






“From knowledge creation to commercialization performance: Non-linear effects on green and digital energy start-ups”

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FROM KNOWLEDGE CREATION TO COMMERCIALIZATION PERFORMANCE: NON-LINEAR EFFECTS ON GREEN AND DIGITAL ENERGY START-UPS

Abstract

The conversion of knowledge into organizational and market performance is a central challenge for innovation-driven economies. This study examines how innovation activity and its commercialization shape the entrepreneurial performance of knowledge ecosystems, using green and digital energy start-ups as an empirical context. The aim is to investigate the non-linear relationships among knowledge creation, knowledge commercialization, and start-up development, with particular attention to whether mismatches between innovation activity and market uptake generate diminishing returns or imitation-driven entrepreneurial dynamics. The analysis is based on a balanced panel of 37 countries over the period 2018–2023, comprising 222 country-year observations. The methodology applies TWFE with DK standard errors, complemented by quadratic specifications, turning-point analysis, and lagged models. The findings reveal an inverted U-shaped relationship between innovation commercialization and start-up activity, confirmed by negative, significant squared terms for sales of new-to-market and new-to-firm innovations in green start-ups ($\beta_2 = -0.1588$) and digital start-ups ($\beta_2 = -0.1462$), with turning points at 0.1428 and 0.0021, respectively. Funding dynamics demonstrate threshold effects: product innovation has a U-shaped relationship with early-stage digital funding ($\beta_2 = 2.0630$), while process innovation strengthens later-stage funding for green ($\beta_2 = 1.8100$) and digital start-ups ($\beta_2 = 1.8434$). The knowledge commercialization gap positively affects digital start-ups ($\beta = 0.1111$), suggesting that uncommercialized knowledge may stimulate market entry. Lagged results confirm temporal effects, with past innovation commercialization reducing digital start-up activity ($\beta = -0.2483$). Knowledge creation alone does not ensure performance growth; sustainable start-up development requires effective knowledge-to-market conversion.

Keywords

knowledge commercialization, commercialization gap, start-up performance, energy start-ups, digital start-ups, knowledge transfer, entrepreneurial ecosystems

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INTRODUCTION

The ability to convert knowledge into organizational and market performance has become a central challenge for contemporary innovation systems. Knowledge creation alone does not guarantee economic value, competitive advantage, or sustainable entrepreneurial growth unless it is effectively identified, transferred, commercialized, and embedded in market-oriented activities (Bartosova et al., 2023). In this context, innovation-driven entrepreneurship represents one of the key mechanisms through which knowledge is transformed into new products, services, business models, and investment opportunities. However, the relationship

between knowledge generation and performance outcomes is not automatic. It depends on the capacity of firms, start-ups, and national innovation ecosystems to translate innovation activity into commercially viable, scalable solutions.

This problem is particularly visible in green and digital energy start-up ecosystems, where the creation and application of knowledge are closely connected with technological change, environmental transformation, and market development (Prokopenko et al., 2024). Recent reports by the International Energy Agency emphasize that achieving climate neutrality and energy security requires not only technological breakthroughs but also the rapid scaling and diffusion of innovations through start-ups and new market entrants (IEA, 2023a; 2023b). In parallel, the International Renewable Energy Agency highlights that renewable energy deployment and digitalization are increasingly driven by entrepreneurial ecosystems that can transform technological advances into market-ready solutions (IRENA, 2022; 2023). Therefore, energy start-ups provide a relevant empirical context for analyzing how knowledge-intensive innovation is converted into organizational and market performance (Prokopenko et al., 2023). These firms accelerate the diffusion of clean technologies, including renewables, storage, and smart energy systems, yet their development remains highly concentrated in a limited number of countries and innovation hubs (IEA, 2023a).

At the same time, evidence from the European Commission suggests that improvements in innovation performance do not always translate proportionally into economic or market outcomes. According to the European Innovation Scoreboard, while many countries report stable or increasing levels of SME innovation activity, the commercialization of these innovations remains uneven and, in some cases, inefficient (EC, n.d.). This mismatch between innovation creation and market uptake reflects a broader knowledge-management problem: the existence of knowledge and innovation assets does not necessarily ensure their effective application, diffusion, or monetization (Bashynska et al., 2024). Consequently, the persistence of innovation without corresponding commercial success raises questions about the efficiency of knowledge transfer, the quality of entrepreneurial activity, and the possible emergence of less differentiated or weakly market-validated business models (Zolkover & Ovcharenko, 2024).

Furthermore, recent analytical reports indicate that innovation systems may exhibit non-linear dynamics, in which additional investments in research and development or innovation activity do not necessarily yield proportional gains in entrepreneurial and market outcomes. Both the International Energy Agency and the International Renewable Energy Agency point to diminishing returns in mature innovation ecosystems, particularly when regulatory frameworks, market demand, and financing mechanisms fail to keep pace with the expansion of innovation activity (IEA, 2023a; IRENA, 2022, 2023). In such conditions, excessive knowledge creation without effective commercialization pathways may lead to market saturation, inefficient capital allocation, and entrepreneurial entry that is less clearly differentiated from existing market solutions. These challenges highlight the need to better understand the non-linear relationships among knowledge creation, innovation, commercialization, and entrepreneurial performance, using green and digital energy start-ups as a knowledge-intensive empirical context.

1. LITERATURE REVIEW

Knowledge has become a central intangible asset through which organizations, start-ups, and innovation ecosystems generate performance, resilience, and competitive advantage. In entrepreneurial settings, knowledge is not valuable only as an input into innovation; it becomes strategically important when it is transformed into orga-

nizational capabilities, commercial solutions, and scalable business models. Entrepreneurial ecosystems are therefore increasingly understood as knowledge-based systems shaped by institutional, technological, and behavioral factors (Bielialov & Gechbaia, 2023). Within these systems, entrepreneurial orientation, leadership, organizational ambidexterity, and managerial capabilities influence firms' ability to transform knowledge into inno-

vation performance and long-term resilience (Abu Taleb et al., 2025; Arfara & Karasavvoglou, 2026; Fitriningrum et al., 2025; Saba et al., 2025). Start-up success also depends on individual and contextual knowledge-related factors, including entrepreneurial attitudes, self-efficacy, and ecosystem quality, which affect firm creation, survival, and growth (Yassin et al., 2024; Subin & Divyashree, 2026). At the macro level, labor market structures and the composition of human capital shape the knowledge base available for entrepreneurial activity, explaining why start-up performance differs significantly across countries (Wosiek, 2025).

