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Industry 4.0 technologies: revenue creator or job destroyer? Understanding the role of green and social innovation pathways in European enterprises

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Innovation Policies for a Global Europe
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Motivation and Background

Policy and Economic Motivation

- Industry 4.0 technologies—AI, cloud, IoT, big data—are central to Europe's growth strategy and climate ambitions.
- The €9.2 billion Digital Europe Programme aims to mobilise scientific capability for stronger market performance (European Commission 2020a).
- Yet the "European paradox" persists: abundant R&D and patents, but weak productivity and modest scale-up (Belitski and Audretsch 2025).
- Digitalisation's potential to turn knowledge into revenue—without eroding jobs—remains unresolved.
- Geopolitical fragmentation and the quest for technological sovereignty add further pressures (Edler et al. 2023).
- EU competitiveness and climate-neutrality goals intensify the urgency (Draghi 2024).

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Digital Tensions, Twin Transition, and missing social pillar

- Industry 4.0 (AI, cloud, IoT, big data) brings both productivity gains, new opportunities and challenges—labor displacement outpacing reinstatement (Acemoglu and Restrepo 2019; Ciarli et al. 2021).
- Digitalisation enables resource-efficient business models, but also increases energy demand (Jones 2018).
- The "twin transition" agenda seeks to align digital and green goals, but trade-offs persist (European Commission 2020b).
- Most studies on sustainability innovation (green and social innovation) focus on green innovation, neglecting the social pillar (Hermundsdottir and Aspelund 2021).

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Research Questions

(1) Does Industry 4.0 adoption increase the likelihood of both green innovation and social innovation in European SMEs?

(2) Is basic knowledge from local spillovers more important for driving green and social innovation than applied knowledge from formal R&D collaboration with Triple Helix (industry, university, government) actors, financial support, or export orientation? Or do these factors amplify or substitute the digital effect?

(3) Do digital-driven green and social innovation translate differently into turnover and employment growth? Under what conditions do digital technologies, via these innovation pathways, generate revenue or protect jobs?

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Digital resources and sustainability innovation

Theory: Resource-Based View (RBV); natural-resource–based extension (Barney 1991; Hart 1995)

- Only valuable, rare, inimitable, non-substitutable (VRIN) resources create sustained advantage; environmental and social capabilities are strategic.
- Industry 4.0 tools—AI, cloud, IoT, big data, networks, blockchain—enable firms to reduce waste, monitor impacts, and include diverse users.
- Digital assets act as niche innovations that can speed up sustainability when supported by policy or market pressure (Geels 2002; Markard, Raven, and Truffer 2012).

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- Digitalisation drives transformative environmental innovation and circular business models (Sareen and Haarstad 2021; Barteková and Börkey 2022).
- Smart use of digital tools advances sustainability, though data centres may raise energy demand (Jones 2018).
- European firm studies: Digitalisation increases both environmental and social sustainability actions—sensors, cloud, and analytics improve sustainability scores (Horbach 2024).
- Digital adoption boosts eco-innovation in SMEs, even in rural areas (Cattani, Montresor, and Vezzani 2025).
- Digital technologies make social innovation more scalable and affordable, and enable network effects and large-scale social models not possible without ICT (Buck et al. 2025; Millard and Carpenter 2014).

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Theory: Knowledge-Based View; Knowledge Spillover Theory of Innovation (KSTE&I) (Grant 1996; Audretsch, Belitski, and Fiedler 2025)

- Knowledge—not physical capital—drives innovation and growth.
- KSTE&I highlights both geographic and social proximity for sharing knowledge.

Logic:

- Basic knowledge (publications, tech reports) spreads among local actors; clusters amplify these spillovers (Porter et al. 1998).
- Firms in clusters absorb more knowledge and show higher innovation and growth (Gilbert, McDougall, and Audretsch 2008).

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- Applied knowledge comes from formal R&D with Triple Helix partners (universities, industry, government) (Etzkowitz and Zhou 2017).
- Collaboration is costly—SMEs gain more from accessible local basic knowledge than from expensive formal R&D.
- Evidence: Local spillovers often matter more than formal partnerships, especially for SMEs (Audretsch, Belitski, and Caiazza 2024).
- Maker spaces and clusters enable low-cost digital social experimentation (OECD 2023).

