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Open Science and Open Access Policies as Drivers of Innovation: Evidence from Patent Activity in European Countries

Maksym W. Sitnicki, ORCID: https://orcid.org/0000-0002-0452-0404
D.Sc., Dr Hab., Professor, Fulbright Scholar, John Chambers College of Business and Economics at West Virginia University, WV, USA; Professor of the School of Business at VIZJA University, Warsaw, Poland
Yuriy Petrushenko, ORCID: https://orcid.org/0000-0001-9902-7577
D.Sc., Professor, Fulbright Scholar, Salisbury University, MD, USA
Elena Kašťáková, ORCID: https://orcid.org/0000-0003-4215-4836
Assoc. Prof. Mgr, Department of International Trade, Faculty of Commerce, Bratislava University of Economics and Business, Slovak Republic
Anabela Luptáková, ORCID: https://orcid.org/0000-0003-1577-6891
Ph.D., Department of International Trade, Faculty of Commerce, Bratislava University of Economics and Business, Slovak Republic
Milena Filipova, ORCID: https://orcid.org/0000-0002-5003-006X
D.Sc., Professor, Department "Business Management and Marketing", Southwest University "Neofit Rilski" – Blagoevgrad, Bulgaria
Viktoriia Hurochkina, ORCID: https://orcid.org/0000-0001-8869-0189
Dr hab., Professor, Institute of Economics and Finance / Department of International Economics and Market Analysis, University of Zielona Góra, Poland
Iurii Volk, ORCID: https://orcid.org/0000-0002-0262-762X
Ph.D., Associate Professor, Dean of Faculty of Electronics and Information Technology, Sumy State University, Ukraine

Corresponding author: Elena Kašťáková, **elena.kastakova@euba.sk**
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Abstract: *Open Science (OS) and Open Access (OA) have become key pillars of research and innovation policy, yet their concrete impacts on innovation outputs remain underexplored. This study aims to assess whether the presence and scope of national OS&OA policies are associated with changes in patent activity across 29 European countries. Using a panel dataset from 2000 to 2023, the analysis applies fixed-effects regression models with clustered standard errors and robust specifications, focusing on the logarithm of total patent applications as the dependent variable. The results indicate a positive and statistically significant association between the presence of OS&OA policy (x2) and the number of patent applications (coefficient=0.3116, $p < 0.001$). While the interaction between policy presence and policy scope was removed due to multicollinearity, the main effects of policy scope also showed statistical significance (coefficient=0.1901, p=0.0019). After log-transformation to address skewness, model robustness was confirmed using heteroskedasticity-consistent standard errors. These findings support the hypothesis that well-developed national OS&OA policies can contribute to innovation performance, as proxied by patent output.*

Keywords: Europe, fixed effects, innovation policy, open access, open science, patent applications, policy evaluation.
JEL Classification: O31, C23, I28, L52, O34.

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INTRODUCTION

In recent years, Open Science (OS) and Open Access (OA) have moved to the forefront of European research and innovation policy. Supranational bodies such as the European Commission and UNESCO have increasingly emphasised the importance of transparent, accessible, and collaborative knowledge production as a foundation for inclusive and sustainable innovation. The European Commission has made Open Science mandatory in its Horizon Europe programme (2021–2027), the EU's key funding programme for research and innovation. All Horizon Europe-funded projects are required to ensure immediate Open Access to scientific publications and are strongly encouraged to share research data following the FAIR principles (Findable, Accessible, Interoperable, and Reusable) (European Commission, 2021).

In 2021, UNESCO adopted a global recommendation on Open Science (UNESCO, 2021), calling on member states – including EU countries – to develop national OS policies and infrastructures. This recommendation reinforced the political will across Europe to mainstream OS as a key driver of innovation, transparency, and equity in knowledge creation and dissemination.

As countries adopt diverse OS&OA policy models, there is growing interest in understanding whether and how such policies translate into measurable economic or technological outcomes, particularly innovation. A handbook from the PATHOS project (Catalano, n.d.), developed for the United Nations Economic Commission for Africa, emphasises that open science practices can drive innovation by broadening access to research and encouraging the reuse of publicly funded data, particularly aiding small and medium enterprises. It suggests that innovation metrics, such as patents referencing open science resources, should be used to assess this impact. Similarly, a report by the Technopolis Group highlights that open science is increasingly viewed as a strategic tool within European research and innovation policies, aimed at promoting knowledge dissemination and tangible innovation through collaboration across sectors. Both documents underscore a rising organisational focus on evaluating the concrete outcomes of open science initiatives.

As a proxy for innovation output, patent applications offer a concrete metric for evaluating these effects. However, empirical evidence on the causal link between national OS&OA policy frameworks and innovation performance remains limited. The OECD's Main Science and Technology Indicators (OECD, n.d.) include patent data as one of the core indicators for tracking innovation output, highlighting their widespread use as proxies for technological advancement. However, the MSTI primarily offers descriptive statistics and does not provide formal causal analysis linking Open Science or Open Access policies to innovation, illustrating the current lack of empirical causal evidence in policy-outcome research. OECD (2018) highlights the importance of using patent data as a measurable proxy for innovation output. The report emphasises that while patent metrics are widely used to quantify innovation, empirical analysis linking these metrics directly to national OS&OA policies remains sparse, due to the complexity of isolating causal relationships in policy impact assessments.

Paic (2021) emphasises that open scientific practices, particularly data sharing, *"facilitate cross-border discovery and reuse"* but acknowledges that quantifying these impacts requires integrating open science metrics with innovation measures like patents. Despite recognising the potential, the report underscores that comprehensive empirical studies establishing causal links between OS&OA frameworks and patent outcomes are minimal.

In light of the growing policy emphasis on transparency, accessibility, and collaboration in scientific research, investigating how national OS&OA policies influence patent applications is timely and highly relevant. As patent activity is a tangible indicator of innovation output, understanding this relationship can provide critical insights into the broader societal and economic value of OS&OA frameworks. Given the ongoing expansion of such policies across Europe and the increasing need for evidence-based policymaking, this line of research addresses a significant knowledge gap. It contributes to a more informed evaluation of research and innovation strategies.