The literature on innovation and knowledge management emphasizes that organizational performance depends not only on the existence of knowledge resources but also on their effective use, integration, and commercialization. Innovation processes are multidimensional and include product, process, and organizational innovations, each reflecting a different mechanism for transforming knowledge into market value. Knowledge management and resource-based capabilities strengthen firm performance by supporting the creation, storage, transfer, and application of knowledge within and across organizations (Alemu, 2025; Fithri et al., 2025; Kuzior et al., 2024; Tippakoon et al., 2025). In sustainability-oriented sectors, eco-innovation and green relational capital further demonstrate that knowledge-based capabilities can improve environmental and business performance when they are embedded in entrepreneurial strategies and stakeholder relationships (Rokhman et al., 2026; Živković & Štrbac, 2025; Vaičiūtė & Išoraitė, 2025). Digital maturity is also an important condition for knowledge-based innovation performance, because technological readiness determines how effectively firms can absorb, process, and apply knowledge in new products, services, and business processes (Semrádová Zvolánková & Krajčík, 2024; Bashynska et al., 2023). However, the relationship between innovation and performance is not always linear, as additional knowledge creation may yield diminishing returns when diffusion, absorption, or commercialization mechanisms are weak.

Green and digital energy start-ups provide a particularly relevant empirical context for analyzing the conversion of knowledge into entrepreneur-

ial and market performance. These firms operate in knowledge-intensive environments characterized by technological complexity, regulatory uncertainty, and strong dependence on infrastructure and financing conditions (Klymenchukova & Riashchenko, 2023). The development of renewable energy start-ups is shaped by grid reliability, access to capital, and regulatory frameworks, which can either accelerate or constrain the transformation of technical knowledge into viable market solutions (Lyeonov et al., 2025a; Myroshnychenko et al., 2024; Podosynnikov et al., 2024). Investment in renewable energy start-ups is also associated with considerable risk, because investors must evaluate uncertain technologies, long commercialization horizons, and changing market conditions (Dobrovolska et al., 2024; Tong & Saladrignes, 2025; Bashynska et al., 2026). At the same time, servitization, digital platforms, and data-driven business models are changing how energy firms create and capture value, allowing start-ups to participate in new knowledge-based value chains (Singh et al., 2022; Mercer-Bey, 2025). Empirical studies further show that infrastructure quality, financial incentives, green promotion, and policy support can strengthen renewable energy entrepreneurship by improving the external conditions under which knowledge is commercialized (Lyeonov et al., 2025b; Burrell et al., 2025; Oláh et al., 2024). The interaction between policy support, technological capabilities, and ecosystem conditions is therefore essential for empowering green energy start-ups and for improving the performance of knowledge-intensive ventures (Alka et al., 2026).

A key challenge in knowledge-based entrepreneurship is the difficulty of translating knowledge into commercial applications. Start-ups often face a “valley of death” when they attempt to transform technological knowledge into viable products, services, and business models. High-technology ventures may possess valuable knowledge assets but still fail to commercialize them due to financing constraints, insufficient market readiness, institutional barriers, or weak business model design (Gbadegeshin et al., 2022; Romme et al., 2023). Start-up failure is frequently connected with structural weaknesses in entrepreneurial ecosystems and with poor alignment between innovation outputs and market needs (D’Andrea et al., 2023).

For this reason, government support, incubators, venture builders, and lean start-up approaches are increasingly viewed as mechanisms that help firms convert knowledge into commercial performance (Islam et al., 2018; Jurgelevičius & Raišienė, 2025; Ghezzi & Cavallo, 2020). Knowledge transfer also depends on proximity, networks, and collaboration between universities, firms, and other ecosystem actors, as these relationships improve access to external knowledge and strengthen start-up performance (Kuzior et al., 2024; Zahidi et al., 2025; Behar-Villegas et al., 2024). Methodological innovations, including digital ethnography, additionally support a deeper understanding of how entrepreneurial knowledge is created, exchanged, and applied in dynamic innovation ecosystems (Oe & Weeks, 2025).

The concept of knowledge commercialization gaps is especially important for explaining why innovation activity does not always generate proportional entrepreneurial or financial outcomes. Such gaps emerge when knowledge creation exceeds the capacity of firms and ecosystems to commercialize, scale, or monetize innovation. In this situation, high levels of innovation activity may coexist with weak market performance, duplication of ideas, or imitation-driven entrepreneurship. This problem is particularly relevant in green and digital sectors, where rapid technological change and strong policy incentives can encourage new firm entry even when differentiation and market validation remain limited. Studies on smart cities and digital ecosystems suggest that technological development does not always have a positive relationship with start-up ecosystem performance, indicating that knowledge-intensive environments may produce inverse or non-linear effects when commercialization mechanisms are insufficient (Kuzior et al., 2025; Mursalov et al., 2023). Similarly, research on sustainable business models and open innovation shows that value creation depends not only on knowledge inputs but also on the ability to design user-oriented solutions and effective commercialization processes (Baldassarre et al., 2017; Spender et al., 2017; Heikkilä et al., 2018).

Financial and institutional conditions are also central to converting knowledge into performance. Access to capital, investment practices, and financial structures determines whether knowledge-

based ventures can move from experimentation to market entry and scaling. Early-stage financing can be interpreted as market validation of knowledge-based ventures, while later-stage funding reflects the ability of commercialized knowledge to support growth and scaling. However, regulatory barriers, administrative burdens, and weak institutional environments may reduce start-ups' ability to transform knowledge into commercial outcomes (Benlefki et al., 2024; Pacheco-Torgal, 2017; Podosynnikov et al., 2024). The relationship between external knowledge sourcing, public support, and innovation performance is also heterogeneous, as the effect of policy support depends on firm capabilities, ecosystem maturity, and the stage of venture development (Tippakoon et al., 2025; Goldstein et al., 2020; Ginevičius et al., 2025). This suggests that knowledge commercialization is not only a firm-level process but also an ecosystem-level performance outcome shaped by financial, institutional, and strategic conditions.

The literature demonstrates that knowledge creation, innovation, commercialization, and entrepreneurial performance are closely interconnected but are governed by complex, often non-linear relationships. Existing studies have identified important determinants of start-up emergence, financing, innovation transfer, and performance. However, less attention has been paid to the possibility that excessive or poorly aligned knowledge creation may generate diminishing returns, threshold effects, or imitation-driven entrepreneurial dynamics. This gap is particularly important in green and digital energy start-up ecosystems, where innovation intensity is high, but market absorption, financing, and commercialization capacity remain uneven across countries. This study addresses this gap by examining non-linear relationships between innovation activity, knowledge commercialization gaps, and the entrepreneurial performance of green and digital energy start-up ecosystems.

This study aims to investigate how knowledge creation and knowledge commercialization shape the entrepreneurial performance of green and digital energy start-up ecosystems, focusing on non-linear effects, commercialization gaps, and the possibility that imbalances between innovation activity and market uptake generate diminishing returns or imitation-driven start-up dynamics.

2. METHODOLOGY

This study investigates the relationship between innovation activity, its commercialization, and entrepreneurial dynamics in the energy sector using a panel dataset covering the period 2018–2023. The empirical analysis is based on a cross-country panel of 37 economies, resulting in 222 country-year observations.

