“Public energy RD&D and green entrepreneurship: Cross-country evidence on energy and green start-ups and venture financing”

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| **AUTHORS** | Maksym W. Sitnicki<br>Serhiy Lyeonov<br>Dmytro Kurinskyi<br>Serhiy Podosynnikov |
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**Maksym W. Sitnicki** (The United States of America, Poland, Ukraine),
**Serhiy Lyeonov** (Poland, Ukraine), **Dmytro Kurinskyi** (Ukraine, The Republic of Singapore),
**Serhiy Podosynnikov** (Ukraine)

# PUBLIC ENERGY RD&D AND GREEN ENTREPRENEURSHIP: CROSS-COUNTRY EVIDENCE ON ENERGY AND GREEN START-UPS AND VENTURE FINANCING

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Maksym W. Sitnicki, DSc. (Econ.), Dr Hab (Management), Professor, Fulbright Scholar at John Chambers College of Business and Economics, West Virginia University, The United States of America; Professor at School of Business, VIZJA University, Poland; Professor at Management of Innovation and Investment Activities Department, Taras Shevchenko National University of Kyiv, Ukraine.

Serhiy Lyeonov, DSc. (Finance), Dr Hab (Finance), Professor, Department of Applied Social Sciences, Faculty of Organisation and Management, Silesian University of Technology, Poland; Economic Cybernetic Department, Sumy State University, Ukraine. (Corresponding author)

Dmytro Kurinskyi, Ph.D. in Management, Junior Research Fellow of Scientific Research Part, Sumy National Agrarian University, Ukraine; Advisor of Strategic Management Department, Selkat Holding in Singapore, The Republic of Singapore.

Serhiy Podosynnikov, Ph.D. Student, Department of Financial Technologies and Entrepreneurship, Sumy State University, Ukraine.



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## Abstract

The transition toward low-carbon energy systems is increasingly viewed not only as an environmental necessity but also as a driver of innovation, competitiveness, and entrepreneurial development in modern economies. This study investigates how public energy research, development, and demonstration (RD&D) expenditures are associated with annual energy and green start-up counts, as well as with the availability of venture financing for clean-technology entrepreneurship across countries. The empirical analysis is based on a panel dataset covering 23 countries over the period 2000–2023 (470 country-year observations). It applies Poisson and negative binomial fixed-effects models, distributed lag specifications, fixed-effects OLS, and Gamma PML and PPML estimators. The results indicate that public RD&D spending does not have a statistically significant immediate effect on the number of green start-ups, as the Poisson FE estimates for renewable RD&D (0.034) and storage RD&D (0.011) remain insignificant. The venture-funding models show positive, though only weakly significant, coefficients for renewable-energy RD&D, with values of 1.41 for early-stage funding and 1.56 for later-stage funding, suggesting a possible association between public research activity and venture financing. Robustness checks indicate that low-carbon RD&D is positively associated with later-stage venture financing in selected model specifications, with a PPML coefficient of 1.77. The findings suggest that public RD&D is not a standalone driver of annual energy and green start-up counts and may be related to selected venture-financing outcomes, particularly in later-stage funding models, such as the scaling and commercialization of green innovation.

**Keywords** public energy RD&D, green entrepreneurship, clean technology start-ups, venture capital financing, innovation policy, energy transition

**JEL Classification** Q42, G24, L26, O32

## INTRODUCTION

The relevance of research dedicated to green entrepreneurship has increased markedly in recent years, as the green transition in Europe is increasingly framed not only as an environmental challenge but also as a matter of competitiveness, innovation capacity, technological sovereignty, and long-term economic resilience. Green start-ups and clean-technology ventures are increasingly expected to contribute to decarburization, industrial renewal, job creation, and the commercialization of new energy solutions. In this context, public energy research, development and demonstration (RD&D) expenditures represent an important policy instrument because they support knowledge creation, technological experimentation, and the development of innovation capacities in energy systems.

This issue is particularly relevant for the European Union, where start-ups, scale-ups, and innovation ecosystems occupy a central place in current policy strategies. The European Commission's EU Startup and Scaleup Strategy positions start-ups and scale-ups as important actors in Europe's future growth model. At the same time, Horizon Europe, with an indicative budget of EUR 93.5 billion for 2021–2027, supports research, innovation, and connected innovation ecosystems across the Union (European Commission, 2025). These initiatives show that the EU increasingly treats innovation-based entrepreneurship as a key mechanism for strengthening competitiveness and accelerating the green transition.

The EU also increasingly links public research funding with university–enterprise collaboration, technology transfer, and commercialization. This is visible in instruments such as the European Institute of Innovation and Technology, which supports innovation ecosystems connecting universities, firms, investors, and entrepreneurs in strategic sectors, including climate and energy (EIT, n.d.). The OECD also emphasizes that university–industry collaboration, knowledge transfer, co-creation, and entrepreneurship support are important mechanisms through which public research can generate broader socio-economic impact (OECD, 2019). These policy priorities indicate that public RD&D should be analyzed not only as a source of scientific knowledge but also as a possible element of wider entrepreneurial and financing ecosystems.

From an international perspective, the topic is equally important because green entrepreneurship and innovation finance are increasingly treated as components of sustainable private-sector development and green competitiveness. The World Bank underlines the role of innovative firms, private-sector development, and green competitiveness in supporting productivity growth, structural transformation, and the commercialization of new technologies (World Bank, 2025). This is especially relevant in the energy sector, where technologies are often capital-intensive, commercialization cycles are long, and private investors may hesitate in the absence of credible public support signals.

Despite extensive research on entrepreneurial ecosystems, venture capital, innovation policy, university–industry collaboration, and sustainable entrepreneurship, there is limited empirical evidence on how public energy RD&D expenditures are associated with entrepreneurial outcomes. Existing studies typically analyze financing conditions, ecosystem characteristics, regulatory barriers, or innovation policies separately. Considerably less attention has been devoted to whether public energy RD&D is associated with annual start-up activity and venture financing across different stages of venture development and across different energy technology domains.

Therefore, analyzing how public energy RD&D expenditures are associated with annual energy and green start-up counts, as well as venture financing, is both policy-relevant and academically important. The study examines whether public research investments are associated with measurable entrepreneurial outcomes, distinguishing between the number of energy and green start-ups, early-stage venture funding, and later-stage venture funding. This study aims to empirically examine how public energy RD&D expenditures are associated with annual energy and green start-up counts and venture financing for clean-technology entrepreneurship across countries.

# 1. LITERATURE REVIEW

## 1.1. Public research, innovation systems, and knowledge spillovers

Public research, innovation systems and knowledge spillovers are increasingly recognized as important determinants of technological commercialization and sustainable entrepreneurship. Innovation and entrepreneurship contribute to economic growth, while emerging technologies support sustainable development and structural transformation (Ziane et al., 2025; Dadkhah et al., 2024). In this context, public energy research, development and demonstration (RD&D) may contribute not only to knowledge creation but also to


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the development of technological capabilities that can be transformed into entrepreneurial and investment outcomes.

Research investments often generate spillover effects beyond directly funded organizations. Evidence suggests that R&D spillovers improve productivity, while investment-related knowledge flows may also support new business creation when economies possess sufficient absorptive capacity and human capital (Dheera-aumpon, 2024; Tanaya & Suyanto, 2024). Similar mechanisms may apply to public energy RD&D through knowledge accumulation, uncertainty reduction, and the attraction of complementary private investment.

Research universities and public knowledge institutions play a central role in innovation systems by generating knowledge and strengthening regional innovation capacity (Zhylinska & Sitnitskiy, 2018). Knowledge management facilitates the transformation of research outputs into practical innovation solutions (Alemu, 2025), while investor and researcher perceptions influence the commercialization of R&D results in innovation-intensive sectors (Kritikos et al., 2025).

## 1.2. University–industry collaboration and technology transfer

Public research is more likely to generate entrepreneurial outcomes when effective technology transfer and university-industry collaboration mechanisms are in place. University–industry links improve knowledge transfer, innovation diffusion and start-up performance, while digital development can strengthen R&D collaboration between academia and business (Kuzior et al., 2024a, 2024b). Business–education collaboration also helps identify gaps in the innovation system and supports the transfer of knowledge from research institutions to firms and markets (Samoilikova et al., 2023).

University entrepreneurial ecosystems support start-up creation by providing mentoring, networks, entrepreneurial culture, and access to knowledge-based resources. Their importance is especially visible when they strengthen opportunity recognition, competence development, and external partnerships (Jurgelevičius & Raišienė, 2025). Student entrepreneurship also depends on perceived advantages and disadvantages of entrepreneurial activity, confirming the role of educational and institutional conditions in annual energy and green start-up activity (Dorusincova et al., 2025).