LITERATURE REVIEW

In recent years, implementing and expanding OS and OA policies have garnered considerable attention within the global scientific and policy community. The growing body of research highlights the role of OS and OA in promoting transparency, accelerating innovation, and improving the efficiency of knowledge dissemination across disciplines and sectors (McKiernan et al., 2016; Vicente-Saez & Martinez-Fuentes, 2018). The increasing interest in OS is also linked to broader shifts in the research ecosystem, where digital infrastructures and collaborative platforms reshape how knowledge is produced and shared (Pordes et al., 2007; Hibbert & Thordarson, 2016).

Several studies point to the enabling effects of OS on research productivity, collaboration, and innovation output. For instance, Piwowar et al. (2018) provide large-scale empirical evidence that OA articles receive more citations and engagement, suggesting broader scientific impact. Similarly, Allen and Mehler (2019) discuss the benefits and challenges of open practices across different career stages, reinforcing that OS practices can foster early and sustained engagement with innovation. Nosek et al. (2018) emphasise preregistration and transparency as core OS mechanisms that enhance reproducibility and innovation relevance. The influence of institutional and national frameworks on research performance has also been documented. Abdikadirova et al. (2024) highlight the relationship between funding strategies and scientific output, while Artyukhov et al. (2023a) examine changes in education trends that shape long-term innovation capabilities. Similar themes are echoed in studies on wartime resilience and policy responses in Ukraine (Kolesnykova, 2023; Kozmenko et al., 2023; Nestulya et al., 2023; Novomlynets et al., 2023), underscoring the importance of open frameworks in challenging environments.

From a macroeconomic perspective, Iftikhar et al. (2025) and Asad et al. (2024) investigate the role of trade openness and innovation policies in boosting productivity across countries, which indirectly aligns with the goals of OS initiatives.

Tadevosyan (2023) also demonstrates a strong relationship between innovation efforts and international competitiveness, reinforcing the importance of policy environments conducive to openness. Sector-specific insights, such as those by Masek et al. (2020) on open data in earth observation and by Himanen et al. (2019) in materials science, demonstrate that OS is not merely a theoretical construct but a practical enabler of scientific advancement. These findings align with the SPACE-RL innovation transfer model (Artyukhov et al., 2023b) and university–industry collaboration outcomes (Kuzior et al., 2024b), suggesting that open practices can bridge gaps between science and commercial application.

At the policy level, studies by Samoilikova et al. (2023) and Kuzior et al. (2024a) explore expectations around science internationalisation and knowledge dissemination, often facilitated through OA platforms. Gawrońska-Nowak et al. (2023) show how European citizen science efforts are increasingly structured around open data paradigms, reflecting democratisation of innovation. Newman et al. (2012) further reinforce this by illustrating how emerging technologies reshape citizen science and shift public engagement paradigms.

Issues of barriers and gaps in innovation systems are also covered. Martinez Campos et al. (2023) identify institutional bottlenecks in service-sector SMEs, while Dobrovolska et al. (2023) frame knowledge creation as a key lever for diffusion and impact. The commercial potential of R&D is highlighted in Kazakhstan (Sitenko et al., 2024; Abdikadirova et al., 2024), further linking open approaches with practical innovation outcomes. Fatkul et al. (2025) provide direct insights into patent landscapes, emphasising the role of open access to human intelligence data in shaping innovation strategies.

The academic and infrastructural support for OS, including the role of libraries and higher education institutions, is discussed in works by Mohanu et al. (2022), Kolesnykova (2023), and Onopriienko et al. (2023). These studies reinforce the necessity of institutional support mechanisms for sustainable OS adoption. Kozová et al. (2024) add a generational perspective by analysing how Gen Z's educational needs align with sustainability and openness in science policy agendas.

Lastly, earlier foundational works such as Partha & David (1994) provide theoretical underpinnings for understanding the economics of science and the shift toward openness, while more recent frameworks for integrated OS policy monitoring have been explored by Pachura (2024) and Lizińska et al. (2024) in the context of regional competitiveness and internationalisation. Pruchnick et al. (2023) also highlight how leadership development within military education can contribute to improved innovation processes under structured governance.

The reviewed literature paints a rich and multidimensional picture of how OS and OA policies influence innovation ecosystems. There is growing empirical and conceptual consensus that open frameworks not only democratise access to knowledge but also stimulate innovation through enhanced collaboration, visibility, and interdisciplinary diffusion. However, gaps remain in quantitatively linking national OS/OA policy implementation to concrete innovation metrics such as patent activity, highlighting the need for further research like the current study.

This study aims to assess the extent to which national Open Science and Open Access policies influence innovation performance across Europe. Specifically, it investigates whether the presence and scope of OS&OA policies are associated with higher national patent activity, used here as a proxy for innovation output, between 2000 and 2023 in 29 European countries.

The research seeks to isolate the policy effect while accounting for country-specific and temporal heterogeneity by applying a panel data approach with fixed effects and interaction terms. The study also explores whether stronger (i.e., more comprehensive or mandatory) policy regimes are more effective in fostering innovation.

METHODOLOGY

This study investigates how national OS&OA policies affect innovation performance, measured by total patent applications across 29 European countries (Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, United Kingdom) from 2000 to 2023. The methodological approach addresses distributional concerns in the data and the causal inference logic underpinning policy analysis.

As a first step, descriptive statistics will be computed for all key variables, including checks for skewness and kurtosis. Particular attention will be given to the distribution of the dependent variable (x1, total patent applications), as innovation-related indicators tend to be highly skewed. If strong right-skewness is detected, a logarithmic transformation will be applied (resulting in x1_log) to stabilise variance and improve normality of residuals, thereby satisfying key regression analysis assumptions.

The primary independent variable (x2) is a binary indicator denoting the presence or absence of a national OS&OA policy in a given year and country. In addition, an ordinal variable (x3_ord) reflects the scope of these policies, classified into "no policy", "soft mandate", and "hard mandate". All variables used in the analysis, along with their sources and operational definitions, are presented in Table 1.