The dependent variables capture both entrepreneurial activity and the financial performance of knowledge-based start-up ecosystems. They include the number of energy and green start-ups, the number of energy and digital start-ups, as well as early-stage and later-stage funding volumes. Start-up counts are interpreted as indicators of entrepreneurial outcomes arising from knowledge creation and innovation activity. Early-stage funding is considered a proxy for the market validation of knowledge-based ventures, reflecting investors' initial assessment of the commercial potential of innovative ideas. Later-stage funding is treated as a proxy for the scaling performance of commercialized knowledge, indicating the ability of start-ups to expand, attract larger capital flows, and transform innovation into sustained market growth. These data are obtained from the International Energy Agency's Energy Start-up Data Explorer (IEA, n.d.), which provides harmonized cross-country data on energy start-up ecosystems.

The key explanatory variables reflect different dimensions of innovation activity and its commercialization. Indicators of SMEs introducing business process innovations, SMEs introducing product innovations, and sales of new-to-market and new-to-firm innovations are drawn from the European Innovation Scoreboard (EC, n.d.), ensuring comparability across countries. These variables capture, respectively, organizational innovation, product-based innovation, and the extent to which innovations are successfully translated into market outcomes. To account for broader macro-economic and technological conditions, the model includes GDP per capita (PPP, constant 2021 international dollars) from the World Bank (n.d.) and research and development expenditure as a share of GDP from the United Nations Economic Commission for Europe (UNECE, n.d.). Together,

these variables provide a comprehensive framework for analyzing both innovation inputs and outputs within national innovation systems.

A detailed description of all variables, including their empirical roles, measurements, interpretations, and data sources, is provided in Appendix B. This table is intended to clarify the proxy-based operationalization of knowledge creation, knowledge commercialization, and entrepreneurial performance used in the empirical analysis.

It should be noted that the empirical indicators used in this study are macro-level proxies rather than direct measures of all the theoretical mechanisms discussed in the paper. SME product and process innovation indicators are used to approximate knowledge creation and innovation activity at the ecosystem level, while sales of new-to-market and new-to-firm innovations proxy the degree to which innovation is translated into market outcomes. The knowledge commercialization gap and the knowledge commercialization gap ratio are therefore operational constructs that capture the mismatch between innovation activity and commercialized innovation. They should not be interpreted as direct measures of knowledge-transfer quality, imitation behavior, market saturation, or the commercial maturity of individual start-ups. Instead, these mechanisms are treated as theoretically grounded interpretations of the observed macro-level relationships.

The study covers 37 countries, including Albania, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Moldova, Netherlands, North Macedonia, Norway, Poland, Portugal, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, and the United Kingdom. This selection ensures a balanced and comparable panel structure while minimizing missing data. However, it may limit the generalizability of the findings to countries with well-developed statistical reporting systems and innovation measurement frameworks. The cross-country comparability of the dataset is ensured by the use of harmonised international data sources. The innovation indicators are taken from the European

Innovation Scoreboard, which applies a consistent methodology across European countries and covers economies integrated into, associated with, or closely aligned with the European innovation and market framework, including EU member states, associated or candidate countries, and the former EU member state, the United Kingdom. Differences in currencies and macroeconomic scales are additionally addressed by using funding data reported in US dollars, GDP per capita in PPP constant international dollars, and standardised innovation indicators. At the same time, differences in economic development, institutional maturity, and country- and year-specific political and economic conditions are controlled for using GDP per capita, R&D expenditure, country fixed effects, and year fixed effects. Although countries such as Ukraine have specific political and economic circumstances during the analysed period, the two-way fixed-effects framework allows the analysis to account for persistent country-specific characteristics and common time shocks, while the results are interpreted as average cross-country effects rather than country-specific estimates.

Given the strong skewness and presence of extreme values in start-up and funding variables, logarithmic transformations ($\ln(1+x)$) are applied to all dependent variables to stabilize variance and reduce the influence of outliers. Innovation indicators are standardized (z-scores) to ensure comparability of coefficients across variables measured in different units. In addition, winsorization at the 1st and 99th percentiles is employed for funding variables to mitigate the impact of extreme observations. To explicitly capture the potential mismatch between innovation creation and its commercialization, two additional variables are constructed: the knowledge commercialization gap, defined as the difference between the number of product innovations introduced by SMEs and the sales of new-to-market and new-to-firm innovations, and the knowledge commercialization gap ratio, defined as the proportion of commercialized innovations relative to total innovation activity.

The empirical strategy relies on panel-data regression models with two-way fixed effects, controlling for unobserved heterogeneity across countries and over time. All models include country- and year-fixed effects, allowing the estimation to focus on within-

country variation over time. To account for potential cross-sectional dependence, serial correlation, and heteroskedasticity, Driscoll-Kraay standard errors are employed, which are particularly suitable for macro-panel settings with relatively short time dimensions. The baseline specification examines linear relationships between innovation indicators and entrepreneurial outcomes. At the same time, extended models incorporate quadratic terms to test for non-linear effects, reflecting the hypothesis that moderate levels of innovation stimulate entrepreneurship. In contrast, excessive levels may lead to diminishing returns or imitation-driven activity.

To improve the transparency of the empirical strategy, the estimated models can be formalized as follows. The baseline two-way fixed-effects specification is:

$$Y_{it} = \alpha + \beta_1 Proc_{it} + \beta_2 Prod_{it} + \beta_3 Sales_{it} + \gamma_1 GDP_{it} + \gamma_2 RD_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \quad (1)$$

where Y_{it} denotes one of the dependent variables for country i in year t , including green start-ups, digital start-ups, early-stage funding, or later-stage funding. $Proc_{it}$ represents SMEs introducing business process innovations, $Prod_{it}$ represents SMEs introducing product innovations, and $Sales_{it}$ captures sales of new-to-market and new-to-firm innovations. Gap_{it} denotes log GDP per capita, RD_{it} denotes R&D expenditure as a share of GDP, μ_i captures country fixed effects, λ_t captures year fixed effects, and ε_{it} is the error term.

To test for non-linear effects, the following quadratic specification is estimated:

$$Y_{it} = \alpha + \beta_1 Proc_{it} + \beta_2 Proc_{it}^2 + \beta_3 Prod_{it} + \beta_4 Prod_{it}^2 + \beta_5 Sales_{it} + \beta_6 Sales_{it}^2 + \gamma_1 GDP_{it} + \gamma_2 RD_{it} + \mu_i + \lambda_t + \varepsilon_{it}. \quad (2)$$

This specification allows the analysis to identify whether innovation activity and commercialization have U-shaped or inverted U-shaped relationships with entrepreneurial outcomes. For statistically significant quadratic relationships, the turning point is calculated as:

$$TP = -\frac{\beta_1}{2\beta_2}, \quad (3)$$

where TP denotes the value of the explanatory variable at which the direction of the relationship changes.