Commercialization further depends on expert support, incubator quality, and proximity to knowledge networks, which shape the capacity of technology ventures to convert innovation into marketable products (Fithri et al., 2025; Raišienė & Raišys, 2024; Zahidi et al., 2025). Since start-up growth usually follows sequential stages of capability accumulation, innovation development, and market expansion, public innovation support may be associated with different phases of entrepreneurial development in different ways (Myllylä & Kaivo-oja, 2025).

## 1.3. Entrepreneurial ecosystems and green start-ups

The transformation of public knowledge into start-ups depends heavily on the quality of the entrepreneurial ecosystem. Ecosystem resources, competencies, self-efficacy, entrepreneurial attitudes, and regional conditions shape start-up success, while digitalization and collaborative governance strengthen support for innovative firms (Imo & Makanjuola, 2025; Yassin et al., 2024; Uctu & Al-Silefanee, 2024). Digital entrepreneurial ecosystems and collaborative governance also link start-up development with regional growth and social sustainability (Mursalov et al., 2023; Zhuravka et al., 2025; Khatami et al., 2024). Therefore, public energy RD&D is unlikely to be a standalone driver of annual energy and green start-up counts; its relevance depends on whether ecosystems can absorb knowledge and transform it into entrepreneurial activity.

Clean and digital energy start-ups face specific institutional and market barriers. Access to credit, minority-investor protection, regulatory barriers, and market-entry procedures influence clean-energy entrepreneurship and may weaken the transformation of technological opportunities into business formation (Artyukhov et al., 2024; Halynskyi & Telizhenko, 2024; Myroshnychenko et al., 2024). These barriers are especially important for renewable energy and storage technologies because they are capital-intensive, highly regulated, and characterized by long commercialization horizons (Podosynnikov et al., 2024; Sitnicki et al., 2026).

Internal start-up capabilities also shape entrepreneurial outcomes. Creative management and entrepreneurial competencies support innovation-oriented ventures, while resilience, adaptability, leadership, and managerial decision-making influence value creation and venture development (Sitnicki et al., 2022; Arfara & Karasavvoglou, 2026; Saba et al., 2025). Digital transformation, human capital upgrading, and artificial intelligence affect organizational performance, technological expectations, and investment decisions (Daowadueng, 2024; Balcerzak et al., 2025; Yu, 2025). Innovation adoption in adjacent sectors also depends on digital tools, researcher capabilities, and learning-oriented institutions, reinforcing the importance of capability-building for entrepreneurial ecosystems (Yarovenko et al., 2024; Mercer-Bey, 2025; Kovács et al., 2025).

## 1.4. Venture capital, financing, and commercialization

Financing is a critical bottleneck between innovation and scaling. Venture capital, financial infrastructure, and alternative financing channels shape start-up growth and productivity, while fintech platforms can expand access to finance for SMEs (Padgureckienė & Cibulskienė, 2024; Ivashchenko et al., 2018). Financing practices also differ across labelled and sustainability-oriented start-ups, indicating that signaling, legitimacy, and investor perceptions influence access to capital (Benlefki et al., 2024).

Macroeconomic and financial conditions further affect entrepreneurial behavior. Perceived financial risk shapes entrepreneurship during recessions, a phenomenon that is especially relevant for green technologies characterized by uncertainty, long payback periods, and dependence on external capital (Civelek et al., 2025). Crisis-period government support may also strengthen SME resilience and continuity during adverse shocks (Kornyliuk et al., 2022). These findings justify distinguishing between early- and later-stage venture financing, as risks, capital needs, and investor expectations differ across development stages.

Commercialization also depends on social legitimacy and demand-side conditions. Social entrepreneurship broadens value creation, while environmental attitudes, public perceptions, and sustainable consumption shape market conditions for green ventures (Urmanaviciene, 2025; Sardianou & Kougias, 2025; Kumar Dey et al., 2025). AI-supported communication and storytelling may also help translate public innovation priorities into entrepreneurial opportunities (Behar Villegas et al., 2024).

## 1.5. Green transition and innovation policy

Climate policy increasingly relies on innovation and entrepreneurial responses. Sustainable public policy instruments, green finance, mandatory disclosure, and behavioral incentives may create more supportive conditions for eco-innovation and sustainable business activity (Juracka et al., 2024; Habib et al., 2025; Burrell et al., 2025). In the European context, the Green Deal, renewable energy targets, and climate policy reforms are redefining opportunities and constraints for entrepreneurs, including through revised renewable energy directives and compliance pressures (Streimikiene et al., 2024; Kawecka-Wyrzykowska, 2025).

The green transition is also technology-specific and territorially differentiated. Research on renewable-energy regulation, building decarbonization strategies, and sustainable development in the EU shows that clean-energy innovation creates different opportunity structures across technologies, regions, and sectors (Benalcazar et al., 2025; Bușu et al., 2024; Kawecka-Wyrzykowska, 2025). In post-lignite and energy-transition regions, the relationship between the state and entrepreneurship is especially important because public intervention may create opportunities for green growth but may also generate dependence or crowding-out effects (Avlogiaris et al., 2023). Public administration may therefore function either as an enabler or a barrier to sustainable organizational development, depending on the consistency and effectiveness of governance arrangements (Rosiak et al., 2024).


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These studies show that public energy RD&D should not be treated as a single undifferentiated policy instrument. Renewable energy, storage, and other power technologies, as well as broader low-carbon technologies, may be associated with different entrepreneurial and financing outcomes. Moreover, the link between public research and green entrepreneurship is likely to depend on climate policy frameworks, financial-market maturity, regulatory conditions, university–industry collaboration, and the strength of entrepreneurial ecosystems.

Although substantial progress has been made in understanding entrepreneurial ecosystems, innovation financing, university–industry collaboration, and green transition policies, considerably less is known about how public energy RD&D expenditures are associated with entrepreneurial outcomes. Existing studies typically analyze financing conditions, ecosystem characteristics, regulatory barriers, or innovation policies separately. Limited evidence exists on whether public energy RD&D is related to annual energy and green start-up counts, whether such relationships differ between early-stage and later-stage venture financing, and whether they vary across renewable energy, storage, and broader low-carbon technology domains. This gap is particularly important in the energy sector, where commercialization cycles are long, technologies are capital-intensive, and private investment may respond differently at different stages of venture development.

This study addresses these gaps by integrating public RD&D expenditures, green start-up activity, venture financing, and lagged innovation dynamics within a unified cross-country empirical framework, by distinguishing between annual energy and green start-up activity, early-stage funding, and later-stage funding, and by separating renewable-energy, storage-related, and low-carbon RD&D categories.

This study aims to empirically examine how public energy RD&D investments are associated with annual energy and green start-up activity, as well as the availability of venture financing for clean-technology entrepreneurship across countries.

# 2. METHODOLOGY

## 2.1. Data

The empirical analysis is based on a cross-country panel dataset covering 23 countries from 2000 to 2023, yielding 470 country-year observations. The dataset combines information on green entrepreneurial activity, venture capital investments in green start-ups, and public research expenditures in energy technologies.

Data on green entrepreneurial activity and venture financing were obtained from the Energy Start-up Data Explorer developed by the International Energy Agency (IEA). The dataset provides internationally comparable country-year data on energy and green start-up activity, along with related venture capital investment. Three indicators were used: the annual number of energy and green start-ups recorded in the IEA database, early-stage funding of energy and green start-ups (USD), and later-stage funding of energy and green start-ups (USD) (IEA, n.d.). Energy and green start-ups (Number) should be interpreted as an annual count of start-up observations recorded by the IEA for a given country and year. It does not represent the cumulative stock of active firms or the total population of operating start-ups.

Information on public energy technology research, development, and demonstration (RD&D) expenditures was obtained from the OECD Data Explorer database. The RD&D dataset provides harmonized statistics on government research spending across different energy technology domains, in constant prices and at constant exchange rates. The empirical analysis uses four RD&D categories: public RD&D budgets in renewable energy technologies, other power and storage technologies, low-carbon energy technologies, and unallocated energy RD&D programs (OECD, n.d.).

All RD&D expenditures are measured in millions of euros at constant prices and exchange rates, ensuring cross-country comparability over time. Venture-funding variables are reported in USD, as provided by the IEA Energy Start-up Data Explorer, and were not further deflated or converted. To reduce skewness, mitigate the influence of extreme observations, and retain zero values, both RD&D and funding variables were transformed using the ln(1+x) transformation before being included in the econometric models.

The final balanced panel comprises 23 countries: Austria, Belgium, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Latvia, Lithuania, the Netherlands, Norway, Poland, Portugal, Slovakia, Spain, Sweden, Switzerland, Turkey, and the United Kingdom, selected based on the simultaneous availability of public energy RD&D and energy start-up indicators for 2000–2023. The country coverage is constrained by data availability in the OECD Energy Technology RD&D database and the IEA Energy Start-up Data Explorer, which limits the inclusion of some emerging and developing economies.