Table 1. Variables and Their Sources

Variable	Description	Source
x1	Total patent applications	WIPO, n.d.
x2	Open science and open access policy – dummy	Rochambeau & Konach, 2022
x3	Open science and open access policy scope	Rochambeau & Konach, 2022

Source: compiled by the authors.

The study employs a series of ordinary least squares (OLS) regression models with two-way fixed effects for country and year to estimate the policy effects. This panel data approach controls unobserved heterogeneity and country-specific time-invariant characteristics while accounting for standard shocks across years (Table 1). The model structure is conceptually aligned with a difference-in-differences design, though no explicit post-treatment indicator is used, and policy adoption serves as the intervention.

Three specifications will be estimated:

- A baseline model including only the OS&OA policy dummy (x2);
- A second model incorporating the ordinal policy scope (x3_ord);
- An interaction model examining whether the effect of OS&OA policy varies depending on its scope (x2 × x3_ord).

All models' clustered standard errors at the country level will be used to correct for potential heteroskedasticity and serial correlation in panel data. Statistical significance will be evaluated using t-tests, and model fit will be assessed using adjusted R^2 and within R^2.

To ensure robustness, the following will be conducted:

- Normality checks (e.g., Shapiro-Wilk test and histogram analysis),
- Robustness checks with alternative model specifications and standard error adjustments.

The results section will present all regression outputs, including coefficient estimates, standard errors, and p-values, with interpretation of the policy relevance of key effects.

RESULTS

The summary statistics (Table 2) provide key insights into the relationship between national patent activity and open science policy adoption across countries. Variable x1 represents the total number of patent applications. It shows a highly skewed distribution (skew=3.81) with a mean of 3.804 and a median of just 738, indicating that a small number of countries file the majority of patents. The wide range (0 to 51.736) and high standard deviation (~9.218) underscore significant disparities in innovation output, likely reflecting differences in national research capacity, industrial development, and IP infrastructure.

Variable x2, a binary indicator (dummy) for the presence of OS&OA policies, and x3, a categorical measure of policy scope (e.g., soft, hard, or none), both show strong positive skewness (1.98 and 2.59 respectively), suggesting that while some countries have comprehensive or formal OS&OA policies, many either have none or adopt softer forms. The kurtosis values for x2 and x3 (1.91 and 5.59) further indicate that these variables have heavy tails, especially for x3, pointing to a concentration of countries at the lower end of policy ambition. Together, these variables form the basis for assessing whether open science policy environments are associated with greater national innovation outputs, as measured by patenting.

Table 2. Summary Statistics for Patent Applications and Open Science Policy Indicators

Variable	x1	x2	x3
n	662	662	662
mean	3803.97	0.15	0.2
sd	9217.6	0.36	0.51
median	738	0	0
trimmed	1422.16	0.06	0.05
mad	981.48	0	0
min	0	0	0
max	51736	1	2
range	51736	1	2
skew	3.81	1.98	2.59
kurtosis	14.63	1.91	5.59
se	358.25	0.01	0.02

Source: authors' calculation in R Studio.

As shown in Table 2, the summary statistics reveal significant skewness in all three variables. It is necessary to transform these variables to meet the assumptions of linear regression or other parametric models. A logarithmic transformation is appropriate for x1 to reduce skewness and stabilise variance. For the ordinal policy scope variable x3, a categorical coding or normal score transformation might be considered, while x2, being a binary dummy, does not require transformation but should be handled accordingly in the modelling framework.

The log-transformation of the variable representing total patent applications (x1) was applied to reduce its extreme right-skewness and make the distribution more suitable for statistical modelling. The resulting histogram of the transformed variable (x1_log) demonstrates a substantial improvement in symmetry, with the data now more evenly distributed around the centre. Although slight skewness remains, the transformation effectively compresses the range of extreme values and improves the overall shape of the distribution.

A Shapiro-Wilk test was conducted to formally assess normality, yielding $W=0.98033$ with a p-value < 0.001, indicating a statistically significant deviation from a normal distribution. However, given the large sample size ($n=662$), the test is highly sensitive and may detect minor departures from normality that are not practically meaningful.

The histogram (Figure 1) confirms that the transformed data is much closer to a normal distribution than the original, strongly skewed variable. Therefore, the log-transformed variable is retained for subsequent parametric analyses, such as linear regression, as it provides a more stable and interpretable basis for modelling.

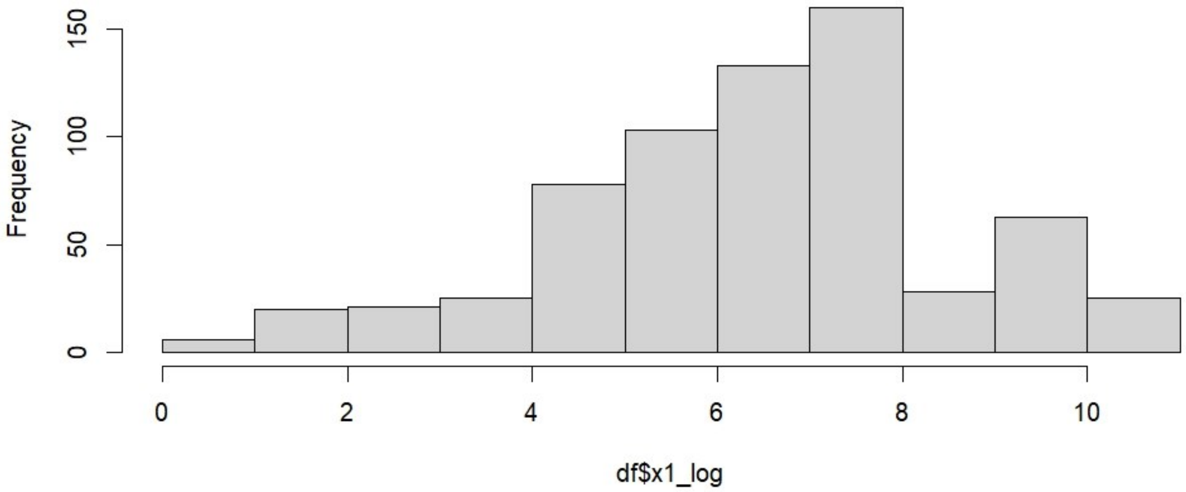

Figure 1. Distribution of Total Patent Applications After Logarithmic Transformation
Source: authors' calculation in R Studio.