H2a: *For SMEs, access to basic knowledge through local spillovers has a stronger positive effect on (a) green innovation and (b) social innovation than applied knowledge via formal R&D collaboration with Triple Helix partners.*

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Finance and Export Channels for Sustainability Innovation

Theory: Resource-Based View (RBV); Stakeholder theory (Barney 1991; Freeman 2010)

- Financial slack and market access help firms invest in costly innovation.
- Social innovation depends more on legitimacy and engaging multiple stakeholders.
- Green innovation needs "scarce, heterogeneous, and inimitable" resources (Qin et al. 2025); SME innovation is often limited by funding but enhanced by international activity (Saunila 2020).
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- Green finance boosts environmental innovation, especially in tech-intensive sectors(Wang 2023; Chang et al. 2024).
- Exports have a stronger and quicker effect on eco-innovation than FDI (Torrecillas and Fernández 2022).
- Exporters, especially in Eastern Europe, are more likely to adopt environmental innovation (Hanley and Semrau 2022).
- Links between finance/export status and social innovation are weak; social innovation relies more on stakeholder engagement.

H2b: *(a) External finance and (b) export status increase the probability of innovation with environmental benefits more than the probability of innovation with social benefits.*

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Connecting External (**H2a**, **H2b**) Channels and Digital Adoption (**H1**)

Bridging Question: Do external factors (**H2a**, **H2b**) boost innovation the same way for digital and non-digital firms, or does digital adoption (**H1**) make a difference?

- Non-digital SMEs with strong partnerships or export links can sometimes match or beat digital firms that lack these connections.
- Digital firms with good access to knowledge, funding, and export markets achieve the best sustainability results.

Purpose: To see if external factors substitute for, or complement, digitalisation in driving sustainability innovation.

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Sustainability Innovation and Firm Growth Performance

Theory: RBV and stakeholder perspective; Industry 4.0 supports both green and social innovation.

- Green innovation improves resource productivity and produces "win–win" outcomes—higher sales, lower costs, reputational gains (Rennings 2000; Ambec and Lanoie 2008).
- Meta-analyses show environmental innovations outperform conventional ones financially (Liao, P. Liu, and S. Liu 2021).
- Social innovation, often via digital platforms, boosts stakeholder engagement and can improve loyalty, employee retention, and resource mobilisation (Osei and Zhuang 2020; Cacciolatti et al. 2020).

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- Financial effects of social innovation are sometimes mixed (Hermundsdottir and Aspelund 2022).
- Cross-country evidence: Social entrepreneurship mainly increases employment, especially for vulnerable workers (Kim 2024).

H3: *Green innovation has a stronger positive effect on turnover growth, while social innovation has a stronger positive effect on employment growth.*

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Data Source and Sample

Data and Variables

- Data: European Flash 486, survey of SMEs, start-ups, and scale-ups (Feb–May 2020).
- Sample: 14,720 firms across 35 European countries (EU-28 plus Turkey, North Macedonia, Serbia, Norway, Iceland, Bosnia and Herzegovina, and Kosovo).
- Importance: Most prior innovation studies focus on large firms; this SME-focused dataset provides new insights on innovation and environmental impact (Ukko et al. 2019; Nasiri et al. 2022).
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- Importance: Most prior innovation studies focus on large firms; this SME-focused dataset provides new insights on innovation and environmental impact (Ukko et al. 2019; Nasiri et al. 2022).
- Sectors: Covers all NACE sectors (B–R), grouped into manufacturing, retail, services, and industry.