To examine the role of mismatches between knowledge creation and market uptake, additional models are estimated using the knowledge commercialization gap and the knowledge commercialization gap ratio:

$$Y_{it} = \alpha + \delta_1 Gap_{it} + \delta_2 Gap_{it}^2 + \gamma_1 GDP_{it} + \gamma_2 RD_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \quad (4)$$

$$Y_{it} = \alpha + \theta_1 Ratio_{it} + \theta_2 Ratio_{it}^2 + \gamma_1 GDP_{it} + \gamma_2 RD_{it} + \mu_i + \lambda_t + \varepsilon_{it}, \quad (5)$$

where Gap_{it} captures the difference between SME product innovation and sales of new-to-market and new-to-firm innovations, while $Ratio_{it}$ captures the proportion of commercialized innovation relative to total innovation activity.

Finally, lagged specifications are estimated to account for delayed effects and reduce concerns about reverse causality:

$$Y_{it} = \alpha + \beta_1 X_{i,t-1} + \beta_2 X_{i,t-1}^2 + \gamma_1 GDP_{i,t-1} + \gamma_2 RD_{i,t-1} + \mu_i + \lambda_t + \varepsilon_{it}, \quad (6)$$

where $X_{i,t-1}$ denotes the lagged innovation, commercialization, knowledge commercialization gap, or knowledge commercialization gap ratio variable. All models include country and year fixed effects, and Driscoll-Kraay standard errors are used to address heteroskedasticity, serial correlation, and cross-sectional dependence.

To further strengthen causal interpretation, lagged specifications are estimated in which all explanatory variables enter the model with a one-period lag. This approach reduces concerns about reverse causality and enables the analysis to capture the delayed effects of innovation activity on start-up formation and funding. Turning point analysis is subsequently conducted for all significant quadratic relationships, with thresholds calculated as $-\beta_1/(2\beta_2)$, enabling the identification of critical levels of innovation intensity at which the direction of the relationship changes. This methodological

framework enables a comprehensive assessment of both linear and non-linear dynamics linking innovation systems to entrepreneurial outcomes in the energy sector.

All data processing, variable construction, and econometric estimations are conducted using RStudio v 4.4.0, ensuring reproducibility and transparency of the analytical procedures.

3. RESULTS

The descriptive statistics reveal substantial heterogeneity across countries in both the scale and the nature of green and digital energy start-up activity. While the average number of energy and green start-ups is 9.77, the median is only 2, indicating that most country-year observations are characterized by very low start-up activity, with only a small number of countries exhibiting exceptionally high values (a maximum of 113). A similar pattern is observed for energy and digital start-ups (mean 5.65; median 2). This strong right skewness (skewness above 3 and high kurtosis) suggests that start-up ecosystems are highly concentrated among a limited number of innovation leaders. Funding variables exhibit even greater dispersion, with means ranging from 32 to 49 million USD and medians close to zero for later-stage investments, indicating that many countries receive little or no venture funding. At the same time, a few attract very large investment volumes. This pattern reflects structural inequalities in access to finance and points to the existence of “hub economies” dominating green and digital innovation.

In contrast, indicators related to innovation activities among SMEs appear more symmetrically distributed and less volatile. The variables capturing SMEs introducing business process and product innovations show relatively moderate dispersion and near-zero skewness, suggesting that incremental innovation activities are more evenly distributed across countries. Similarly, sales of new-to-market and new-to-firm innovations exhibit only mild skewness, suggesting a more balanced pattern of commercialization outcomes than the highly concentrated start-up and funding variables. However, the coexistence of highly skewed start-up activity with relatively stable SME inno-

vation indicators may signal a potential mismatch between start-up dynamics and actual innovation commercialization, supporting the hypothesis that not all start-up growth translates into genuinely novel market innovations.

Given the pronounced non-normality and presence of extreme outliers in key variables, particularly start-up counts and funding measures, the descriptive statistics confirm the relevance of the transformation procedures described in the Methodology section. The logarithmic transformation of dependent variables, winsorization of funding indicators, and standardization of innovation variables reduce the influence of extreme observations, stabilize variance, and improve coefficient comparability across indicators. Therefore, the subsequent panel estimates are based on transformed and standardized variables rather than raw distributions.

The results based on Driscoll-Kraay standard errors (Table 1) provide robust evidence on the non-linear relationship between innovation dynamics and start-up activity. For both green and digital start-ups (models 1 and 2), the most consistent and statistically significant finding concerns the squared term for sales of new-to-market and new-to-firm innovations. The negative and significant coefficient for the squared term indicates an inverted U-shaped relationship, suggesting that

moderate levels of innovation commercialization are associated with higher start-up activity. In contrast, excessive levels are associated with a decline in start-up formation. This pattern supports the hypothesis that beyond a certain threshold, innovation systems may become saturated, leading to imitation rather than genuinely novel entrepreneurial activity. In contrast, SME process and product innovation indicators do not exhibit robust linear effects on start-up counts. However, weak evidence of non-linearity is observed for product innovation, particularly in the green start-up model.

Although several coefficients are statistically significant, the within R² values indicate that the models explain only a limited share of short-term within-country variation. This is expected in a two-way fixed-effects framework with a short panel and slowly changing innovation indicators, where much of the variation is absorbed by country and year effects. Therefore, the results should not be interpreted as evidence of strong predictive power at the country-year level. Rather, they indicate specific non-linear associations between innovation commercialization indicators and entrepreneurial outcomes after controlling for unobserved country heterogeneity and common time shocks.

The analysis of early-stage funding reveals a different pattern. In model 3, SME process innova-

Table 1. Non-linear effects of innovation indicators on start-ups and funding (Driscoll-Kraay standard errors)

Variables	(1) Green start-ups	(2) Digital start-ups	(3) Early funding (green)	(4) Late funding (green)	(5) Early funding (digital)	(6) Late funding (digital)
SME process innovation	0.0462	0.0300	1.519**	-1.460	1.893*	0.2244
SME process innovation ²	-0.0885	-0.0020	-0.4179	1.810**	-1.737	1.843**
SME product innovation	-0.0266	-0.0744	-0.8365	0.4135	-1.360*	-0.1212
SME product innovation ²	0.1066*	0.1405	1.214	0.0112	2.063*	-0.7942
Sales of new-to-market and new-to-firm innovations	0.0454	0.0006	-1.521	0.1508	-0.7952	-0.8187
Sales of new-to-market and new-to-firm innovations ²	-0.1588**	-0.1462*	1.210	-0.7673	0.7697	0.3544
GDP per capita (log)	1.411	1.419	-4.411	0.2440	-3.428	-2.099
R&D expenditure	0.2281	0.2312	-2.233	-1.433	-2.236	-1.425
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	222	222	222	222	222	222
R ²	0.917	0.888	0.748	0.744	0.714	0.740
Within R ²	0.070	0.077	0.052	0.045	0.051	0.064

Note: Driscoll-Kraay standard errors in parentheses. ***, **, and *, denote significance at the 1%, 5%, and 10% levels, respectively.

tion has a positive, statistically significant effect on early-stage funding for green start-ups, indicating that improvements in organizational and operational capabilities are associated with greater investor interest. However, the absence of a significant quadratic term suggests that this relationship is largely linear. For early-stage digital funding (model 5), both linear and quadratic terms of product innovation are significant with opposite signs, indicating a U-shaped relationship. This implies that only sufficiently high levels of product innovation attract funding, whereas intermediate levels may be less attractive to investors. These findings highlight that early-stage financing is selective and sensitive to the depth and quality of innovation.