## 2.2. Empirical strategy

The empirical strategy focuses on three related dimensions of green innovation: annual energy and green start-up activity, early-stage venture financing, and later-stage venture financing. The baseline dependent variable is the number of energy and green start-ups, which represents a count variable. Because count outcomes are non-negative integers and typically exhibit non-normal distributions, the baseline econometric specification employs a Poisson fixed-effects estimator. The general specification can be expressed as:

$$Startups_{it} = f\left(RD\&D_{it}, \alpha_i, \lambda_t\right) + \varepsilon_{it} \qquad (1)$$

where $Startups_{it}$ denotes the number of green start-ups in country $i$ in year $t$; $RD\&D_{it}$ represents public research expenditures across energy technology domains; $\alpha_i$ captures country fixed effects, controlling for time-invariant national characteristics; and $\lambda_t$ represents year fixed effects capturing global technological trends, policy changes, and macroeconomic shocks.

Because the variance of start-up counts exceeds the mean, indicating overdispersion, a negative binomial model is estimated as a robustness check. While the Poisson fixed-effects estimator provides consistent estimates when the conditional mean is correctly specified, the negative binomial model relaxes the equidispersion assumption by allowing the variance to exceed the mean through an additional dispersion parameter.

To account for the possibility that the possible delayed association between public research investments emerges only after several years, the analysis also estimates distributed lag models with up to 5 annual lags of RD&D expenditures. This approach reflects the long innovation cycles characteristic of energy technologies, where research programs may influence entrepreneurial activity and investment decisions only with significant delays.

In addition to annual energy and green start-up activity, the study examines the relationship between public RD&D spending and venture capital financing of green start-ups, distinguishing between early-stage and later-stage funding. Because venture funding variables exhibit strong right-skewness and contain a substantial share of zero observations, several complementary estimators are applied. First, fixed-effects OLS models with log-transformed dependent variables (using log1p) are estimated. Second, Gamma pseudo-maximum likelihood (Gamma PML) models are estimated on the subsample of observations with positive funding values, which is appropriate for modeling continuous positive outcomes with strong asymmetry. Finally, Poisson pseudo-maximum likelihood (PPML) estimators are applied to the full dataset to account for zero observations and to ensure robustness to heteroskedasticity.

Standard errors in all panel regressions are clustered at the country level to account for potential serial correlation and heteroskedasticity within panel units. Country and year fixed effects are included in all specifications to control for unobserved heterogeneity across countries and common temporal shocks affecting the energy innovation ecosystem.

All empirical analyses and calculations were conducted using the R statistical software environment (version 4.4.0). The estimation procedures relied on standard econometric packages for panel-data analysis and pseudo-maximum likelihood estimation.

The combination of multiple econometric approaches allows us to evaluate the robustness of results across alternative distributional assumptions and to capture different stages of the green



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innovation process, ranging from the creation of start-ups to the mobilization of venture capital financing for scaling and commercialization.

## 3. RESULTS

The dataset (Table A1, Appendix A) consists of 470 observations covering 23 countries over the period 2000–2023, forming a balanced panel in terms of the number of variables available across the sample. The average year in the dataset is 2012, indicating that the observations are relatively evenly distributed across the analyzed period. The dependent variable, the number of energy and green start-ups, shows substantial variation across countries and years. On average, countries record approximately 20 start-ups per year, while the median is 9, indicating a highly asymmetric distribution. The maximum value reaches 139 start-ups, whereas some country–year observations report no start-up activity. The strong positive skewness (2.08) and high kurtosis (4.73) indicate a right-skewed distribution with several high-value observations, suggesting that green entrepreneurial activity is concentrated in a relatively small number of highly innovative economies.

The financing variables demonstrate even stronger dispersion. The average early-stage funding for energy and green start-ups is approximately USD 26.7 million. In contrast, the median is only USD 0.58 million, indicating that most observations involve relatively small funding rounds, while a few very large investments drive the mean upward. A similar pattern is observed for later-stage funding, where the mean reaches USD 26.8 million. Still, the median is zero, reflecting that later-stage investments occur only in a limited subset of country-year observations. Both funding variables exhibit extremely high skewness and kurtosis, particularly for later-stage funding (skewness = 16.35; kurtosis = 309.17), indicating the presence of rare but very large venture capital deals, which is typical of technology-intensive sectors.

Public research investments in energy technologies also exhibit considerable cross-country heterogeneity. The average RD&D budget for renewable energy technologies amounts to approximately €60 million, while spending on other power and storage technologies averages about €25 million. In contrast, the largest funding category is low-carbon energy technologies, with an average annual public RD&D budget of nearly €290 million, reflecting the broad scope of programs aimed at decarburization and climate mitigation. All RD&D variables display substantial dispersion and positive skewness, suggesting that a small number of technologically advanced countries account for a large share of public research investments. The descriptive statistics reveal pronounced heterogeneity in both entrepreneurial activity and public RD&D spending across countries and over time, which justifies the use of panel-data econometric techniques with fixed effects in subsequent analyses.

The empirical analysis estimates the relationship between public energy RD&D expenditures and the number of energy and green start-ups using panel count-data models (Table 2). Because the dependent variable is the number of start-ups, a Poisson fixed-effects estimator is used as the baseline specification, controlling for unobserved heterogeneity across countries and time through country- and year-fixed effects. Standard errors are clustered at the country level to account for serial correlation within panel units.

The results of the Poisson fixed-effects model (Table 1) indicate that public RD&D spending across different energy technology categories does not exhibit a statistically significant direct association with the number of energy and green start-ups. The coefficient for renewable-energy RD&D spending is positive (0.034) but statistically insignificant, suggesting that increases in public research funding in renewable technologies are not systematically associated with higher annual energy and green start-up activity across countries. Similarly, RD&D investments in other power and storage technologies show a small positive coefficient (0.011), while low-carbon RD&D spending exhibits a slightly negative coefficient (–0.026). None of these effects reaches conventional levels of statistical significance, indicating that public RD&D expenditures alone may not directly translate into immediate entrepreneurial activity within the green technology sector.

**Table 1.** Effects of public energy RD&D budgets on the number of green start-ups (Poisson FE model)

| Variables | Poisson FE |
|---|---|
| log(RD&D Renewable energy) | 0.034 (0.075) |
| log(RD&D Storage and other power technologies) | 0.011 (0.052) |
| log(RD&D Low-carbon technologies) | –0.026 (0.066) |
| log(RD&D Unallocated energy technologies) | –0.005 (0.018) |
| Country fixed effects | Yes |
| Year fixed effects | Yes |
| Clustered SE | Country |
| Observations | 470 |
| Pseudo $R^2$ | 0.807 |
| Log-Likelihood | –1358.4 |

*Note:* Standard errors clustered at the country level are reported in parentheses.

The absence of statistically significant coefficients suggests that the impact of public research spending on annual energy and green start-up activity may operate through indirect channels or longer innovation cycles. Public RD&D programs frequently contribute to knowledge accumulation, technological experimentation, and demonstration projects, which may influence venture creation only after several years or through complementary mechanisms such as venture capital markets, technology transfer systems, and innovation policy frameworks. Moreover, entrepreneurial activity in the energy sector is often shaped by broader institutional and market conditions, including regulatory incentives, carbon pricing mechanisms, and access to private financing.

Descriptive diagnostics reveal substantial overdispersion in the dependent variable, as the variance of the number of start-ups (671.95) exceeds its mean (20.18). This characteristic violates the strict equidispersion assumption of the Poisson distribution, motivating the estimation of a negative binomial model as a robustness check. The negative binomial specification allows the variance to exceed the mean by introducing an additional dispersion parameter.

The negative binomial results (Table 2) confirm the findings obtained from the Poisson specification. The coefficients associated with renewable-energy RD&D, storage technologies, low-carbon RD&D, and unallocated RD&D budgets remain statistically insignificant and exhibit similar magnitudes and signs to those observed in the Poisson model. This consistency indicates that the main findings are robust to alternative distributional assumptions and are not driven by overdispersion.

**Table 2.** Robustness check: Negative binomial model

| Variables | Negative Binomial |
|---|---|
| log(RD&D Renewable energy) | 0.075 (0.076) |
| log(RD&D Storage and other power technologies) | –0.010 (0.052) |
| log(RD&D Low-carbon technologies) | –0.058 (0.064) |
| log(RD&D Unallocated energy technologies) | –0.003 (0.020) |
| Country fixed effects | Yes |
| Year fixed effects | Yes |
| Clustered SE | Country |
| Observations | 470 |
| Overdispersion parameter | 28.13 |
| BIC | 2946.5 |

*Note:* Standard errors clustered at the country level are reported in parentheses.