Variable Definitions

Table: Variable definitions

Variable	Definition
Dependent Variables	
Digital	$= 1$ if adopted any Industry 4.0 technology (e.g. AI, cloud, robotics)
Green Innovation (GI)	$= 1$ if introduced innovation with environmental benefits
Social Innovation (SI)	$= 1$ if introduced any innovation that have the aim of improving society
Turnover Growth	1 (decreased), 2 (stable), 3 (growth)
Employment Growth	1 (decline), 2 (stable), 3 (growth)
Key Enablers & Instruments	
Cluster	$= 1$ if member of business cluster
Collaboration	$= 1$ if collaboration with Tripple-Helix actors
Financial Support	$= 1$ if very good access to public and private finance
Exporter	$= 1$ if exports goods or services
No Digital Interest	$= 1$ if not interested in digital technology
Patent	$= 1$ if holds a patent
Controls	
log Age	Log of firm age (years)
log Size	Log of employees (firm size)
Big City	$= 1$ if located in large urban area
Growth Barriers	$= 1$ if any reported barrier to growth
Family Business	$= 1$ if family owned

Econometric Strategy: Model Structure

Seemingly Unrelated Multivariate Mixed-Process Model with Random Effects

- Jointly estimates digital, green, social innovation, and growth as interconnected outcomes.
- Accounts for firms nested within countries.

$$\begin{cases} Digital_{ij} = \beta_1 X_{ij} + U_{1j} + \epsilon_{1ij} \\ GI_{ij} = \gamma_1 Digital_{ij} + \gamma_2 X_{ij} + U_{2j} + \epsilon_{2ij} \\ SI_{ij} = \delta_1 Digital_{ij} + \delta_2 X_{ij} + U_{3j} + \epsilon_{3ij} \\ Growth_{ij} = \theta_1 GI_{ij} + \theta_2 SI_{ij} + \theta_3 X_{ij} + U_{4j} + \epsilon_{4ij} \end{cases}$$

$$\begin{pmatrix} \epsilon_{1ij} \\ \epsilon_{2ij} \\ \epsilon_{3ij} \\ \epsilon_{4ij} \end{pmatrix} \sim N(0, \Sigma_\epsilon), \qquad \begin{pmatrix} U_{1j} \\ U_{2j} \\ U_{3j} \\ U_{4j} \end{pmatrix} \sim N(0, \Sigma_U).$$

Here Σ_ϵ and Σ_U are the 4×4 covariance matrices capturing cross-equation correlation at the firm and country levels, respectively.

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Econometric Strategy: Endogeneity and IVs

Why instruments are needed (endogeneity)

Digital adoption may be driven by unobserved factors (e.g., managerial skill, strategic orientation) that also influence innovation and growth.

Instrumental Variables (IVs) and requirements

- **No digital interest**: predicts digital adoption (*relevance*); any effect on green, social innovation, or growth operates only through digitalization (*exogeneity*), following Wooldridge (2010).
- **Patent holding**: predicts green and social innovation (*relevance*); any effect on growth operates only through innovation (*exogeneity*).

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Econometric Strategy: Exclusion Restrictions and Identification

Exclusion restrictions and identification

- **No digital interest** is excluded from the green, social innovation, and growth equations.
- **Patent holding** is excluded from the growth equations.
- In the growth equation, all firm-level characteristics except size (labor) are excluded; size appears in all equations as a parameter shifter.
- All 4 equations in system include industry fixed effects to control for sectoral heterogeneity.

The system is estimated via **CRMP** (conditional recursive mixed process), accommodating binary (digital, green, social) and ordinal (growth) outcomes, and accounts for firms nested in countries (Roodman 2011).

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Results: Marginal Effects on Turnover Growth

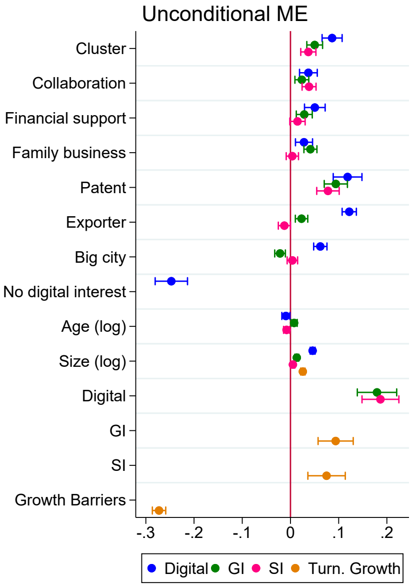
Table: Marginal Effects: Random Effects Model with Turnover Growth