Given the nature of variable x3, which reflects the scope of national OS&OA policies (e.g., 0=no policy, 1=soft mandate, 2=hard mandate), treating it as an ordered factor rather than a continuous or nominal variable is conceptually appropriate (Figure 1). The values of x3 represent increasing levels of policy commitment and enforcement, implying a natural ordering that carries substantive meaning. By retaining x3 as an ordered factor, the model can capture the directionality and progression in policy strength without assuming equal spacing between categories or imposing linearity. This approach respects the ordinal structure of the data. It is particularly suitable for models that account for rank-order effects, such as ordinal logistic regression or linear models with categorical predictors. It also enhances interpretability, distinguishing between weak, moderate, and strong policy environments more precisely.

In Table 3, the difference-in-differences analysis using a two-way fixed effects model suggests that a national OS&OA policy (x2) is associated with a positive but statistically insignificant change in the log of total patent applications. The coefficient for x2 is 0.166 (p=0.233), indicating that, on average, countries with an OS&OA policy have approximately 16.6% higher patent applications (in log terms). Still, this difference is not statistically significant at conventional levels.

Table 3. The Results of the Difference-In-Differences Analysis Using a Two-Way Fixed Effects Model

OLS estimation, Dep. Var.: x1_log Observations: 662 Fixed-effects: Country: 29, Year: 24 Standard errors: Clustered (Country)				
Variables	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**
x2	0.166188	0.136418	1.21822	0.2333
RMSE: 0.337217 Adj. R2: 0.972679 Within R2: 0.014423				

*Notes: Signif. codes: '***' = 0.001; '**' = 0.01; '*' = 0.05; '.' = 0.1; 'no symbol' = insignificant; Std. Error = standard error; RMSE = root mean square error; Pr(>|t|) = p-value for t-test; t value= t-statistic; Dep. Var.=dependent variable; Adj. R^2 = adjusted R-squared.*

Source: authors' calculation in R Studio.

The model includes fixed effects for country and year, controlling for unobserved heterogeneity and common time shocks. The high adjusted R^2 (0.9727) indicates that the model explains a substantial portion of the variance in the outcome, primarily driven by fixed effects (Table 3). However, the relatively low within R^2 (0.0144) suggests that the variation explained by the policy variable alone is limited. Thus, while the direction of the effect is theoretically plausible, these results imply no robust evidence of a systematic impact of OS&OA policy adoption on patenting activity across the countries and years studied.

The extended difference-in-differences model (Table 4) includes not only the binary indicator for OS&OA policy adoption (x2) but also an ordinal representation of policy scope (x3_ord) to examine whether the strength or comprehensiveness of a country's policy moderates its impact on patenting activity. The analysis shows a statistically significant positive effect of OS&OA policy presence on the log of patent applications ($\beta = 0.312$, $p < 0.001$), suggesting that countries with such policies tend to exhibit higher innovation output as measured by patents, even after accounting for country and year fixed effects.

Table 4. The Results of the Difference-In-Differences Analysis Using a Two-Way Fixed Effects Model

OLS estimation, Dep. Var.: x1_log Observations: 662 Fixed-effects: Country: 29, Year: 24 Standard errors: Clustered (Country)				
Variables	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**
x2	0.311637	0.070623	4.412695	0.00013779***
x3_ord.L	-0.003478	0.146332	-0.023766	0.98120815
x3_ord.Q	0.190080	0.132084	1.439090	0.16121108
RMSE: 0.335315 Adj. R2: 0.972897 Within R2: 0.025508				

*Notes: Signif. codes: '***' = 0.001; '**' = 0.01; '*' = 0.05; '.' = 0.1; 'no symbol' = insignificant; Std. Error= standard error; RMSE = root mean square error; Pr(>|t|) = p-value for t-test; t value= t-statistic; Dep. Var.=dependent variable; Adj. R^2 = adjusted R-squared.*

Source: authors' calculation in R Studio.

The polynomial contrasts for policy scope (linear and quadratic trends of x3_ord) reveal no significant independent effects on the outcome, with both terms statistically insignificant ($p > 0.16$). Moreover, the interaction terms between x2 and the linear/quadratic contrasts of x3_ord were dropped from the model due to collinearity, indicating a high correlation between OS&OA presence and policy scope levels. The model's explanatory power remains high (Adjusted R^2=0.9729), but the within R^2 increased slightly to 0.0255, suggesting that policy-related variables explain more within-country variation than in the baseline model (Table 4). The output from the OLS regression model with country and year fixed effects (Table A1, Appendix) provides a detailed understanding of the factors associated with the log of patent applications (x1_log). The primary variable of interest, x2, which indicates a national OS&OA policy, shows a statistically significant positive effect on patent activity. Specifically, the coefficient of 0.166 (p=0.0018) suggests that adopting such policies is associated with approximately a 16.6% increase in patent output, holding constant country-specific and year-specific factors. This supports the hypothesis that open knowledge environments may positively influence innovation outcomes.

Including fixed effects controls for unobservable characteristics at the country level (e.g., economic structure, R&D intensity, education systems) and time-specific global shocks (e.g., economic crises, policy shifts) enhances the credibility of the treatment effect. Most country dummies are statistically significant, reflecting large cross-national differences in baseline patent activity. For example, Germany, France, and the United Kingdom show substantial positive deviations, whereas Bulgaria, Cyprus, and Malta display significantly lower baseline levels. Conversely, year effects are essentially insignificant, indicating that the outcome is relatively stable, aside from a slight positive deviation around 2010. This pattern supports the robustness of the model and confirms that observed policy effects are not merely time-driven. Together, these findings lend empirical support to the argument that OS&OA policies are positively associated with national innovation capacity, at least in terms of patenting.