The estimated overdispersion parameter in the negative binomial model (approximately 28.13) indicates substantial heterogeneity in start-up counts across countries and years. Nevertheless, the similarity between the Poisson and negative binomial coefficients suggests that the conditional mean specification of the Poisson fixed-effects model remains appropriate, as it provides consistent estimates even when the Poisson variance assumption is violated.

The fixed-effects estimates further reveal strong cross-country heterogeneity in entrepreneurial activity. Countries such as the United Kingdom, Germany, France, Italy, the Netherlands, and Switzerland exhibit significantly higher levels of green start-up activity than the reference country, reflecting more developed innovation ecosystems and venture capital markets. Conversely, several smaller economies exhibit significantly lower start-up counts, highlighting the uneven distribution of green innovation capacity across Europe.

Temporal fixed effects reveal a general increase in green entrepreneurial activity during the late 2000s and 2010s, with several years showing significantly higher start-up counts relative to the base year. This pattern is consistent with the rapid expansion of renewable energy markets, increasing climate policy commitments, and growing investor interest in clean technologies during this


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period. However, the negative coefficient for the most recent year suggests a potential slowdown in annual energy and green start-up activity, which may reflect macroeconomic uncertainty or tightening venture capital conditions.

The results suggest that public RD&D spending alone does not appear to be a primary driver of annual energy and green start-up counts in the short term. Instead, the emergence of energy start-ups likely depends on a broader combination of technological, financial, and institutional factors that shape the innovation ecosystem.

The correlation analysis (Tables 3 and 4) was conducted to examine relationships among different categories of public energy RD&D expenditures and to assess the potential presence of multicollinearity among the explanatory variables used in the econometric models. The results indicate that the RD&D variables are positively correlated across all technology categories, suggesting that countries that invest heavily in one area of energy technology research typically allocate substantial resources to other energy innovation domains as well.

The strongest correlation is observed between renewable energy RD&D and low-carbon energy RD&D expenditures ($r = 0.87$). This very high positive correlation suggests that these two funding categories are closely linked within national research programs. In many countries, renewable technologies are a central component of broader decarburization strategies; therefore, public research budgets for low-carbon transitions often include substantial investments in renewable energy technologies. As a result, countries with large low-carbon research budgets tend to simultaneously invest heavily in renewable energy innovation.

A similarly strong relationship exists between renewable energy RD&D and storage and other power technologies RD&D ($r = 0.74$). This correlation reflects the technological complementarity between renewable energy deployment and energy storage systems. As renewable electricity generation expands, research investment in storage technologies, grid integration, and power system flexibility becomes increasingly important. Consequently, national research strategies often fund these technology areas simultaneously.

The correlation between storage-related RD&D and low-carbon RD&D ($r = 0.73$) also indicates substantial overlap in research priorities across energy transition technologies. Storage technologies, hydrogen systems, and advanced power infrastructure are frequently funded under broader low-carbon innovation programs designed to support decarburization of energy systems.

In contrast, unallocated RD&D budgets exhibit considerably weaker correlations with other technology categories, ranging from 0.38 to 0.48. This result suggests that unallocated RD&D expenditures likely reflect a more heterogeneous set of funding streams, including general research programs, cross-sectoral innovation funds, and administrative allocations not directly linked to specific energy technologies.

All correlation coefficients are statistically significant at conventional levels ($p < 0.01$), reflecting the relatively large sample size of the panel dataset. However, the magnitude of several correlations, particularly the relationship between renewable and low-carbon RD&D, suggests the potential for multicollinearity among the explanatory variables. High correlations between regressors can inflate standard errors and reduce the statistical significance of estimated coefficients in regression models, even when underlying relationships exist.

These findings help explain why the Poisson and negative binomial regressions do not detect statistically significant effects of individual RD&D variables on annual energy and green start-up activity. Because countries tend to increase investments across multiple energy technology domains simultaneously, it becomes difficult to isolate the independent effect of each RD&D category within a single regression specification.

From a methodological perspective, this pattern suggests that future specifications could consider alternative modeling strategies, such as aggregating RD&D variables into a composite energy innovation index, estimating separate regressions for individual RD&D categories, or applying dimensionality-reduction techniques such as principal component analysis to capture the common variation across energy research investments.

**Table 3.** Correlation matrix of public energy RD&D expenditure variables

| Variables | RD&D Renewable | RD&D Storage | RD&D Low-carbon | RD&D Unallocated |
|---|---|---|---|---|
| RD&D Renewable | 1.000 | 0.735 | 0.872 | 0.403 |
| RD&D Storage | 0.735 | 1.000 | 0.735 | 0.479 |
| RD&D Low-carbon | 0.872 | 0.735 | 1.000 | 0.376 |
| RD&D Unallocated | 0.403 | 0.479 | 0.376 | 1.000 |

*Note:* Pearson correlation coefficients. Number of observations = 470.

**Table 4.** Significance of correlations between RD&D expenditure variables

| Variable pair | Correlation | p-value |
|---|---|---|
| Renewable – Storage | 0.735 | < 0.001 |
| Renewable – Low-carbon | 0.872 | < 0.001 |
| Renewable – Unallocated | 0.403 | < 0.001 |
| Storage – Low-carbon | 0.735 | < 0.001 |
| Storage – Unallocated | 0.479 | < 0.001 |
| Low-carbon – Unallocated | 0.376 | < 0.001 |

*Note:* p-values adjusted for multiple comparisons using the procedure implemented in the psych package.

The correlation analysis reveals strong complementarities among public RD&D investments across energy technology domains, reflecting integrated national innovation strategies that support the broader transition toward low-carbon energy systems.

Appendix B illustrates the temporal dynamics of green entrepreneurial activity and public investments in energy technology research across the analyzed countries. Each figure reports the average value of the respective variable over time, along with a fitted trend line, enabling a visual assessment of long-term developments in green innovation ecosystems.

Figure B1 presents the evolution of the average number of energy and green start-ups. The trend indicates a gradual increase in entrepreneurial activity during the late 2000s and 2010s, reflecting the expansion of clean-energy markets and growing interest in green technologies. However, the series also shows noticeable fluctuations in recent years, suggesting that start-up creation may be sensitive to macroeconomic conditions and investment cycles.

Figure B2 displays the time trend of public RD&D expenditures in renewable energy technologies. The figure shows a general upward trajectory of public research investments over the analyzed period, particularly during the 2010s, when many countries intensified support for renewable energy innovation as part of broader decarburization strategies.

Figure B3 illustrates RD&D expenditures allocated to other power and storage technologies. The trend suggests a gradual increase in funding over time, highlighting the growing importance of grid flexibility, storage systems, and power system integration technologies required to support higher shares of renewable electricity generation.

Figure B4 presents the dynamics of public RD&D spending in low-carbon energy technologies. The figure shows the highest overall funding levels across the analyzed categories and indicates a sustained increase in investment in the later years of the sample period. This pattern reflects the broad policy emphasis on accelerating the transition toward low-carbon energy systems.

The graphical analysis suggests that while public RD&D spending in energy technologies has generally increased over time, the relationship between these investments and green start-up creation may not be immediate. The visual trends support the econometric results, indicating that the relationship between research spending and entrepreneurial activity may operate through delayed innovation processes and broader innovation ecosystem dynamics.

To further address potential multicollinearity among individual RD&D categories, an alternative specification was estimated using a composite measure of public energy RD&D spending, defined as the sum of RD&D expenditures across all


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energy technology categories. This specification (Table 5) captures the overall public effort devoted to energy innovation, rather than the effect of specific technological domains.

**Table 5.** Effect of total public energy RD&D spending on annual energy and green start-up counts (Poisson FE)

| Variables | Poisson FE |
|---|---|
| log(Total RD&D spending) | −0.0008 (0.046) |
| Country fixed effects | Yes |
| Year fixed effects | Yes |
| Clustered SE | Country |
| Observations | 470 |
| Log-Likelihood | −1359.6 |
| Pseudo $R^2$ | 0.800 |
| BIC | 3008.3 |

*Note:* Standard errors clustered at the country level are reported in parentheses. The dependent variable is the number of energy and green start-ups. Total RD&D spending represents the aggregate public expenditure across renewable energy, storage, and power technologies, low-carbon technologies, and unallocated energy RD&D categories.

The results of the Poisson fixed-effects model indicate that total public energy RD&D spending is not statistically significantly associated with the number of energy and green start-ups. The estimated coefficient for the logarithm of total RD&D expenditure is extremely small and statistically insignificant ($\beta = -0.0008$; $p = 0.987$). This result suggests that increases in aggregate public research funding are not systematically associated with changes in annual energy and green start-up counts across countries during the analyzed period.