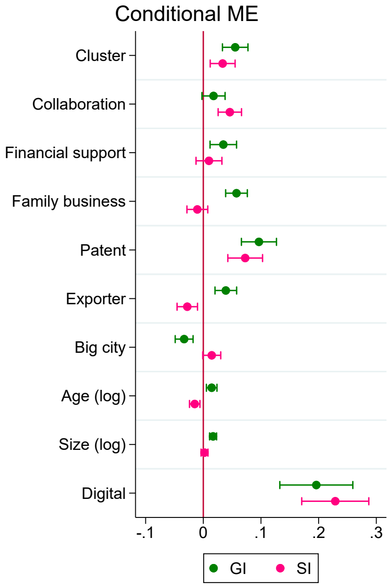
Variable	Unconditional				Conditional	
	Digital	GI	SI	Turn. Growth	GI—SI	SI—GI
Digital		0.180***	0.187***		0.196***	0.229***
Cluster	0.086***	0.050***	0.037***		0.055***	0.034**
Collaboration	0.037***	0.024***	0.039***		0.018	0.046***
Financial support	0.051***	0.029***	0.015		0.035**	0.010
Family business	0.028***	0.041***	0.004		0.058***	-0.010
Has patent	0.119***	0.094***	0.078***		0.096***	0.073***
Exporter	0.122***	0.023***	-0.013*		0.039***	-0.028**
Big city	0.062***	-0.022***	0.004		-0.033***	0.015
No digital interest	-0.247***					
Log age	-0.010*	0.008*	-0.008**		0.015***	-0.015***
Green Innovation (GI)				0.094***		
Social Innovation (SI)				0.075***		
Growth barriers				-0.273***		
Log size	0.046***	0.013***	0.005**	0.026***	0.017***	0.002
Manufacturing	-0.007	-0.000	0.038***	-0.055***	-0.019	0.058***
Retail	0.009	-0.004	0.061***	-0.028**	-0.034**	0.094***
Services	0.057***	-0.015	0.042***	-0.002	-0.043***	0.070***

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Standard errors in parentheses.
GI = green innovation; SI = social innovation; columns and rows are color-coded to match all plots.

Significant cross-equation correlations validate the simultaneous equations and random effects approach. Next, we visualize marginal effects.

Results: Marginal Effects Visualization (Turnover Growth)





Results: Marginal Effects on Employment Growth

Table: Marginal Effects: Random Effects Model with Employment Growth

Variable	Unconditional				Conditional	
	Digital	GI	SI	Emp. Growth	GI—SI	SI—GI
Digital		0.151***	0.138***		0.165***	0.159***
Cluster	0.092***	0.053***	0.038***		0.057***	0.036***
Collaboration	0.038***	0.030***	0.045***		0.023*	0.054***
Financial support	0.058***	0.034***	0.021**		0.039***	0.018
Family business	0.035***	0.050***	0.009		0.066***	-0.005
Has patent	0.129***	0.112***	0.083***		0.114***	0.076***
Exporter	0.118***	0.038***	0.000		0.054***	-0.014
Big city	0.065***	-0.021***	0.005		-0.032***	0.015
No digital interest	-0.242***					
Log age	-0.013**	0.010**	-0.007*		0.017***	-0.014**
Green Innovation (GI)				0.070***		
Social Innovation (SI)				0.071**		
Growth barriers				-0.103***		
Log size	0.046***	0.015***	0.008***	0.178***	0.018***	0.006
Manufacturing	-0.007	-0.004	0.035***	0.008	-0.023	0.054***
Retail	0.009	-0.009	0.057***	-0.002	-0.040**	0.089***
Services	0.054***	-0.017	0.045***	0.039***	-0.045***	0.074***

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Standard errors in parentheses.

GI = green innovation; SI = social innovation; columns and rows are color-coded to match all plots.

Next, we visualize the marginal effects for both turnover and employment growth models.