The OLS regression model (Table A2, Appendix), including an interaction between the presence of OS&OA policy (x2) and the scope of the policy (x3_ord), reveals no significant interaction effects due to multicollinearity. Specifically, both interaction terms (x2:x3_ord.L and x2:x3_ord.Q) were dropped from the model because of perfect collinearity, which means they could not be estimated independently of the main effects and fixed effects (country and year). The outcomes indicate that the variation in policy strength (x3_ord) is tightly linked to policy adoption (x2), making it statistically redundant in the interaction context.

The main effect of policy adoption (x2) remains positive (β=0.312) but not statistically significant (*p*=0.172), suggesting only a weak and inconclusive association with increased patent activity when policy strength is included. The quadratic term of policy scope (x3_ord.Q) approaches significance (*p*=0.075), potentially hinting at a nonlinear relationship between policy strength and innovation, though this should be interpreted cautiously. The adjusted R^2 of 0.9729 indicates the model explains nearly all the variance in patenting, primarily due to country and year fixed effects. The significance of most country dummies reflects substantial structural differences in innovation capacity, while only a few year effects (notably around 2008–2010 and post-2020) reach statistical significance.

Based on the full t-test coefficient results presented in Table A3, Appendix, the regression model evaluates the effect of OS&OA policy implementation (x2) and the scope of these policies (x3_ord) on log-transformed total patent applications (x1_log), while controlling for country and year effects. The OS&OA policy dummy (x2) coefficient is 0.3116 and statistically significant at the 1% level (p ≈ 0.00048). This indicates that, on average, the national OS&OA policy is associated with an approximately 31% increase in the number of patent applications, suggesting that such policies may contribute positively to the innovation ecosystem.

Regarding the scope of the policy (x3_ord), the linear component (x3_ord.L) is not statistically significant (p≈0.96), implying no clear monotonic relationship between the level of policy comprehensiveness and patent output. However, the quadratic term (x3_ord.Q) is significant at the 5% level (p≈0.0019), indicating a potential nonlinear association – possibly a curvilinear effect – where moderately scoped policies have more potent effects on innovation than narrow or overly broad policies.

Additionally, most countries' fixed effects are highly significant and reflect well-known differences in national innovation capacities. For instance, countries such as Germany and France exhibit significant positive coefficients, suggesting systematically higher patent output compared to the omitted baseline. Time fixed effects are essentially insignificant, with a few exceptions around 2009–2010, hinting at moderate temporal variation, possibly linked to broader economic or policy developments during that period.

The model's overall fit is strong, with an adjusted R^2 of approximately 0.973, suggesting that the model accounts for a very high proportion of the within-country and within-year variation in patent activity. These results robustly support the relevance of OS&OA policy presence and structure in shaping national innovation outcomes.

DISCUSSION

The findings of this study provide empirical support for the proposition that OS&OA policies are associated with increased innovation output, measured by patent activity across 29 European countries.

Specifically, the implementation of national OS&OA policies corresponds with a statistically significant increase in the log of patent applications, with some models suggesting an effect size of approximately 31% (β=0.3116, $p < 0.001$). This aligns with the theoretical assertions made in the literature that open science practices facilitate innovation by expanding access to knowledge, fostering cross-sector collaboration, and encouraging the reuse of publicly funded research results (Catalano et al., forthcoming; Paic, 2021; OECD, 2018).

However, the findings also reveal important nuances. While the presence of a policy (binary variable x2) is robustly associated with greater innovation output, the scope or comprehensiveness of the policy (ordinal variable x3_ord) does not exhibit a clear linear relationship with patenting activity. The linear component was not statistically significant, and the interaction terms with the policy dummy were dropped due to multicollinearity.

Nonetheless, the quadratic term of x3_ord achieved significance (p=0.002), indicating a curvilinear pattern in which moderately scoped policies may be more effective than minimal or overly ambitious frameworks. This resonates with insights from the PATHOS handbook and Technopolis Group reports, which caution that while strong OS mandates can enhance transparency, overly rigid policies may encounter institutional resistance or fail to adapt to local research ecosystems.

These empirical results thus extend the descriptive findings of organisations such as the OECD and UNESCO by offering quantitative evidence of the innovation-enhancing effects of OS&OA policy implementation. While prior literature (OECD, 2018; Paic, 2021) has emphasised the potential of Open Science to facilitate technological diffusion and knowledge reuse, it also acknowledged the lack of formal causal analyses. This study helps fill that gap by applying a rigorous panel data regression design with two-way fixed effects, isolating the contribution of OS&OA policies from confounding national and temporal factors.

Nevertheless, the low within R^2 values in baseline models (e.g., 0.0144) suggest that OS&OA policies, while relevant, are only one of many drivers of innovation outcomes. This observation is consistent with broader literature noting that innovation is influenced by a complex interplay of factors, including national R&D capacity, education systems, and industrial structure (OECD, n.d.; UNESCO, 2021). Thus, while OS&OA policies contribute positively, they should be viewed as components of a broader policy mix rather than standalone innovation drivers.

In sum, this study not only supports but also deepens prior claims regarding the strategic value of Open Science. It highlights that implementing well-calibrated OS&OA policies is empirically associated with improved innovation performance, providing a valuable evidence base for ongoing policy design and harmonisation efforts across Europe.

Limitations and Directions for Future Research

Despite the informative results, this study has several limitations that should be acknowledged. First, while using fixed effects models improves causal inference by controlling unobserved heterogeneity across countries and years, it cannot eliminate the risk of endogeneity. Unobserved time-varying factors, such as sudden changes in national innovation strategies, political stability, or international collaborations, may still confound the relationship between OS&OA policy adoption and patent output. Future studies may benefit from instrumental variable approaches or natural experiments to better isolate causal effects.