The absence of a statistically significant effect may reflect several structural characteristics of innovation processes in the energy sector. First, public RD&D programs often generate long-term technological knowledge rather than immediate entrepreneurial activity, meaning that their impact on annual energy and green start-up activity may emerge only after extended periods. Second, the creation of green start-ups depends not only on research investments but also on broader elements of the innovation ecosystem, including venture capital availability, market incentives, regulatory frameworks, and mechanisms for technology diffusion. Third, aggregated RD&D expenditures may mask heterogeneous effects across technology domains, as investments in different energy technologies may influence entrepreneurial dynamics in distinct ways.

The findings suggest that public research investments alone are unlikely to be sufficient to drive green entrepreneurial activity, highlighting the importance of complementary policy instruments to support innovation, commercialization, and access to private financing.

To account for potential delays between public research investments and entrepreneurial activity, a distributed lag specification of the Poisson fixed-effects model was estimated (Table 6). This approach allows the effect of RD&D expenditures to unfold over multiple years, reflecting the long innovation cycles characteristic of energy technologies. The model includes lags of up to five years for public RD&D spending on renewable energy, storage, and other power technologies, as well as low-carbon energy technologies, before annual energy and green start-up activity.

**Table 6.** Distributed lag effects of public energy RD&D expenditures on annual energy and green start-up counts (Poisson FE)

| Variables | | Distributed lag Poisson FE |
|---|---|---|
| Renewable | RD&D (t−1) | 0.001 (0.085) |
| | RD&D (t−2) | 0.058 (0.072) |
| | RD&D (t−3) | −0.075 (0.065) |
| | RD&D (t−4) | 0.060 (0.069) |
| | RD&D (t−5) | −0.009 (0.056) |
| Storage | RD&D (t−1) | 0.002 (0.047) |
| | RD&D (t−2) | −0.046* (0.021) |
| | RD&D (t−3) | 0.053 (0.040) |
| | RD&D (t−4) | −0.025 (0.025) |
| | RD&D (t−5) | −0.079** (0.030) |
| Low-carbon | RD&D (t−1) | −0.011 (0.095) |
| | RD&D (t−2) | −0.048 (0.080) |
| | RD&D (t−3) | 0.004 (0.104) |
| | RD&D (t−4) | 0.093 (0.057) |
| | RD&D (t−5) | 0.084 (0.061) |
| Country fixed effects | | Yes |
| Year fixed effects | | Yes |
| Clustered SE | | Country |
| Observations | | 355 |
| Log-Likelihood | | −1016.9 |
| Pseudo $R^2$ | | 0.811 |
| BIC | | 2350.9 |

*Note:* Cluster-robust standard errors at the country level are reported in parentheses. The dependent variable is the number of energy and green start-ups. RD&D variables represent logarithmic transformations of public research expenditures, lagged by 1 to 5 years. Significance levels: * p < 0.05, ** p < 0.01.

The results indicate that public RD&D spending in renewable energy technologies does not exhibit a statistically significant delayed effect on the number of green start-ups. None of the five lagged renewable RD&D variables is statistically significant at conventional levels in the combined distributed lag model. The separate distributed lag specification confirms this finding: although the fourth lag of renewable RD&D displays a weak positive association with annual energy and green start-up activity (β = 0.085, $p \approx 0.083$), the joint significance test of all renewable RD&D lags shows that the cumulative effect is statistically insignificant ($\chi^2 = 0.049$, $p = 0.825$). This result suggests that increases in renewable energy research spending are not systematically associated with subsequent increases in green start-up creation across the analyzed countries.

In contrast, RD&D investments in storage and other power technologies display statistically significant delayed effects on annual energy and green start-up activity. Specifically, RD&D spending in storage technologies two years earlier (β = −0.046, $p = 0.031$) and five years earlier (β = −0.079, $p = 0.007$) shows a significant negative relationship with the number of green start-ups. These results may reflect the capital-intensive nature of storage technologies, where innovation and commercialization tend to occur within established firms rather than through new entrepreneurial ventures. No statistically significant effects are observed for lagged low-carbon RD&D expenditures, although the fourth lag shows a weak positive association with annual energy and green start-up activity. The distributed lag results suggest that the relationship between public energy RD&D spending and green entrepreneurial activity is heterogeneous across technology domains and does not operate through immediate or uniformly positive channels.

The estimated model demonstrates a strong overall fit, with a pseudo $R^2$ of approximately 0.81 and a squared correlation of 0.957, indicating that the fixed-effects specification successfully captures a large share of cross-country and temporal variation in start-up activity.

## 3.1. Interpretation of the effects of RD&D spending on venture funding

To further investigate whether public research investments influence the financing environment for green innovation, additional fixed-effects models were estimated, with early-stage and later-stage funding for energy and green start-ups as dependent variables. Both variables were log-transformed using the log1p function to account for the highly skewed distribution of venture capital investments and the presence of zero observations.

The results (Table 7) indicate that public RD&D spending on renewable energy technologies is positively associated with venture funding for green start-ups, although the effect is only weakly statistically significant. In the early-stage funding model, the coefficient of renewable RD&D expenditures equals 1.41 ($p \approx 0.063$), suggesting that increases in public investment in renewable energy research may stimulate early-stage venture capital flows into green start-ups. A similar relationship is observed for later-stage funding, where the coefficient for renewable RD&D equals 1.56 ($p \approx 0.091$). These results suggest only a possible association between public research programs and investor interest, while the channels behind this relationship cannot be identified within the present empirical design.

**Table 7.** Effects of public energy RD&D expenditures on venture funding of green start-ups

| Variables | Early-stage funding | Later-stage funding |
|---|---|---|
| log(RD&D Renewable energy) | 1.410 (0.720) | 1.565 (0.885) |
| log(RD&D Storage and power technologies) | −0.544 (0.602) | −0.036 (0.661) |
| log(RD&D Low-carbon technologies) | −0.525 (0.421) | −0.981 (0.612) |
| Country fixed effects | Yes | Yes |
| Year fixed effects | Yes | Yes |
| Clustered SE | Country | Country |
| Observations | 470 | 470 |
| Adj. $R^2$ | 0.610 | 0.459 |
| Within $R^2$ | 0.012 | 0.014 |

*Note:* Cluster-robust standard errors at the country level are reported in parentheses. The dependent variables are the logarithms of early-stage and later-stage funding for energy and green start-ups (log1p-transformed). Significance levels: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

In contrast, RD&D expenditures in storage and other power technologies do not exhibit a statisti-


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cally significant relationship with venture funding. The estimated coefficients are small and statistically insignificant in both early-stage and later-stage funding models. This result may reflect the fact that innovation in storage technologies often involves large-scale industrial projects and capital-intensive infrastructure, which are typically financed through corporate investment or public programs rather than through venture capital markets.

Similarly, public RD&D spending in broader low-carbon technologies does not display a statistically significant association with venture funding for green start-ups. Although the estimated coefficients are negative in both models, they remain statistically insignificant. This pattern may indicate that low-carbon RD&D programs primarily support technological development and demonstration projects rather than directly stimulating private investment in entrepreneurial ventures.

The findings provide only limited evidence that public RD&D spending influences the financing environment for green innovation. Positive associations are observed in some specifications, but most coefficients remain statistically insignificant. At the same time, other technology categories do not appear to generate comparable effects on venture capital investment. However, the relatively low within-$R^2$ values indicate that variations in venture funding are largely explained by broader market conditions and country-specific innovation ecosystems rather than by public RD&D spending alone.

To examine whether public energy RD&D spending influences the financing of green start-ups with temporal delays, distributed lag fixed-effects models were estimated for both early-stage funding and later-stage funding. The models include up to five annual lags of RD&D expenditures for renewable energy, storage, and power technologies, and low-carbon technologies, while controlling for country- and year-fixed effects and clustering standard errors at the country level.

The results for early-stage venture funding (Table 8) indicate that none of the lagged RD&D variables exhibits statistically significant effects. Both renewable-energy RD&D and storage-related RD&D exhibit coefficients that flip sign across different lags, suggesting that their influence on early-stage funding is neither stable nor systematic over time. Similarly, lagged low-carbon RD&D expenditures do not show statistically significant associations with early-stage venture financing. These findings imply that variations in early-stage investment flows are not strongly driven by public RD&D spending in the analyzed energy technology categories.