The results for later-stage funding (models 4 and 6) further emphasize the importance of non-linear effects. The positive and significant squared terms for SME process innovation indicate that funding responsiveness increases at higher levels of innovation intensity, suggesting threshold effects in more mature stages of venture development. Additionally, weak evidence of a negative non-linear effect on sales of new-to-market and new-to-firm innovations in green later-stage funding suggests diminishing returns to commercialization intensity. These patterns suggest that venture capital allocation is not uniform but varies significantly across innovation types and financing stages.

The adjustment of the Driscoll-Kraay variance-covariance matrices due to non-positive semi-

definiteness reflects the short time dimension of the panel. Therefore, the statistical significance of individual coefficients should be interpreted with caution. However, the consistency of the main non-linear patterns across contemporaneous, turning-point, and lagged specifications supports the robustness of the overall interpretation. Nevertheless, the persistence of key non-linear relationships, particularly the inverted U-shaped effect of innovation commercialization on start-up activity, strengthens the overall conclusion that the relationship between innovation and entrepreneurship is fundamentally non-linear and subject to diminishing returns.

The turning point analysis (Table 2) provides strong support for the existence of economically meaningful non-linear relationships between innovation indicators and both start-up activity and funding dynamics. Importantly, all estimated turning points lie within the observed range of the data, confirming that the identified quadratic effects are not merely statistical artefacts but reflect substantively relevant thresholds. For both green and digital start-ups, the relationship with sales of new-to-market and new-to-firm innovations follows an inverted U-shape, with turning points at 0.1428 and 0.0021 (in standardized terms), respectively. This indicates that start-up activity increases with higher levels of innovation commercialization up to a certain point, beyond which additional increases are associated with declining start-up formation. This finding is consistent with the notion of an “innovation saturation” or “imitation”

Table 2. Turning points of non-linear relationships between innovation indicators and entrepreneurial outcomes

Dependent variable	Innovation indicator	β_1	β_2	Turning point (z-score)	Observed range (z)	Within range	Shape	Observed range (original units)
Green start-ups	Sales of new-to-market and new-to-firm innovations	0.0454	-0.1588	0.1428	[-1.9727; 2.3293]	Yes	Inverted U-shape	[0;187.31]
Digital start-ups	Sales of new-to-market and new-to-firm innovations	0.0006	-0.1462	0.0021	[-1.9727; 2.3293]	Yes	Inverted U-shape	[0;187.31]
Early funding (digital)	SMEs introducing product innovations	-1.3596	2.0630	0.3295	[-2.0916; 2.1495]	Yes	U-shape	[0;225.27]
Late funding (green)	SMEs introducing business process innovations	-1.4598	1.8100	0.4033	[-2.0306; 2.1319]	Yes	U-shape	[0;218.29]
Late funding (digital)	SMEs introducing business process innovations	0.2244	1.8434	-0.0609	[-2.0306; 2.1319]	Yes	U-shape	[0;218.29]

Note: Turning points are calculated as $-\beta_1/(2\beta_2)$. All variables are standardized (z-scores). The original units correspond to the raw values of the respective indicators. All reported turning points lie within the observed range, confirming the economic relevance of the estimated non-linear effects.

Table 3. Effects of the knowledge commercialization gap on start-ups and funding (Driscoll–Kraay standard errors)

Variables	(1) Green start-ups	(2) Digital start-ups	(3) Early funding (green)	(4) Late funding (green)	(5) Early funding (digital)	(6) Late funding (digital)
Knowledge commercialization gap	0.0782	0.1111*	0.7875	0.8293	0.4194	0.5446
Knowledge commercialization gap ²	-0.0051	-0.0345	0.9772*	-0.8423	0.8465	-1.260.
GDP per capita (log)	1.515.	1.340	-6.551	-1.184	-3.596	-5.965
R&D expenditure	0.2081	0.2069	-2.648*	-1.033	-2.780	-1.341
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	222	222	222	222	222	222
R ²	0.914	0.884	0.738	0.734	0.701	0.724
Within R ²	0.033	0.035	0.013	0.008	0.006	0.007

Note: Driscoll–Kraay standard errors in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

effect, in which excessive commercialization may diminish the novelty of entrepreneurial activity.

In contrast, the results for funding variables reveal predominantly U-shaped relationships, indicating threshold effects rather than diminishing returns. For early-stage digital funding, the turning point for SMEs introducing product innovations is estimated at 0.3295, suggesting that only sufficiently high levels of product innovation stimulate investment. In contrast, lower or moderate levels may be insufficient to attract funding. A similar pattern is observed for later-stage funding, where SMEs introducing business process innovations exhibit turning points at 0.4033 (green) and -0.0609 (digital). These results imply that investors respond more strongly once innovation intensity surpasses a certain threshold, reflecting increasing selectivity in capital allocation as projects mature.

Taken together, the turning point estimates highlight a clear asymmetry between start-up formation and funding dynamics. While start-up activity is characterized by diminishing returns to innovation commercialization, funding processes appear to require a minimum level of innovation intensity before responding positively. This divergence suggests that innovation ecosystems may simultaneously experience over-expansion in entrepreneurial entry alongside increasing selectivity in financial support. The findings reinforce the central argument that the relationship between innovation and entrepreneurship is inherently non-linear and governed by threshold and saturation effects.

Table 3 provides nuanced evidence regarding the role of the innovation–commercialization gap in shaping entrepreneurial dynamics. Starting with the linear specifications, the coefficient of the knowledge commercialization gap is positive and statistically significant only for digital start-ups, suggesting that a larger gap between innovation creation and its commercialization is associated with higher start-up activity in the digital energy sector. This may reflect an expansion of start-up entry associated with the diffusion of uncommercialized knowledge, although the data do not allow direct identification of imitation-based behavior. However, for green start-ups and all funding variables, the knowledge commercialization gap remains statistically insignificant, indicating that the mismatch between innovation and commercialization does not systematically translate into financing outcomes or broader entrepreneurial activity in a linear framework.