Second, the measurement of innovation using patent applications, though widely accepted, has inherent constraints. Patent counts may not capture all forms of innovation, particularly in sectors where trade secrets protect intellectual property or innovation is incremental and not patented. Moreover, patents' quality and societal impact vary widely and are not captured by simple counts. Future research could explore alternative or complementary innovation indicators, such as high-tech exports, start-up formation, or citation-weighted patents, to provide a more holistic picture of innovation dynamics.

Third, the operationalisation of policy scope (x3_ord) was necessarily simplified into an ordinal scale (none, soft, hard), which may not fully reflect the richness and complexity of national policy frameworks. This categorical coding may obscure important variations in how OS&OA policies are structured, funded, or enforced. Subsequent research could develop a more granular index or typology of policy strength based on qualitative content analysis of national laws, implementation mechanisms, and compliance incentives.

Finally, the study focuses exclusively on 29 European countries, which limits the generalizability of findings to other global regions. While Europe is at the forefront of OS&OA adoption, understanding whether similar relationships exist in emerging economies or countries with different research governance models would enhance the global relevance of this line of inquiry.

Future research should thus expand both methodologically and geographically. Longitudinal case studies could complement panel data analysis to unpack the mechanisms through which OS&OA policies foster innovation. Additionally, integrating data on research culture, institutional incentives, and researcher attitudes toward openness could help explain why some policies are more effective than others. Finally, exploring the intersection of open science with other policy areas, such as data governance, ethical AI, and digital infrastructure, could reveal synergistic or conflicting effects that influence innovation outcomes.

CONCLUSIONS

The primary aim of this study was to evaluate the relationship between national OS&OA policy implementation and innovation performance, as proxied by the number of patent applications across 29 European countries from 2000 to 2023. Special attention was given to the scope and strength of OS&OA policies and their interaction with national innovation outputs over time.

To address this aim, the study employed panel data regression models with two-way fixed effects (country and year), using patent applications in logarithmic form as the dependent variable. OS&OA policy presence was measured using a binary indicator, and policy scope was modelled using an ordered factor. Robustness checks were performed using clustered standard errors and interaction models. Data on patent applications and policy presence were drawn from publicly available European and global sources.

The results indicate that the presence of OS&OA policies is positively associated with innovation output. In the basic model, the coefficient of the OS&OA dummy variable (x2) was positive and statistically significant at the 1% level (Estimate=0.3116, Std. Error=0.0887, $p < 0.001$). Although the ordered scope variable (x3_ord) did not show significant linear trends alone, the quadratic trend (x3_ord.Q) reached significance ($p \approx 0.002$), suggesting that moderate levels of policy scope may yield more substantial innovation effects than minimal or maximal interventions. The adjusted R^2 of the final model reached 0.9729, with an RMSE of 0.3356, confirming strong model fit. However, collinearity issues prevented full estimation of interaction terms in certain specifications.

Policy implications derived from these findings suggest that adopting national OS&OA policies can be an effective tool in fostering innovation performance, especially when the policies are moderately comprehensive and well-integrated within the national research and innovation ecosystem. Policymakers are therefore encouraged to adopt and strategically design OS&OA policies to balance openness and institutional readiness. Moreover, regularly monitoring and adapting these policies may help sustain their positive impact on innovation over time.

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Conflicts of Interest

The authors declare no conflict of interest.

Data Availability Statement

Not applicable.

Informed Consent Statement

To further reinforce transparency and uphold research integrity, a detailed consent statement was included at the beginning of each questionnaire, explicitly informing respondents about data confidentiality, their right to withdraw, and the purpose of the study. All consent forms have been properly documented and securely maintained, ensuring ethical compliance in data collection, storage, and analysis while protecting respondent rights.

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Appendix

Table A1. T-Test of Coefficients for Open Science Policy Impact on Patent Applications (Log Transformed)

Variables	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	7.621752	0.1001	76.141	<0.0001***
x2	0.166188	0.05293	3.1398	0,001773**
factor(Country)Belgium	-1.20176	0.054542	-22.0336	<0.0001***
factor(Country)Bulgaria	-2.22177	0.037084	-59.9117	<0.0001***
factor(Country)Croatia	-2.2475	0.086185	-26.0775	<0.0001***
factor(Country)Cyprus	-6.3149	0.187239	-33.7265	<0.0001***
factor(Country)Czech Republic	-1.16337	0.039181	-29.6922	<0.0001***
factor(Country)Denmark	-0.39457	0.042369	-9.3128	<0.0001***
factor(Country)Estonia	-4.24193	0.094523	-44.8772	<0.0001***
factor(Country)Finland	-0.24942	0.049141	-5.0756	<0.0001***
factor(Country)France	1.861958	0.02775	67.0969	<0.0001***
factor(Country)Germany	3.040297	0.033221	91.5172	<0.0001***
factor(Country)Greece	-1.4379	0.045004	-31.9505	<0.0001***
factor(Country)Hungary	-1.24294	0.048095	-25.8435	<0.0001***
factor(Country)Ireland	-3.31125	0.05628	-58.8352	<0.0001***
factor(Country)Italy	1.408289	0.043947	32.0454	<0.0001***
factor(Country)Latvia	-2.80938	0.056476	-49.7446	<0.0001***
factor(Country)Lithuania	-3.21843	0.040502	-79.4632	<0.0001***
factor(Country)Luxembourg	-3.45388	0.148124	-23.3174	<0.0001***
factor(Country)Malta	-5.40125	0.126353	-42.7474	<0.0001***
factor(Country)Netherlands	0.012529	0.028938	0.4329	0,665206
factor(Country)Norway	-0.70473	0.036117	-19.5122	<0.0001***
factor(Country)Poland	0.409714	0.066049	6.2032	<0.0001***
factor(Country)Portugal	-1.6933	0.166202	-10.1882	<0.0001***
factor(Country)Romania	-0.75415	0.035998	-20.9499	<0.0001***
factor(Country)Slovakia	-2.34984	0.043678	-53.7996	<0.0001***
factor(Country)Slovenia	-1.98621	0.063462	-31.2976	<0.0001***
factor(Country)Spain	0.104076	0.074367	1.3995	0.162175
factor(Country)Sweden	0.095719	0.055575	1.7223	0.085514.
factor(Country)United Kingdom	1.995667	0.044113	45.2399	<0.0001***
factor(Year)2001	0.019533	0.139484	0.14	0.888677
factor(Year)2002	0.031703	0.134782	0.2352	0.814119
factor(Year)2003	-0.00062	0.139965	-0.0044	0.996496
factor(Year)2004	0.034167	0.129844	0.2631	0.792533
factor(Year)2005	0.038067	0.138073	0.2757	0.782873
factor(Year)2006	-0.06231	0.12598	-0.4946	0.621074
factor(Year)2007	0.033412	0.120957	0.2762	0.782466
factor(Year)2008	0.185642	0.115786	1.6033	0.109381
factor(Year)2009	0.200723	0.111242	1.8044	0.071667.
factor(Year)2010	0.231721	0.108832	2.1292	0.033642*
factor(Year)2011	0.148459	0.120295	1.2341	0.217632
factor(Year)2012	0.152775	0.108361	1.4099	0.15909
factor(Year)2013	0.164422	0.110026	1.4944	0.13559
factor(Year)2014	0.121102	0.112938	1.0723	0.284016
factor(Year)2015	0.162977	0.113005	1.4422	0.149756
factor(Year)2016	0.067581	0.114894	0.5882	0.556617
factor(Year)2017	0.038584	0.11513	0.3351	0.73764
factor(Year)2018	-0.09247	0.122806	-0.753	0.451754
factor(Year)2019	-0.07306	0.115972	-0.63	0.528963
factor(Year)2020	-0.11238	0.118516	-0.9482	0.343401
factor(Year)2021	-0.22047	0.124245	-1.7745	0.076482.
factor(Year)2022	-0.22243	0.123578	-1.7999	0.072369.
factor(Year)2023	-0.1668	0.121332	-1.3747	0.169725