**Table 8.** Distributed lag effects of public RD&D spending on early-stage funding of green start-ups

| Variables | | Early-stage funding |
|---|---|---|
| Renewable | RD&D (t–1) | 0.832 (1.094) |
| | RD&D (t–2) | 1.450 (1.029) |
| | RD&D (t–3) | –1.067 (1.246) |
| | RD&D (t–4) | –0.458 (1.435) |
| | RD&D (t–5) | 0.038 (1.326) |
| Storage | RD&D (t–1) | –0.647 (0.616) |
| | RD&D (t–2) | –0.061 (0.782) |
| | RD&D (t–3) | –1.010 (1.070) |
| | RD&D (t–4) | 1.249 (0.825) |
| | RD&D (t–5) | –0.047 (0.397) |
| Low-carbon | RD&D (t–1) | 0.608 (0.760) |
| | RD&D (t–2) | –0.452 (0.794) |
| | RD&D (t–3) | 1.664 (1.783) |
| | RD&D (t–4) | –0.470 (1.105) |
| | RD&D (t–5) | –1.498 (1.045) |
| Country fixed effects | | Yes |
| Year fixed effects | | Yes |
| Clustered SE | | Country |
| Observations | | 355 |
| Adj. $R^2$ | | 0.559 |
| Within $R^2$ | | 0.072 |

*Note:* Cluster-robust standard errors at the country level are reported in parentheses.

The later-stage funding model (Table 9) reveals a somewhat different pattern. Although most lagged RD&D variables remain statistically insignificant, a significant negative relationship is observed for low-carbon RD&D expenditures lagged by five years ($\beta = -2.23$, $p < 0.05$). This result may indicate that increased public spending on broader low-carbon technologies is associated with reduced venture investment in later-stage green start-ups after several years, potentially reflecting substitution effects between public funding programs and private venture capital. In addition, the coefficient for storage RD&D lagged by one year is weakly significant ($p \approx 0.087$), suggesting a potential short-term positive association between storage-related research spending and later-stage investment activity, although this effect is not robust.

**Table 9.** Distributed lag effects of public RD&D spending on later-stage funding of green start-ups

| Variables | | Later-stage funding |
|---|---|---|
| Renewable | RD&D (t–1) | –0.179 (0.666) |
| | RD&D (t–2) | –0.692 (1.024) |
| | RD&D (t–3) | 1.176 (1.097) |
| | RD&D (t–4) | –0.474 (1.251) |
| | RD&D (t–5) | 1.838 (1.282) |
| Storage | RD&D (t–1) | 1.166 (0.649) |
| | RD&D (t–2) | –1.412 (0.847) |
| | RD&D (t–3) | –0.789 (1.121) |
| | RD&D (t–4) | 0.369 (1.140) |
| | RD&D (t–5) | –0.065 (0.906) |
| Low-carbon | RD&D (t–1) | –0.009 (0.840) |
| | RD&D (t–2) | 0.621 (0.771) |
| | RD&D (t–3) | 0.066 (1.222) |
| | RD&D (t–4) | –0.036 (0.810) |
| | RD&D (t–5) | –2.228* (0.877) |
| Country fixed effects | | Yes |
| Year fixed effects | | Yes |
| Clustered SE | | Country |
| Observations | | 355 |
| Adj. $R^2$ | | 0.472 |
| Within $R^2$ | | 0.058 |

*Note:* Cluster-robust standard errors at the country level are reported in parentheses. * $p < 0.05$.

To further evaluate the cumulative impact of RD&D investments, joint significance tests were conducted for the sum of the lagged coefficients. The results indicate that the combined lagged effects of renewable-energy RD&D on both early-stage and later-stage funding are statistically insignificant. Similarly, the joint effect of storage-related RD&D expenditures on early-stage funding is not statistically significant. These findings suggest that public RD&D investments do not appear to generate strong or consistent lagged effects on venture funding for green start-ups across the analyzed countries.

The distributed lag analysis supports the conclusion that the relationship between public research spending and venture financing of green start-ups is relatively weak and heterogeneous. Venture funding dynamics are likely to be more strongly influenced by broader market conditions, investor expectations, and the institutional characteristics of national innovation systems than by public RD&D spending alone.

The descriptive analysis shows that venture funding contains many zero observations. About 44.7% of country-year observations report no early-stage funding (210 cases), while 70.9% report no later-stage funding (333 cases). This reflects the structure of green venture capital markets, where investment is concentrated in a limited number of innovation-intensive countries and occurs irregularly over time.

Because of the large share of zeros, Gamma PML is not appropriate for the full sample, as it requires strictly positive dependent variables. Instead, PPML is more suitable, since it accommodates zero outcomes and remains robust to heteroskedasticity. Therefore, the main models should employ PPML with country- and year-fixed effects, while Gamma PML should be used only as a robustness check on the subsample of positive funding observations.

The PPML models (Table 11), estimated on the full sample that includes zero-funding observations, broadly confirm these patterns. For early-stage funding, none of the RD&D categories shows a statistically significant effect, reinforcing the conclusion that early venture financing is only weakly associated with public RD&D spending. However, for later-stage funding, public RD&D spending on low-carbon technologies again shows a positive, statistically significant effect. This robustness across estimation methods suggests that public research investment in low-carbon technologies plays an important role in supporting the expansion and scaling of green start-ups, even though its influence on the emergence of early-stage venture financing remains limited.

The Gamma PML estimates (Table 10) for positive funding observations indicate that public RD&D spending has limited direct effects on early-stage venture funding in the green energy sector. None of the RD&D categories (renewable energy, storage technologies, or low-carbon technologies) demonstrates statistically significant coefficients in the early-stage funding model. This suggests that increases in public research expenditures do not immediately translate into larger early-stage investment volumes once funding is provided. Instead, early venture financing appears to be influenced primarily by country-specific innovation ecosystems, as reflected in several significant country-fixed effects (e.g., Germany, Sweden, or the United Kingdom).


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**Table 10.** Effects of public RD&D spending on early-stage funding of green start-ups

| Variables | Gamma PML (positive funding) | PPML (full sample) |
|---|---|---|
| log1p(RD&D renewable) | 0.053 (0.226) | −0.303 (0.366) |
| log1p(RD&D storage) | −0.219 (0.164) | −0.179 (0.224) |
| log1p(RD&D low-carbon) | 0.123 (0.213) | 0.274 (0.220) |
| Country fixed effects | Yes | Yes |
| Year fixed effects | Yes | Yes |
| Observations | 260 | 438 |
| Model type | Gamma PML | PPML |

*Note:* Standard errors in parentheses. The dependent variable is early-stage venture funding of green start-ups. Gamma PML is estimated on observations with positive funding values, while PPML is estimated on the full sample, including zero outcomes.

In contrast, the results for later-stage venture funding (Table 11) reveal a statistically significant positive relationship with public RD&D spending on low-carbon technologies. The coefficient for log1p(rdd_lowcarbon) is positive and significant at the 5% level, indicating that higher public investment in low-carbon energy research is associated with larger volumes of later-stage venture financing. This finding suggests a possible association between public RD&D investments and later-stage venture financing, although the mechanisms underlying this relationship cannot be identified within the present empirical design.

**Table 11.** Effects of public RD&D spending on later-stage funding of green start-ups

| Variables | Gamma PML (positive funding) | PPML (full sample) |
|---|---|---|
| log1p(RD&D renewable) | −0.214 (0.342) | −0.247 (0.388) |
| log1p(RD&D storage) | −0.001 (0.251) | −0.724 (0.470) |
| log1p(RD&D low-carbon) | 0.731* (0.352) | 1.770 (0.718) |
| Country fixed effects | Yes | Yes |
| Year fixed effects | Yes | Yes |
| Observations | 137 | 361 |
| Model type | Gamma PML | PPML |

*Note:* Standard errors in parentheses. * $p < 0.05$, ** $p < 0.01$. The dependent variable is later-stage venture funding of green start-ups.

The findings indicate that public RD&D spending primarily contributes to later-stage venture investment dynamics rather than to the initial emergence of early-stage funding.

Tables 1–11 collectively provide a comprehensive assessment of the relationship between public energy RD&D expenditures and green entrepreneurial activity. The baseline Poisson and negative binomial models show that direct contemporaneous effects of RD&D spending on the number of green start-ups are generally weak. However, the distributed lag specifications suggest that some delayed effects emerge over time, particularly for storage-related RD&D investments, indicating that innovation policies may influence entrepreneurial dynamics with temporal lags. The analysis of venture funding further reveals that public RD&D spending appears to be more closely associated with selected later-stage financing outcomes than with the initial formation of start-ups. While fixed-effects OLS models show limited associations between RD&D expenditures and early-stage investment, robustness checks using Gamma PML and PPML estimators indicate that higher public investment in low-carbon technologies is positively associated with later-stage venture financing. The results suggest that public RD&D primarily strengthens the scaling and commercialization phase of green innovation rather than the immediate creation of start-ups.