The results based on the knowledge commercialization gap ratio further reinforce the absence of strong linear effects. The coefficients are generally insignificant across both start-up and funding models, with only weak evidence of a negative association for later-stage digital funding. This suggests that a higher proportion of commercialized innovation relative to total innovation activity does not directly stimulate entrepreneurial activity or funding. In other words, the efficiency of innovation commercialization alone does not appear to be a sufficient driver of entrepreneurial performance of knowledge ecosystems, or investment flows, when considered in a linear setting.

Table 4. Effects of the knowledge commercialization gap ratio on start-ups and funding (Driscoll–Kraay standard errors)

Variables	(1) Green start-ups	(2) Digital start-ups	(3) Early funding (green)	(4) Late funding (green)	(5) Early funding (digital)	(6) Late funding (digital)
Knowledge commercialization gap ratio	-0.1038*	-0.1090.	-0.6218	0.9290	-0.3899	0.3596
Knowledge commercialization gap ratio ²	0.0406*	0.0267	0.1524*	-0.7280*	0.0908	-0.5370.
GDP per capita (log)	1.325	1.229	-6.994	3.629	-3.952	-2.990
R&D expenditure	0.2389	0.1957	-2.780*	-2.687	-2.840	-2.575
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	222	222	222	222	222	222
R ²	0.915	0.883	0.737	0.753	0.701	0.739
Within R ²	0.047	0.030	0.010	0.079	0.006	0.061

Note: Driscoll–Kraay standard errors in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

However, the non-linear specifications (Table 4) reveal more meaningful patterns. For the knowledge commercialization gap ratio, both green and digital start-ups exhibit a U-shaped relationship, with a negative linear term and a positive squared term. This indicates that at low levels of commercialization efficiency, increases in the ratio are associated with declining start-up activity. In contrast, beyond a certain threshold, further improvements in commercialization begin to stimulate entrepreneurial entry. A similar pattern is observed for early-stage green funding, where the positive and significant squared term suggests that only sufficiently high levels of commercialization efficiency attract investment. In contrast, for later-stage funding (both green and digital), the negative and significant squared terms indicate an inverted U-shaped relationship, suggesting diminishing returns to commercialization efficiency at more advanced financing stages.

Finally, the non-linear models based on the absolute knowledge commercialization gap provide more limited but still informative evidence. A positive and significant squared term for early-stage green funding indicates a U-shaped relationship, suggesting that both very low and very high levels of the knowledge commercialization gap may be associated with stronger funding dynamics. Conversely, weak evidence of a negative non-linear effect for later-stage digital funding suggests diminishing returns. These findings highlight that the relationship between innovation imbalances and entrepreneurial outcomes is not linear but governed by threshold effects, with different pat-

terns emerging across start-up activity and funding stages. This supports the broader argument that both insufficient and excessive mismatches between innovation creation and commercialization can shape the quality and direction of entrepreneurial ecosystems.

The lagged specifications (Table 5) provide additional insights into the temporal dynamics between innovation and entrepreneurial outcomes, strengthening the interpretation of causal direction. For start-up activity, the results indicate that past innovation commercialization has a statistically significant and negative effect on digital start-ups. In contrast, no robust effect is observed for green start-ups. This suggests that higher levels of previously realized innovation may reduce subsequent digital entrepreneurial entry, potentially reflecting market saturation or intensified competition. At the same time, the absence of strong quadratic effects implies that the non-linear relationships identified in contemporaneous models are less pronounced when temporal dynamics are taken into account. In contrast, lagged GDP per capita remains positively associated with start-up activity, confirming the importance of macroeconomic conditions in shaping entrepreneurial ecosystems.

The funding models reveal more differentiated patterns across stages and sectors. For early-stage green funding, past product innovation exhibits a weak negative effect. In contrast, process innovation shows a positive association, suggesting that investors may prioritise organizational ca-

Table 5. Lagged non-linear effects of innovation indicators on start-ups and funding (Driscoll–Kraay standard errors)

Variables	(1) Green start-ups	(2) Digital start-ups	(3) Early funding (green)	(4) Late funding (green)	(5) Early funding (digital)	(6) Late funding (digital)
Innovation sales (lag)	-0.1549	-0.2483*	-0.6981	-1.437	-2.460	-2.843.
Innovation sales ² (lag)	-0.1180	-0.0101	-0.6124	0.4989	-0.1167	1.147*
Product innovation (lag)	0.0243	0.0549	-1.766.	-0.5233	-1.336*	-0.0254
Product innovation ² (lag)	0.1420	0.0855	0.5204	-1.965.	0.2238	-0.6896
Process innovation (lag)	0.2070	0.1182	2.517.	-0.9455	1.948*	0.3061
Process innovation ² (lag)	-0.2286	-0.1348	-0.6380	3.765*	-0.3971	1.309
GDP per capita (lag, log)	1.580**	1.623*	1.463	2.372	-11.76*	-2.461
R&D expenditure (lag)	-0.1241	0.2793	-5.152*	4.341	-6.400*	5.225
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	185	185	185	185	185	185
R ²	0.917	0.887	0.779	0.767	0.751	0.747
Within R ²	0.103	0.072	0.045	0.104	0.071	0.051

Note: Driscoll–Kraay standard errors in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

pabilities over product novelty in earlier stages. Moreover, lagged R&D expenditure negatively affects early-stage green funding, indicating potential inefficiencies or delays in translating research investment into investable opportunities. For later-stage funding, the presence of significant quadratic effects for process innovation and innovation sales indicates non-linear dynamics, with threshold effects becoming more relevant as ventures mature. In particular, the positive squared term for process innovation in late-stage green funding suggests increasing returns at higher levels of innovation intensity. At the same time, the digital sector exhibits a similar pattern for innovation sales.

The analysis of the knowledge commercialization gap under lagged specifications (Table 6) provides important evidence for the study’s core hypothesis. The positive and significant coefficient of the lagged knowledge commercialization gap indicates that a larger mismatch between innovation creation and commercialization is associated with higher subsequent green start-up activity. This may reflect the emergence of start-ups exploiting uncommercialized knowledge or market gaps. However, the absence of a significant quadratic term suggests that this relationship is largely linear. In contrast, the knowledge commercialization gap ratio exhibits a negative and statistically significant linear effect alongside a positive squared

term, indicating a U-shaped relationship. This implies that at lower levels of commercialization efficiency, increases in the ratio reduce start-up activity, whereas beyond a certain threshold, further improvements begin to stimulate entrepreneurial entry.

The lagged models confirm that the relationship between innovation dynamics and entrepreneurial outcomes is both temporally dependent and structurally non-linear. While some contemporaneous effects weaken with lags, the persistence of key relationships, particularly for the knowledge commercialization gap ratio, supports the argument that the balance between innovation creation and commercialization plays a critical role in shaping entrepreneurial ecosystems over time. The warning regarding the non-positive-definite variance-covariance matrix reflects the short time dimension of the panel. It does not invalidate the results, but it suggests that they should be interpreted as robust evidence.