Results: Marginal Effects Visualization (Employment Growth)

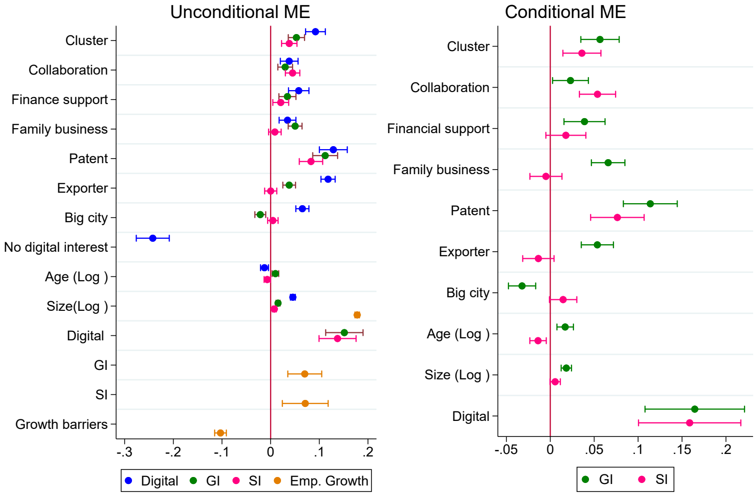


Figure: Marginal effects; green innovation (GI), and social innovation (SI).
Note: Effects are from the RE model; significance based on 90% confidence intervals.

Results: Pairwise Comparison by Digital, Collaboration, Cluster

Table: Pairwise Comparisons: Predicted Probabilities (Turnover Growth Model)

Digital	Collaboration	Cluster	Green innovation (GI)			Social innovation (SI)		
			Margin	Std. Err.	Group	Margin	Std. Err.	Group
0	0	0	0.1037	0.0140	A	0.0642	0.0091	
0	0	1	0.1409	0.0203	BC	0.0844	0.0132	A
0	1	0	0.1203	0.0171	AB	0.0854	0.0126	A
0	1	1	0.1621	0.0240	C	0.1103	0.0175	
1	0	0	0.3219	0.0194	D	0.2649	0.0186	
1	0	1	0.3917	0.0204	EF	0.3143	0.0197	B
1	1	0	0.3551	0.0202	DE	0.3165	0.0200	B
1	1	1	0.4270	0.0212	F	0.3697	0.0210	

GI = green innovation; SI = social innovation.
Margins sharing a letter in "Group" are not significantly different at the 10% level.

Next, we examine financial and export channels.

Table: Pairwise Comparisons: Predicted Probabilities (Turnover Growth Model)

Digital	Financial support	Exporter	Green innovation (GI)			Social innovation (SI)		
			Margin	Std. Err.	Group	Margin	Std. Err.	Group
0	0	0	0.1104	0.0143	A	0.0844	0.0110	A
0	0	1	0.1282	0.0187	AB	0.0767	0.0121	A
0	1	0	0.1324	0.0185	AB	0.0938	0.0137	A
0	1	1	0.1525	0.0236	B	0.0854	0.0147	A
1	0	0	0.3363	0.0211	C	0.3143	0.0212	B
1	0	1	0.3695	0.0176	DE	0.2962	0.0170	B
1	1	0	0.3770	0.0225	CD	0.3352	0.0223	B
1	1	1	0.4114	0.0197	E	0.3166	0.0189	B

GI = green innovation; SI = social innovation.
Margins sharing a letter in "Group" are not significantly different at the 10% level.

We now visualize how combinations of digital, financial, and export status affect predicted innovation probabilities.