# 4. DISCUSSION

The empirical results indicate that public energy RD&D expenditures do not exert a statistically significant direct effect on the number of green start-ups, which suggests that the relationship between public research investments and entrepreneurial activity is more complex than a simple linear mechanism. These findings are broadly consistent with previous studies, which highlight that the emergence of innovative ventures depends not only on research spending but also on the quality of entrepreneurial ecosystems, institutional frameworks, and access to finance. Earlier research emphasizes that entrepreneurial outcomes are shaped by ecosystem conditions, including entrepreneurial competencies, innovation networks, and supportive institutional environments (Imo & Makanjuola, 2025; Yassin et al., 2024; Uctu & Al-Silefanee, 2024). In this context, the absence of an immediate effect of RD&D spending on annual energy and green start-up activity observed in the empirical analysis may reflect the fact that public research investments primarily generate knowledge and technological capabilities rather than directly creating new firms. These findings therefore support the argument that transforming research outcomes into entrepreneurial activity requires complementary mechanisms, such as technology transfer systems, venture financing, and university-industry collaboration.

At the same time, the results provide limited evidence of an association between public RD&D investments and venture financing, although these relationships are not consistently significant across specifications. Positive coefficients for renewable RD&D are observed across several models, although these relationships remain only marginally significant and are not consistently robust across alternative specifications. This result aligns with the existing literature, which emphasizes the importance of venture capital and financial infrastructure for the development of innovative firms. Studies have shown that venture capital financing plays a crucial role in supporting the commercialization of new technologies and improving firm productivity (Padgureckienė & Cibulskienė, 2024; Ivashchenko et al., 2018). One possible interpretation is that public research investments may serve as a signaling mechanism, reducing perceived technological uncertainty among private investors. However, the present empirical design does not directly test this mechanism, so this explanation should be treated as theoretical rather than empirical.

Some evidence of a positive association between public RD&D spending and venture financing appears in the later stages of the innovation cycle, although this relationship is observed only in selected specifications. The PPML results indicate a positive association between low-carbon RD&D expenditures and later-stage venture financing in one robustness specification, although this relationship is not consistently supported across all models. This pattern is consistent with studies emphasizing the importance of mature innovation ecosystems and effective university-industry collaboration for the diffusion of technological knowledge (Kuzior et al., 2024a, 2024b). One possible interpretation is that public RD&D investments may contribute to technological infrastructures, demonstration projects, and knowledge spillovers that could influence investor perceptions of technological risk, although this mechanism is not directly examined in the present study.

Finally, the results highlight the structural characteristics of venture capital markets in the energy sector. The high share of zero funding observations and the strong concentration of investment in a limited number of countries confirm that green venture financing is highly uneven across national innovation systems. This observation is consistent with the broader literature on entrepreneurial ecosystems, which emphasizes that the availability of financial resources, institutional quality, and innovation networks strongly influence the geographical distribution of start-ups and venture capital investments (Mursalov et al., 2023). Consequently, public RD&D spending alone is unlikely to generate widespread entrepreneurial activity unless complemented by policies that strengthen venture capital markets, improve regulatory frameworks, and enhance collaboration between research institutions and industry. The results, therefore, suggest that an effective green innovation policy should integrate research funding with broader ecosystem-oriented measures that facilitate technology transfer, entrepreneurial experimentation, and access to private capital.

The evidence suggests that any relationship between public energy RD&D and venture financing is weak, heterogeneous, and highly dependent on model specification. Therefore, public energy RD&D should not be viewed as a standalone instrument for stimulating green entrepreneurship, but rather as one component of a broader innovation ecosystem in which financing conditions, institutional quality, market maturity, and technology-transfer mechanisms may play a more decisive role in shaping investment outcomes than public RD&D expenditures alone.

Despite providing new cross-country evidence on the relationship between public energy RD&D spending and green entrepreneurship, this study has several limitations. First, the analysis relies on aggregated national-level data, which may mask important heterogeneity across regions, sectors, and types of green technologies. Second, the dataset focuses on a limited number of countries (23) and observations (470 country-year cases), which


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may constrain the generalizability of the results to other innovation systems or emerging economies. This limited country coverage is largely determined by the availability of comparable data on public energy RD&D expenditures in the OECD (n.d.) database, which does not provide consistent long-term statistics for all countries. Third, the empirical models capture statistical associations rather than fully causal relationships, as venture financing and entrepreneurial activity may also be influenced by unobserved institutional factors, regulatory frameworks, or macroeconomic conditions that are not explicitly included in the analysis. In addition, the measurement of RD&D expenditures aggregates different types of public research programs, which may affect entrepreneurial dynamics in distinct ways. An additional limitation is that venture-funding indicators and public RD&D expenditures originate from different databases and are reported in different currencies and price conventions, although logarithmic transformations and fixed-effects estimators help reduce comparability concerns. Future research could therefore extend the analysis by incorporating more granular sectoral data, alternative measures of innovation ecosystems, and micro-level information on start-up behavior and investment dynamics.

## CONCLUSION

This study aimed to examine how public energy research, development, and demonstration expenditures are associated with green entrepreneurial activity and venture financing for energy start-ups across countries. In particular, the paper sought to identify whether public investments in different energy technology domains are related to the annual number of recorded energy and green start-ups and to venture capital mobilization at different stages of the innovation cycle.

The empirical analysis was based on a cross-country panel dataset covering 23 countries during 2000–2023, comprising 470 country-year observations. The dataset combined information on the number of energy and green start-ups, early-stage and later-stage venture funding, and public RD&D expenditures in renewable energy, storage, and power technologies, low-carbon technologies, and unallocated energy programs. The empirical strategy employed several complementary econometric approaches, including Poisson and negative binomial fixed-effects models, distributed lag specifications, fixed-effects OLS models, and Gamma PML and PPML estimators. All models controlled for country- and year-fixed effects, and standard errors were clustered at the country level.

The empirical results reveal a mixed and heterogeneous pattern rather than a uniformly positive relationship between public RD&D and green entrepreneurship. First, the baseline Poisson and negative binomial estimations indicate that public RD&D expenditures are not significantly associated with the annual number of recorded energy and green start-ups in the contemporaneous specification. Second, the distributed lag analysis shows heterogeneous delayed associations for storage-related RD&D, with effects that are not uniformly positive. Third, the venture-financing models report positive coefficients for renewable-energy RD&D, with values of 1.41 for early-stage funding and 1.56 for later-stage funding; however, their statistical significance is weak and inconsistent across specifications, so these results should be interpreted cautiously. Fourth, the Gamma PML and PPML robustness checks indicate that low-carbon RD&D is positively associated with later-stage venture financing in selected specifications, with the PPML coefficient reaching 1.77. Finally, venture financing is highly concentrated across the sample: 44.7% of observations report zero early-stage funding, while 70.9% report zero later-stage funding, confirming the uneven distribution of green venture capital across countries. The central conclusion of this study is that the relationship between public energy RD&D and green entrepreneurship is complex, heterogeneous, and conditional rather than uniformly positive. Public RD&D expenditures are not significantly associated with the annual number of recorded energy and green start-ups, show only weak and inconsistent associations with early-stage venture funding, and are related to later-stage financing only in selected specifications, particularly for low-carbon technologies. These findings suggest that public RD&D should be interpreted as one element of a broader green innovation ecosystem rather than as an independent or immediate driver of green entrepreneurial activity.

These findings should be interpreted with caution and in a conditional manner, with policy implications. The results do not provide strong evidence that public RD&D investments alone are sufficient to stimulate immediate annual energy and green start-up counts. Therefore, public research funding should be treated as one component of a broader innovation ecosystem rather than as a standalone policy instrument. Measures that improve access to venture capital, strengthen technology transfer mechanisms, reduce regulatory barriers, and support university–industry collaboration remain essential for transforming public research outputs into entrepreneurial activity. The evidence provides limited support for the view that public RD&D may be related to selected financing outcomes, especially later-stage venture financing, than for the initial creation of green start-ups. Accordingly, policymakers should focus not only on increasing RD&D budgets but also on improving the channels through which research results reach private investors and scaling-oriented firms. The findings suggest that policymakers may consider complementary measures such as demonstration projects, innovation clusters, co-investment schemes, and stronger university–industry partnerships, as well as partnerships between public research institutions, start-ups, and venture capital funds, to help reduce technological uncertainty and support the commercialization of clean technologies. Given the strong concentration of green venture funding in a limited number of innovation-intensive countries, policy efforts should also address financial and institutional gaps in weaker innovation ecosystems to promote more balanced development of green entrepreneurship.

