGOV = e-government usage; INTERNET = household internet access; EDUC = tertiary education rate; GDP = GDP per capita PPS; WGI_GE = Government Effectiveness.

Table A4. Variance inflation factors for the full-controls specification (Model D), computed on within-country demeaned values, full EU27 sample.

Variable	VIF	1/VIF (Tolerance)	Assessment
E-Government usage (EGOV_USE)	2.15	0.465	Acceptable
Internet access (INTERNET)	2.64	0.379	Acceptable
Tertiary education (EDUC)	3.33	0.300	Acceptable
GDP per capita, PPS (GDP_PC_PPS)	3.08	0.325	Acceptable

Note. VIF = $1/(1 - R^2_j)$, where R^2_j is the R^2 from regressing variable j on all other predictors (within-country demeaned). The widely used threshold for problematic multicollinearity is VIF > 10 [52] or, under a more conservative criterion, VIF > 5. All values are below 3.5, indicating no multicollinearity concern. Tolerance = 1/VIF.

Appendix B

Additional Robustness Checks

Table A5. Interaction model: EGOV_USE × EU15 dummy, full EU27 sample.

	SDG 9	SDG 16	SDG Index
EGOV_USE	0.060 (0.055)	−0.058 (0.031) †	−0.005 (0.008)
EU15	24.887 (10.195) *	14.280 (3.176) ***	9.877 (0.965) ***
EGOV × EU15	−0.056 (0.082)	0.062 (0.036) †	0.001 (0.009)
ln(GDP_PC)	7.594 (6.722)	0.105 (2.754)	0.168 (0.890)
EDUC	−0.349 (0.206) †	−0.166 (0.074) *	−0.014 (0.033)
n	242	242	242
R^2	0.983	0.980	0.989
p (interaction)	0.497	0.089	0.882

Note. Two-way fixed effects (country + year) OLS estimates. Standard errors clustered at the country level in parentheses. *n* = 242 (France 2020 excluded). The interaction term EGOV × EU15 tests whether the within-country effect of e-government usage differs between EU15 and EU13 member states. Controls: ln(GDP per capita PPS) and tertiary education. † $p < 0.10$, * $p < 0.05$, *** $p < 0.001$.

Table A6. COVID-19 robustness, excluding 2020–2021.

	SDG 9 Full	SDG 9 EU15	SDG 9 EU15 + Int	SDG 16 Full	SDG Idx Full
EGOV_USE	0.028 (0.041)	0.096 (0.065)	−0.059 (0.059)	−0.031 (0.030)	−0.003 (0.006)
INTERNET			0.567 (0.149) ***		
n	189	98	97	189	189
R^2	0.982	0.964	0.981	0.978	0.990

Note. Two-way fixed effects (country + year) OLS estimates excluding 2020 and 2021. Standard errors clustered at the country level in parentheses. All models include ln(GDP per capita PPS) and tertiary education as controls. *** $p < 0.001$.

The non-Internet SDG 9 composite is constructed from five sub-indicators available in the SDR 2025 backdated data: R&D expenditure (% of GDP), patent applications (per million population), scientific articles (per 1000 population), Times Higher Education university ranking score, and researchers (per 1000 employed). Each sub-indicator is min-

max normalised to a 0–100 scale and then averaged. This composite excludes indicators on internet usage, mobile broadband, and the internet access gap.

Table A7. SDG 9 disaggregation: Non-Internet composite as dependent variable.

	EU15 Baseline	EU15 + Internet	EU27 Baseline	EU27 + Internet
EGOV_USE	0.178 (0.045) ***	0.113 (0.071)	0.086 (0.060)	0.058 (0.057)
INTERNET		0.216 (0.157)		0.165 (0.137)
ln(GDP_PC)	−10.424 (9.492)	−4.933 (12.322)	3.952 (8.123)	1.322 (7.971)
EDUC	0.092 (0.208)	0.190 (0.193)	0.249 (0.219)	0.343 (0.252)
n	125	124	242	241
R^2	0.957	0.958	0.973	0.973

Note. Two-way fixed effects (country + year) OLS estimates. Standard errors clustered at the country level in parentheses. Dependent variable: non-Internet SDG 9 composite (0–100). Controls: ln(GDP per capita PPS) and tertiary education. *** $p < 0.001$.

Mediation Test: EGOV → Internet → Non-Internet SDG 9 (EU15).

1. a-path (EGOV → Internet): β = 0.264, SE = 0.053, $p < 0.001$
2. b-path (Internet → SDG9_nonet | EGOV): β = 0.216, SE = 0.157, $p = 0.170$
3. c-path (EGOV → SDG9_nonet, total): β = 0.178, SE = 0.045, $p < 0.001$
4. c′-path (EGOV → SDG9_nonet | Internet): β = 0.113, SE = 0.071, $p = 0.112$
5. Indirect effect (a × b): 0.057; Sobel z = 1.324, $p = 0.186$

95% bias-corrected bootstrap CI (5000 country-block replications): [−0.037, 0.136].
Proportion mediated: 31.9%.