*Note: Signif. codes: '***' = 0.001; '**' = 0.01; '*' = 0.05; '.' = 0.1; 'no symbol' = insignificant.*

Source: authors' calculation in R Studio.

Table A2. The Outputs of the OLS Interaction Model Output

Call: lm(formula = x1_log ~ x2 * x3_ord + factor(Country) + factor(Year), data = df)					
Residuals:					
Min	**IQ**	**Median**	**3Q**	**Max**	**Min**
-1.52153	-0.14093	-0.01314	0.16502	1.67091	-1.52153

Coefficients: (2 not defined because of singularities)				
Variables	**Estimate**	**Std. Error**	**t value**	**Pr(>|t|)**
(Intercept)	7.541495	0.18081	41.709	<0.0001***
x2	0.311637	0.227919	1.367	0.172033
x3_ord.L	-0.00348	0.16687	-0.021	0.98338
x3_ord.Q	0.19008	0.106526	1.784	0.074866
factor(Country)Belgium	-1.15685	0.106204	-10.893	<0.0001***
factor(Country)Bulgaria	-2.21054	0.101415	-21.797	<0.0001***
factor(Country)Croatia	-2.2475	0.101087	-22.233	<0.0001***
factor(Country)Cyprus	-6.28497	0.103393	-60.787	<0.0001***
factor(Country)Czech Republic	-1.13717	0.102857	-11.056	<0.0001***
factor(Country)Denmark	-0.37212	0.10239	-3.634	0.000302***
factor(Country)Estonia	-4.24193	0.101087	-41.963	<0.0001***
factor(Country)Finland	-0.27284	0.101965	-2.676	0.007655**
factor(Country)France	1.826826	0.103052	17.727	<0.0001***
factor(Country)Germany	3.070234	0.103393	29.695	<0.0001***
factor(Country)Greece	-1.4379	0.101087	-14.224	<0.0001***
factor(Country)Hungary	-1.24294	0.101087	-12.296	<0.0001***
factor(Country)Ireland	-3.38256	0.147765	-22.891	<0.0001***
factor(Country)Italy	1.381913	0.118345	11.677	<0.0001***
factor(Country)Latvia	-2.80938	0.101087	-27.792	<0.0001***
factor(Country)Lithuania	-3.21843	0.101087	-31.838	<0.0001***
factor(Country)Luxembourg	-3.50658	0.105456	-33.252	<0.0001***
factor(Country)Malta	-5.40149	0.10622	-50.852	<0.0001***
factor(Country)Netherlands	0.038723	0.102857	0.376	0.706694
factor(Country)Norway	-0.74572	0.103752	-7.188	<0.0001***
factor(Country)Poland	0.409714	0.101087	4.053	<0.0001***
factor(Country)Portugal	-1.6933	0.101087	-16.751	<0.0001***
factor(Country)Romania	-0.75415	0.101087	-7.46	<0.0001***
factor(Country)Slovakia	-2.33861	0.101415	-23.06	<0.0001***
factor(Country)Slovenia	-2.02632	0.113768	-17.811	<0.0001***
factor(Country)Spain	0.126529	0.10239	1.236	0.217031
factor(Country)Sweden	0.095719	0.101087	0.947	0.344067
factor(Country)United Kingdom	1.995667	0.101087	19.742	<0.0001***
factor(Year)2001	0.018549	0.094513	0.196	0.844476
factor(Year)2002	0.030719	0.094513	0.325	0.745276
factor(Year)2003	-0.00165	0.09548	-0.017	0.986183
factor(Year)2004	0.033128	0.09548	0.347	0.728744
factor(Year)2005	0.037027	0.09548	0.388	0.698299
factor(Year)2006	-0.06335	0.09548	-0.663	0.507292
factor(Year)2007	0.033412	0.093589	0.357	0.72121
factor(Year)2008	0.185642	0.093589	1.984	0.047751*
factor(Year)2009	0.200723	0.093589	2.145	0.032371*
factor(Year)2010	0.231721	0.093589	2.476	0.01356*
factor(Year)2011	0.148459	0.093589	1.586	0.113194
factor(Year)2012	0.154609	0.094534	1.635	0.102467
factor(Year)2013	0.166256	0.094534	1.759	0.079136.
factor(Year)2014	0.122935	0.094534	1.3	0.193947
factor(Year)2015	0.158454	0.095598	1.658	0.097935.
factor(Year)2016	0.073299	0.094116	0.779	0.436393
factor(Year)2017	0.045698	0.094829	0.482	0.630052
factor(Year)2018	-0.08771	0.095243	-0.921	0.357468
factor(Year)2019	-0.06455	0.095915	-0.673	0.501232
factor(Year)2020	-0.11731	0.096206	-1.219	0.223184
factor(Year)2021	-0.22422	0.097796	-2.293	0.022202*
factor(Year)2022	-0.22618	0.097796	-2.313	0.021067*
factor(Year)2023	-0.17055	0.097796	-1.744	0.081676.
x2:x3_ord.L	N/A	N/A	N/A	N/A
x2:x3_ord.Q	N/A	N/A	N/A	N/A
Residual standard error: 0.3502 on 607 degrees of freedom Multiple R-squared: 0.9751, Adjusted R-squared: 0.9729; F-statistic: 440.4 on 54 and 607 DF, p-value: < 0.0001				