## AUTHOR CONTRIBUTIONS

Conceptualization: Maksym W. Sitnicki, Serhiy Lyeonov, Dmytro Kurinskyi, Serhiy Podosynnikov.
Data curation: Serhiy Podosynnikov.
Formal analysis: Serhiy Podosynnikov.
Funding acquisition: Dmytro Kurinskyi.
Investigation: Serhiy Podosynnikov.
Methodology: Serhiy Podosynnikov.
Project administration: Serhiy Lyeonov.
Resources: Dmytro Kurinskyi.
Software: Maksym W. Sitnicki, Serhiy Podosynnikov.
Supervision: Serhiy Lyeonov.
Validation: Serhiy Podosynnikov.
Visualization: Maksym W. Sitnicki, Serhiy Podosynnikov.
Writing – original draft: Maksym W. Sitnicki, Serhiy Lyeonov, Dmytro Kurinskyi, Serhiy Podosynnikov.
Writing – review & editing: Maksym W. Sitnicki, Serhiy Lyeonov, Dmytro Kurinskyi, Serhiy Podosynnikov.

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# APPENDIX A

**Table A1.** Descriptive statistics of the main variables

| Variable | Obs. | Mean | Std. Dev. | Median | Min | Max | Skewness | Kurtosis |
|---|---|---|---|---|---|---|---|---|
| Energy and green start-ups (Number) | 470 | 20.18 | 25.92 | 9.00 | 0 | 139 | 2.08 | 4.73 |
| Early-stage funding of energy and green start-ups (USD) | 470 | 26,677,577.58 | 89,032,720.50 | 578,988.84 | 0 | 792,449,700 | 5.78 | 37.75 |
| Later-stage funding of energy and green start-ups (USD) | 470 | 26,767,247.44 | 172,429,616.71 | 0 | 0 | 3,397,459,000 | 16.35 | 309.17 |
| Public RD&D budgets in Renewable energy sources (million €) | 470 | 60.10 | 74.99 | 32.47 | 0 | 403.39 | 1.98 | 3.71 |
| Public RD&D budgets in Other power and storage technologies (million €) | 470 | 24.83 | 33.87 | 12.97 | 0 | 195.98 | 2.16 | 4.52 |
| Public RD&D budgets in Unallocated energy technologies (million €) | 470 | 8.95 | 45.52 | 0 | 0 | 381.93 | 6.39 | 41.86 |
| Public RD&D budgets in Low-carbon energy technologies (million €) | 470 | 289.97 | 420.93 | 133.51 | 0.29 | 2,353.26 | 2.41 | 5.51 |

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# APPENDIX B. Temporal trends in green start-up activity and public energy RD&D expenditures

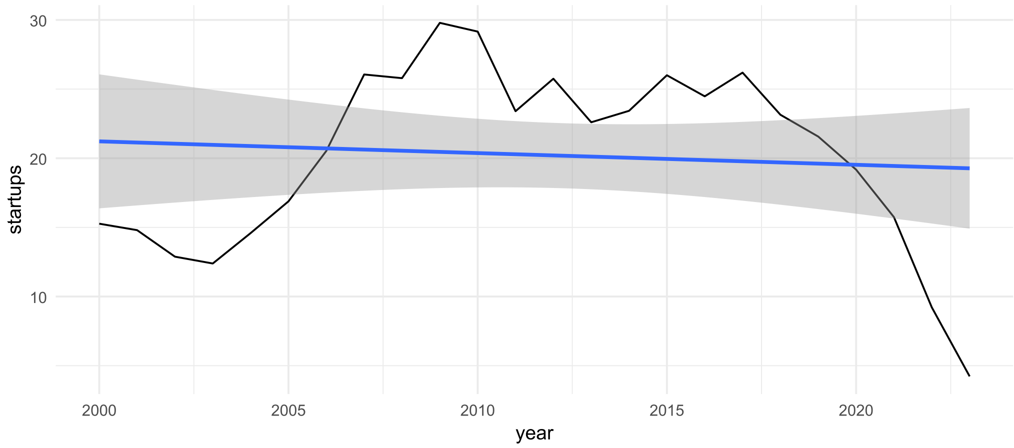


**Figure B1.** Average number of energy and green start-ups across countries, 2000–2023

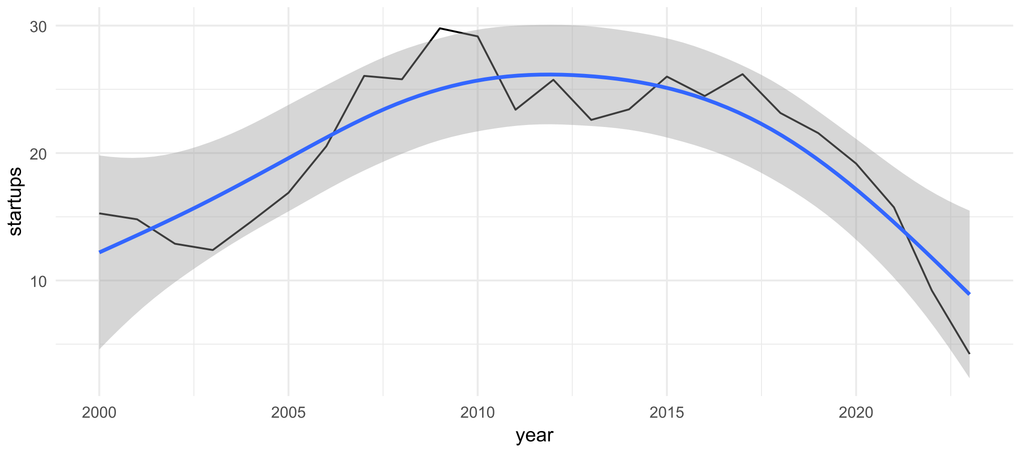


**Figure B2.** Public RD&D expenditures in renewable energy technologies (million euros), 2000–2023

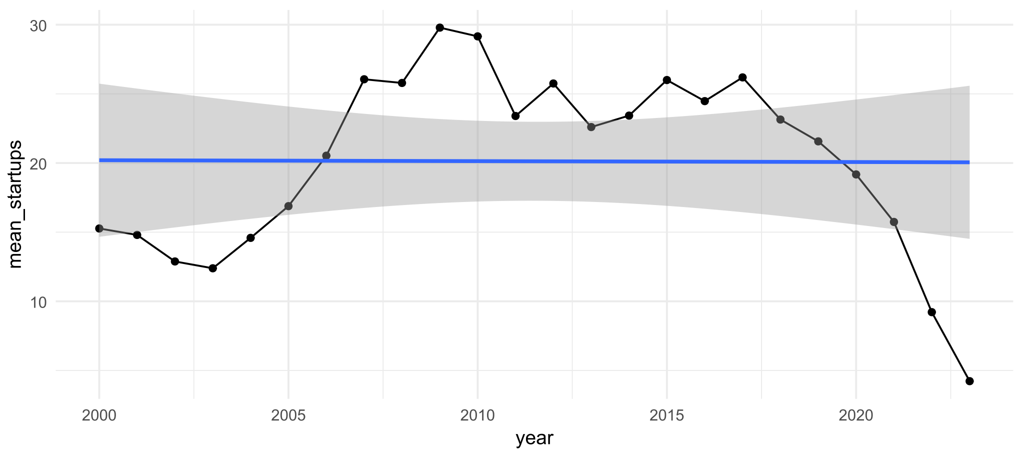


**Figure B3.** Public RD&D expenditures in other power and storage technologies (million euros), 2000–2023

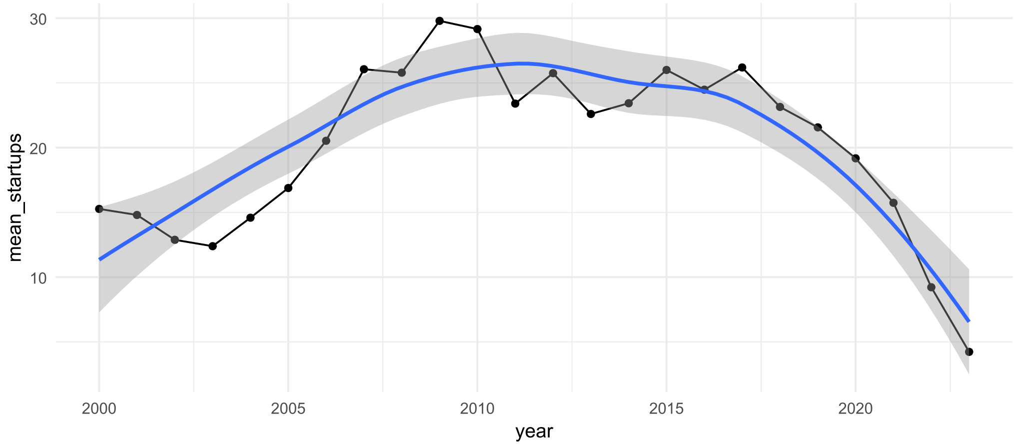


**Figure B4.** Public RD&D expenditures in low-carbon energy technologies (million euros), 2000–2023


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