Results: Predicted Probabilities by Firm Type

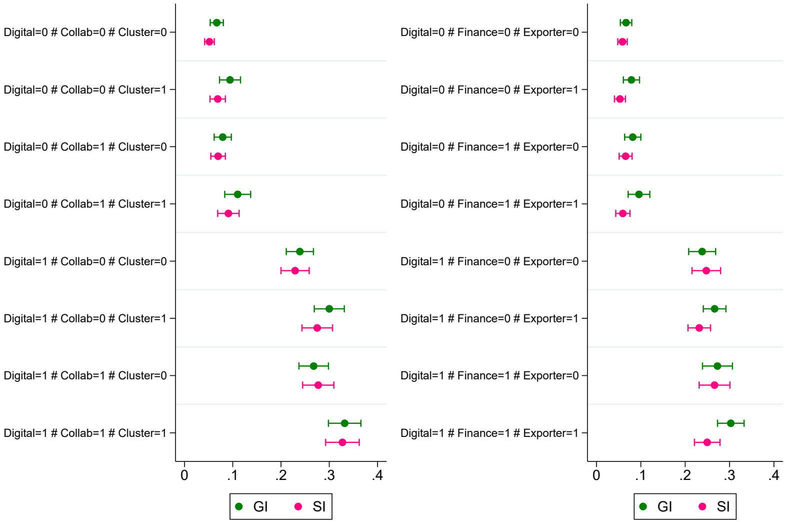
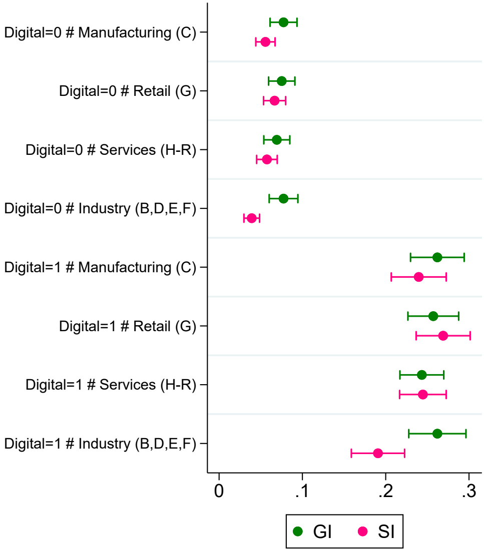


Figure: Industry 4.0: green innovation (GI) and social innovation (SI)

Additional results:Pairwise Margins Digital Adoption × Industry Sectors



Discussion: Synopsis of Hypothesis Tests and Outcomes

Table: Synopsis of hypothesis tests and outcomes

Hypothesis	Core expectation	Empirical check	Outcome
H1	Digital adopters are more likely to introduce green and social innovation.	Marginal effects tables and plots	Yes ✓
H2a	For SMEs, basic cluster spillovers raise green and social innovation more than formal Triple Helix collaboration.	Marginal effects, pairwise comparisons, interaction plots	Partly ✓ (Effect for green innovation only; not for social)
H2b	External finance and export orientation benefit green innovation more than social innovation.	Marginal effects, pairwise contrasts	Yes ✓
Bridging Q.	Do external enablers (cluster, collaboration, finance, export) substitute or complement the digital premium?	Joint-bundle contrasts, interaction plots	Complementary ✓ (External channels reinforce digital)
H3	Green innovation boosts turnover; social innovation boosts employment.	Marginal effects, growth model results	Yes ✓

Notes: GI = green innovation, SI = social innovation. "Partly" = only green innovation is supported.

Conclusion

- **Main question:** Can digital adoption help SMEs turn knowledge into both green and social innovation, and do these pathways translate into growth?
- Digitalisation is pivotal—boosting both green and social innovation. Basic knowledge spillovers (*clusters*) are most effective for green innovation, while both basic (*clusters*) and applied (*Triple Helix collaboration*) knowledge matter for social innovation.
- External levers such as finance and export amplify—but do not replace—digital effects; green innovation mostly benefits turnover, social innovation mainly benefits employment.
- Actionable insights: managers should sequence investments, combining digital incentives, cluster networks, and green finance for a balanced transition.
- This work advances twin-transition research by restoring the social pillar and clarifying how digitalisation drives both green and social (sustainability) innovation pathways to turnover and employment growth.
- In sum, Industry 4.0 adoption enables firms to increase revenue and protect jobs through a comprehensive sustainability strategy integrating both green and social innovation.
- **Outlook:** Future studies should track the dynamic interplay of digitalisation, sustainability innovation, and firm performance—especially the organisational capabilities that help SMEs adapt and thrive.

Balancing digital and sustainability goals is not only possible but necessary for European competitiveness and climate ambitions.

Conclusion

- **Main question:** Can digital adoption help SMEs turn knowledge into both green and social innovation, and do these pathways translate into growth?
- Digitalisation is pivotal—boosting both green and social innovation. Basic knowledge spillovers (*clusters*) are most effective for green innovation, while both basic (*clusters*) and applied (*Triple Helix collaboration*) knowledge matter for social innovation.
- External levers such as finance and export amplify—but do not replace—digital effects; green innovation mostly benefits turnover, social innovation mainly benefits employment.
- Actionable insights: managers should sequence investments, combining digital incentives, cluster networks, and green finance for a balanced transition.
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Thank You!

Feedback/Comments and Questions