The obtained results also have direct managerial relevance for organizations involved in the creation, transfer, and commercialization of knowledge. For incubators and accelerators, the identified inverted U-shaped relationship means that supporting a larger number of start-ups is not always equivalent to improving ecosystem performance. Managers of incubation programs should

Table 6. Lagged effects of the knowledge commercialization gap and knowledge commercialization gap ratio on green start-ups (Driscoll–Kraay standard errors)

Variables	(1) Knowledge commercialization gap	(2) Knowledge commercialization gap ratio
Knowledge commercialization gap (lag)	0.1900*	
Knowledge commercialization gap ² (lag)	0.0022	
Knowledge commercialization gap ratio (lag)		-0.3642**
Knowledge commercialization gap ratio ² (lag)		0.0600.
GDP per capita (lag, log)	1.404*	1.144.
R&D expenditure (lag)	-0.1781	-0.1588
Country FE	Yes	Yes
Year FE	Yes	Yes
Observations	185	185
R ²	0.914	0.914
Within R ²	0.064	0.067

Note: Driscoll-Kraay standard errors in parentheses. ***, **, and * denote significance at the 1%, 5%, and 10% levels, respectively.

therefore focus not only on increasing the number of start-ups but also on assessing the commercial maturity, differentiation, and market validation of knowledge-based ideas. Universities and technology-transfer offices can use these findings to strengthen mechanisms that connect research outputs with market needs, for example, through proof-of-concept funding, industry mentoring, intellectual property support, and early customer validation. SMEs and innovation managers should also interpret the results as evidence that product and process innovations generate stronger performance effects when supported by organizational capabilities, business model development, and clear commercialization pathways.

For venture funds and investors, the threshold effects observed in funding models suggest that investment decisions should focus on the stage at which knowledge becomes commercially scalable. Early-stage funding can be seen as a signal of market validation, while later-stage funding reflects a venture’s ability to transform commercialized knowledge into sustained growth. Therefore, investors should evaluate not only technological novelty but also the quality of knowledge application, process maturity, team capabilities, and evidence of market absorption. The positive effect of the knowledge commercialization gap on digital start-ups further indicates that uncommercialized knowledge may create new entrepreneurial opportunities, but it may also encourage imitation if market differentiation is weak. Consequently, managers of start-up ecosystems should monitor

not only innovation intensity but also the balance between knowledge creation, commercialization efficiency, and market demand.

4. DISCUSSION

The empirical findings strengthen the argument that the relationship between knowledge creation, knowledge commercialization, and entrepreneurial performance is non-linear rather than automatic. From the perspective of knowledge management theory, the results show that the accumulation of innovation outputs does not necessarily lead to higher organizational or market performance unless knowledge is effectively absorbed, applied, and commercialized. The identified inverted U-shaped relationship between innovation sales and both green and digital start-ups suggests that moderate levels of commercialization support entrepreneurial entry, while excessive commercialization intensity may generate diminishing returns, market saturation, or imitation-driven dynamics. This finding contributes to knowledge management theory by showing that knowledge is not performance-enhancing in itself; its value depends on the ecosystem’s capacity to transform it into differentiated, market-validated, and scalable entrepreneurial activity. In this sense, the findings extend previous studies by demonstrating that when the pace of knowledge generation exceeds market absorption capacity, the novelty and quality of start-up activity may decline (Kuzior et al., 2025; Mursalov et al., 2023). At the same time, the

absence of strong linear effects for SME innovation indicators confirms that innovation inputs alone are insufficient to explain entrepreneurial outcomes, reinforcing the importance of knowledge application, ecosystem quality, institutional conditions, and commercialization pathways (Alemu, 2025; Tippakoon et al., 2025).

The funding-related results further develop this theoretical interpretation by showing that investors respond not simply to the presence of innovation, but to the maturity and performance potential of commercialized knowledge. The U-shaped relationships observed for product and process innovations indicate that funding becomes more responsive only after innovation intensity exceeds a critical threshold, particularly in early-stage digital funding and later-stage financing dynamics. This contributes to knowledge management and performance management literature by suggesting that financial markets act as selective evaluators of knowledge-based ventures. Early-stage funding can therefore be interpreted as market validation of knowledge-based entrepreneurial ideas, while later-stage funding reflects the scaling performance of knowledge that has already been commercialized. This finding is consistent with prior research showing that investors prioritize high-quality and scalable innovations, especially in risky sectors such as renewable energy (Dobrovolska et al., 2024; Tong & Saladrignes, 2025). Moreover, the stronger role of process innovation in later-stage funding indicates that organizational routines, operational capabilities, and business-model maturity become increasingly important as start-ups scale. This supports the view that overcoming the “valley of death” requires not only technological novelty but also effective knowledge organization, managerial capability, and ecosystem support mechanisms (Gbadegeshin et al., 2022; Romme et al., 2023).

The analysis of knowledge commercialization gaps provides an additional contribution by showing how structural mismatches between knowledge creation and market uptake shape entrepreneurial ecosystems. The positive effect of the knowledge commercialization gap on digital start-ups suggests that uncommercialized or weakly commercialized knowledge may stimulate new entry, for example, by creating opportunities for entrepre-

neurial experimentation or by supporting less differentiated business models. However, imitation-based behavior is not directly measured and should therefore be interpreted only as a possible mechanism. The U-shaped effects of the knowledge commercialization gap ratio indicate that both insufficient and excessive commercialization efficiency can influence start-up dynamics, confirming that knowledge-to-market conversion is governed by threshold effects. This finding enriches knowledge management theory by demonstrating that the efficiency of knowledge transfer and market absorption is as important as the volume of innovation itself. It also supports studies emphasizing that effective innovation ecosystems require knowledge transfer, collaboration, proximity, user-oriented value creation, and market alignment (Kuzior et al., 2024; Zahidi et al., 2025; Baldassarre et al., 2017). The lagged results further reinforce this interpretation by showing that past innovation commercialization may reduce subsequent entrepreneurial performance in digital knowledge ecosystems, possibly because previous commercialization success increases competition, reduces unexploited market space, or accelerates saturation. Overall, the findings show that sustainable start-up performance depends not on knowledge creation alone, but on the balanced conversion of knowledge into market-validated and scalable outcomes.

Despite providing novel evidence on the non-linear relationship between innovation, its commercialization, and energy start-up dynamics, this study has several limitations that open avenues for future research. First, the analysis is based on aggregated country-level data, which may obscure important heterogeneity across regions, sectors, and types of start-ups, particularly between different energy technologies or business models. Second, the relatively short time dimension (2018–2023) constrains the ability to capture long-term dynamics and structural changes in innovation ecosystems, which may evolve over longer horizons. Third, although lagged specifications are employed, the models primarily identify associations rather than fully causal relationships, as unobserved institutional, regulatory, or market-specific factors may still influence both innovation and entrepreneurial outcomes. Fourth, the use of proxy indicators for innovation and commercialization, such as SME innovation measures, may not fully capture the complexity and quality

of innovation processes. In addition, the study does not directly observe imitation-driven entrepreneurship, start-up novelty, or the commercial maturity of individual ventures; therefore, these mechanisms should be tested in future research using firm-level data, patent-level indicators, product-level information, or survey-based measures of business-model differentiation. Future research could therefore extend this analysis by incorporating micro-level firm

data, sector-specific indicators, and longer time series, as well as by applying quasi-experimental methods (e.g., difference-in-differences or instrumental variables) to strengthen causal inference. Additionally, further studies could explore the role of policy interventions, financing instruments, and institutional quality in moderating the identified non-linear relationships, as well as examine differences between emerging and advanced economies.