Interpretation. The baseline EGOV effect on the non-Internet SDG 9 composite is positive and significant (β = 0.178, $p < 0.001$), confirming that the e-government–SDG 9 association extends beyond the internet sub-indicator. When internet access is added, EGOV attenuates to 0.113 ($p = 0.112$), consistent with partial mediation (~32%). The Sobel test does not meet conventional significance thresholds (z = 1.32, $p = 0.186$), and the bootstrap CI includes zero, indicating that mediation through internet access is not statistically established for the non-internet components. This pattern is theoretically expected: internet infrastructure fully mediates internet-related SDG 9 gains, but non-internet innovation gains (R&D, patents, publications) are only partially channelled through broadband.

Table A8. Dynamic specification: Leads and lags, EU15 sub-sample, SDG 9.

Variable	Coefficient (SE)	*p*-Value	Interpretation
EGOV (t + 1) [lead]	0.039 (0.044)	0.368	No reverse causality
EGOV (t) [contemp.]	0.037 (0.015)	0.014 *	Main effect
EGOV (t − 1) [lag 1]	−0.017 (0.032)	0.596	No delayed add. effect
EGOV (t − 2) [lag 2]	0.024 (0.104)	0.816	No delayed add. effect
ln(GDP_PC)	−12.544 (5.074)	0.013 *	
EDUC	−0.085 (0.190)	0.654	
n	80		
R^2	0.986		

Note. Two-way fixed effects (country + year) OLS estimates. EU15 sub-sample (14 countries). Standard errors clustered at the country level in parentheses. The lead variable (t + 1) tests for reverse causality: a significant lead would suggest that improvements in SDG 9 precede e-government uptake. The non-significance of the lead ($p = 0.368$) is consistent with the absence of reverse causality. The significant contemporaneous coefficient ($p = 0.014$) is the main effect of interest. * $p < 0.05$.

Table A9. COVID-19 robustness: Mediation a-path (EGOV → Internet), EU15, excluding 2020–2021.

Path	Relationship	β	SE	*p*-Value	*n*
a-path	EGOV → Internet	0.250	0.064	<0.001	97
b-path	Internet → SDG 9 | EGOV	0.567	0.149	<0.001	97
c′-path	EGOV → SDG 9 | Internet	−0.059	0.059	0.312	97

Interpretation. The mediation pathway EGOV → Internet → SDG 9 in EU15 is robust to excluding the COVID-19 period (2020–2021). The a-path remains large and significant (β = 0.250, $p < 0.001$), internet access continues to dominate the SDG 9 specification (β = 0.567, $p < 0.001$), and the direct effect of EGOV is fully attenuated (β = −0.059, $p = 0.312$). The pattern of full mediation is preserved.

Table A10. Alternative mediator comparison: E-government usage → Mediator → SDG 9, EU27, 2015–2023.

Candidate Mediator	a-Path	b-Path	Indirect (a × b)	Bootstrap 95% CI	Mediation
Household internet engagement	+0.1170 ***	+0.5751 ***	+0.0673	[+0.018, +0.133]	Yes
WGI Government Effectiveness	+0.0089 ***	+1.9874	+0.0178	[−0.051, +0.077]	No
WGI Composite governance	+0.0051 ***	−0.3873	−0.0020	[−0.083, +0.044]	No
R&D expenditure (% GDP)	+0.0952	+0.2925 ***	+0.0279	[−0.099, +0.145]	No

Note. Pooled OLS with year fixed effects and country-clustered standard errors, $n = 241$. The a-path estimates the effect of e-government use on the candidate mediator; the b-path estimates the effect of the mediator on SDG 9, conditional on e-government use. Confidence intervals derived from 2000 country-cluster bootstrap replications. All specifications control for GDP per capita PPS (thousands), tertiary education, and the Corruption Perception Index; R&D intensity is included as a control except where it is the candidate mediator. Significance: *** $p < 0.01$. Only household internet engagement yields a statistically significant indirect effect.

Table A11. Instrumental variable (2SLS) estimates of e-government usage on SDG 9, EU27, 2015–2023.

	Coef.	(SE)	*p*	Coef.	(SE)	*p*
EGOV_USE (instrumented)	+0.0255	(0.0631)	$p = 0.686$	+0.0179	(0.0694)	$p = 0.796$
First-stage coef. on instrument	0.931	—	—	0.903	—	—
First-stage Kleibergen–Paap F	685.8	—	—	206.9	—	—
Wu–Hausman endogeneity test (*p*)	$p = 0.504$	—	—	$p = 0.374$	—	—
Observations	214	—	—	187	—	—

Note. Two-stage least squares estimates of the effect of e-government usage on SDG 9 (Innovation and Infrastructure). Columns 2–4: Instrument is EGOV_USE (t − 1); Columns 5–7: Instrument is EGOV_USE (t − 2). Both specifications include controls (GDP per capita PPS in thousands, tertiary education, R&D intensity, Corruption Perception Index) and year fixed effects. Standard errors clustered at the country level. The first-stage Kleibergen–Paap F-statistic far exceeds the Stock–Yogo [47] weak-instrument threshold of 10 in both specifications, confirming instrument relevance. The Wu–Hausman test fails to reject the exogeneity null in both specifications, indicating that the two-way fixed-effects estimates reported in the main text are not materially affected by reverse causality.

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