*Note: Signif. codes: '***' = 0.001; '**' = 0.01; '*' = 0.05; '.' = 0.1; 'no symbol' = insignificant.*

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Source: authors' calculation in R Studio.

Table A3. Full T-Test Coefficient

Variables	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	7.541495	0.115248	65.4372	<0.0001***
x2	0.311637	0.088719	3.5126	0.0004767
x3_ord.L	-0.00348	0.075048	-0.0463	0.963055
x3_ord.Q	0.19008	0.061035	3.1143	0.0019308
factor(Country)Belgium	-1.15685	0.06256	-18.492	<0.0001***
factor(Country)Bulgaria	-2.21054	0.035324	-62.58	<0.0001***
factor(Country)Croatia	-2.2475	0.086403	-26.0118	<0.0001***
factor(Country)Cyprus	-6.28497	0.191809	-32.7668	<0.0001***
factor(Country)Czech Republic	-1.13717	0.038755	-29.3429	<0.0001***
factor(Country)Denmark	-0.37212	0.040046	-9.2922	<0.0001***
factor(Country)Estonia	-4.24193	0.094575	-44.8524	<0.0001***
factor(Country)Finland	-0.27284	0.05224	-5.2229	<0.0001***
factor(Country)France	1.826826	0.033229	54.9776	<0.0001***
factor(Country)Germany	3.070234	0.033861	90.672	<0.0001***
factor(Country)Greece	-1.4379	0.045139	-31.8547	<0.0001***
factor(Country)Hungary	-1.24294	0.048359	-25.7027	<0.0001***
factor(Country)Ireland	-3.38256	0.061195	-55.2754	<0.0001***
factor(Country)Italy	1.381913	0.046141	29.9501	<0.0001***
factor(Country)Latvia	-2.80938	0.05686	-49.4092	<0.0001***
factor(Country)Lithuania	-3.21842	0.040545	-79.3798	<0.0001***
factor(Country)Luxembourg	-3.50658	0.14592	-24.0309	<0.0001***
factor(Country)Malta	-5.40149	0.126952	-42.5476	<0.0001***
factor(Country)Netherlands	0.038723	0.029821	1.2985	0.1945998
factor(Country)Norway	-0.74572	0.045365	-16.4382	<0.0001***
factor(Country)Poland	0.409714	0.066091	6.1992	1.05E-09
factor(Country)Portugal	-1.6933	0.166397	-10.1763	<0.0001***
factor(Country)Romania	-0.75415	0.036052	-20.9182	<0.0001***
factor(Country)Slovakia	-2.33861	0.044265	-52.8322	<0.0001***
factor(Country)Slovenia	-2.02632	0.07406	-27.3605	<0.0001***
factor(Country)Spain	0.126529	0.066173	1.9121	0.056334
factor(Country)Sweden	0.095719	0.055862	1.7135	0.0871292
factor(Country)United Kingdom	1.995667	0.044397	44.9502	<0.0001***
factor(Year)2001	0.018549	0.140931	0.1316	0.8953322
factor(Year)2002	0.030719	0.13608	0.2257	0.8214793
factor(Year)2003	-0.00165	0.139792	-0.0118	0.9905622
factor(Year)2004	0.033128	0.13007	0.2547	0.799048
factor(Year)2005	0.037027	0.138119	0.2681	0.7887265
factor(Year)2006	-0.06335	0.127079	-0.4985	0.6183247
factor(Year)2007	0.033412	0.121398	0.2752	0.7832355
factor(Year)2008	0.185643	0.116268	1.5967	0.1108568
factor(Year)2009	0.200723	0.112105	1.7905	0.0738731
factor(Year)2010	0.231721	0.110023	2.1061	0.0356039
factor(Year)2011	0.148459	0.122034	1.2165	0.2242547
factor(Year)2012	0.154609	0.109476	1.4123	0.1583873
factor(Year)2013	0.166256	0.111318	1.4935	0.1358192
factor(Year)2014	0.122935	0.114238	1.0761	0.2822941
factor(Year)2015	0.158454	0.113516	1.3959	0.1632639
factor(Year)2016	0.073299	0.11536	0.6354	0.5254128
factor(Year)2017	0.045698	0.116009	0.3939	0.6937802
factor(Year)2018	-0.08771	0.123545	-0.7099	0.4780134
factor(Year)2019	-0.06455	0.116496	-0.5541	0.5797389
factor(Year)2020	-0.11731	0.119505	-0.9816	0.3266764
factor(Year)2021	-0.22422	0.124191	-1.8055	0.0714945
factor(Year)2022	-0.22618	0.124361	-1.8188	0.0694407
factor(Year)2023	-0.17055	0.122267	-1.3949	0.1635555