CONCLUSIONS

This study examined the non-linear relationships among knowledge creation, knowledge commercialization, and the entrepreneurial performance of green and digital energy start-up ecosystems, with particular attention to whether knowledge-to-market imbalances generate diminishing returns or imitation-driven entrepreneurial dynamics.

The study uses a balanced panel of 37 countries for 2018–2023, combining IEA start-up data, European Innovation Scoreboard indicators, and World Bank/UNECE controls. It applies two-way fixed-effects models with Driscoll-Kraay standard errors, quadratic specifications, turning-point analysis, and lagged models.

The results indicate non-linear links between innovation commercialization and entrepreneurial outcomes, although they should be interpreted cautiously due to proxy-based measurement and modest within-country explanatory power. Innovation sales show an inverted U-shaped relationship with green and digital start-ups, with significant squared terms of -0.1588 and -0.1462 and turning points at 0.1428 and 0.0021 . Funding also demonstrates threshold effects: product innovation supports early-stage digital funding only after a certain level ($\beta_2 = 2.0630$), while process innovation strengthens later-stage green and digital funding ($\beta_2 = 1.8100$ and 1.8434). The knowledge commercialization gap is positively associated with digital start-ups ($\beta = 0.1111$), while lagged models confirm temporal effects, including a negative effect of past innovation commercialization on digital start-ups ($\beta = -0.2483$) and a non-linear lagged effect of the commercialization gap ratio.

These findings have important policy and managerial implications. Policy support should focus not only on increasing knowledge creation but also on improving its conversion into marketable and scalable outcomes. Public measures should strengthen commercialization pathways, R&D–industry cooperation, financial instruments, and stage-specific support for moving innovations from product development to market deployment. For managers, incubators, universities, SMEs, and venture funds, the key task is to assess not only the number of innovations or start-ups but also their commercial maturity, differentiation, customer validation, and scalability. A balanced approach linking knowledge creation with market demand and business model development is essential for the sustainable growth of green and digital energy start-ups.

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APPENDIX A

Table A1. Descriptive statistics of variables used in the analysis

Source: Authors' calculations in R.

Variable	Mean	Median	Std. Dev.	Min	Max	Skewness	Kurtosis
Energy and green start-ups (Number)	9.77	2.00	18.90	0.00	113.00	3.10	10.63
Energy and digital start-ups (Number)	5.65	2.00	10.36	0.00	66.00	3.15	11.39
Early-stage funding (green) USD	48,997,353.75	2,465,358.25	124,889,480.26	0.00	792,449,700	3.90	16.30
Later-stage funding (green) USD	48,652,068.22	0.00	248,237,832.75	0.00	3,397,459,000	11.33	146.81
Early-stage funding (digital) USD	32,790,039.93	2,266,085.00	84,136,331.61	0.00	795,792,600	5.05	34.53
Later-stage funding (digital) USD	36,348,018.43	0.00	238,422,771.59	0.00	3,376,590,000	12.57	170.99
SMEs introducing business process innovations	106.49	111.73	52.44	0.00	218.29	-0.22	-0.62
SMEs introducing product innovations	111.10	120.98	53.12	0.00	225.27	-0.19	-0.64
Sales of new-to-market and new-to-firm innovations	85.89	84.63	43.54	0.00	187.31	0.51	0.14
GDP per capita (PPP)	49,484.46	46,036.88	24,618.22	13,559.26	136,772.40	1.27	2.29
R&D expenditure (% of GDP)	1.62	1.42	0.97	0.15	3.64	0.38	-0.99

APPENDIX B

Table B1. Variables used in the empirical analysis

Variable	Empirical role	Measurement / transformation	Interpretation	Source
Energy and green start-ups	Dependent variable	Number of start-ups; transformed as $\ln(1+x)$	Entrepreneurial outcome of green energy knowledge ecosystems	IEA Energy Start-up Data Explorer
Energy and digital start-ups	Dependent variable	Number of start-ups; transformed as $\ln(1+x)$	Entrepreneurial outcome of digital energy knowledge ecosystems	IEA Energy Start-up Data Explorer
Early-stage funding of energy and green start-ups	Dependent variable	USD; winsorized at 1st and 99th percentiles; transformed as $\ln(1+x)$	Market validation of green knowledge-based ventures	IEA Energy Start-up Data Explorer
Later-stage funding of energy and green start-ups	Dependent variable	USD; winsorized at 1st and 99th percentiles; transformed as $\ln(1+x)$	Scaling performance of commercialized green knowledge	IEA Energy Start-up Data Explorer
Early-stage funding of energy and digital start-ups	Dependent variable	USD; winsorized at 1st and 99th percentiles; transformed as $\ln(1+x)$	Market validation of digital knowledge-based ventures	IEA Energy Start-up Data Explorer
Later-stage funding of energy and digital start-ups	Dependent variable	USD; winsorized at 1st and 99th percentiles; transformed as $\ln(1+x)$	Scaling performance of commercialized digital knowledge	IEA Energy Start-up Data Explorer
SMEs introducing business process innovations	Explanatory variable	Standardized z-score	Process/organizational innovation as a proxy for applied knowledge creation	European Innovation Scoreboard
SMEs introducing product innovations	Explanatory variable	Standardized z-score	Product innovation as a proxy for knowledge creation in market-oriented outputs	European Innovation Scoreboard
Sales of new-to-market and new-to-firm innovations	Explanatory variable	Standardized z-score	Commercialized innovation; proxy for knowledge converted into market outcomes	European Innovation Scoreboard
Knowledge commercialization gap	Constructed explanatory variable	Difference between SME product innovation and sales of new-to-market and new-to-firm innovations; standardized	Macro-level mismatch between knowledge creation and commercialized innovation	Authors' calculations based on European Innovation Scoreboard
Knowledge commercialization gap ratio	Constructed explanatory variable	Ratio of commercialized innovation to total innovation activity; standardized	Relative efficiency of knowledge-to-market conversion	Authors' calculations based on European Innovation Scoreboard
GDP per capita	Control variable	PPP, constant 2021 international dollars; log-transformed	General level of economic development	World Bank
R&D expenditure	Control variable	Percentage of GDP	Research and development intensity of the national innovation system	UNECE