Energizing EU Regions: Smart Grids at the Crossroads of Technological Relatedness and Smart Specialization

Abstract

The transition to smart grid technologies is a key initiative within the European Union (EU), aimed at advancing energy efficiency and sustainability over the long term. This paper delves into the driving forces behind the development of SG technologies, particularly emphasizing the roles of digital and green technologies as well as intra- and inter-regional collaboration across the EU regions. Our empirical research reveals that digital technology enhances a region's capacity for SG technologies. Moreover, when examining the aspect of knowledge recombination, this effect remains significant only when digital technology is combined with green technology. This highlights the synergy between these two fields and the importance of an integration of digital and green technology to promote sustainable development and technological advancement. Furthermore, intra-regional collaboration significantly increases a region's ability to produce new knowledge, reinforcing the significance of local innovation networks. Our findings present a nuanced perspective on the twin transition toward sustainability, offering valuable insights to guide policymakers in accelerating the adoption of SG technologies and promoting sustainable development across the EU.

1. Introduction

The twin transition, a core concept for the European Union (EU), signals a shift towards a future characterized by sustainability and digital advancement. This shift entails the simultaneous pursuit of two intertwined objectives: digitalization and sustainability, which act as mutually reinforcing pillars of progress in our rapidly evolving world (Bauer et al., 2021). The EU's commitment to the twin transition is encouraged through a range of policy initiatives and funding programs aimed at reducing greenhouse gas emissions and fostering the transition to renewable energy sources (Ortega Gras et al., 2021).

Bachtrögler-Unger et al. (2023) underscore in their report on technological capabilities and the twin transition in EU regions that this concept includes technologies that integrate knowledge from both digital and green domains (Bianchini et al., 2023). Such integration necessitates specialized skills (van Eechoud & Ganzaroli, 2023). By merging digital technologies with green practices, innovative solutions can be developed to maximize technological benefits while minimizing environmental impact.

Smart grid technologies are a typical representation of the twin transition, combining digital and green knowledge to create its novel forms of inventions. On one hand, SG leverages digital technologies to optimize energy usage, integrate renewable energy sources, and improve overall grid efficiency. On the other hand, it focuses on sustainability principles, paving the way for a greener and more sustainable landscape. This dual approach aims to optimize electricity delivery, enhancing efficiency and reliability (Refaat et al., 2021), reducing losses, improving quality, security, and safety of resources (ERGEG, 2009). As the ongoing shift towards sustainability and digitalization, there is a growing focus on enhancing regional innovation capacity through SG technology development.

Existing literature on regional capacity tends to focus on either green or non-green technological diversification (Montesor & Quatraro, 2020). Many studies examine how relatedness to green and non-green domains supports diversification into green technologies, indicating relatedness as a key driver of regional green specialization (van den Berge & Weterings, 2014; Tanner, 2016; van den Berge et al., 2020). Moreover, alternative perspectives have emerged in current research. Santoalha and Boschma (2021) explore how political support and regional capabilities contribute to the diversification of European regions into green technologies, while also examining the impact on regions specialized in "dirty" technology, such as transportation and electricity production. Orsatti et al. (2024) suggest that recombinant novelty and the presence of academic inventors positively influence new entries in green technological specializations, compensating for regions with restrained capabilities. However, research on regional capacity in twin transition technologies remains limited. To date, no studies have examined the technological stock level of digital and green technologies or investigated the collaborative effect on SG capacity in EU regions.

Smart grid technology stands out as a complex innovation that requires to apply both digital and green technologies. This complexity may inspire us to identify which aspects of knowledge exert a greater influence on the advancement of SG technology. Additionally, collaboration with a diverse community of partners and stakeholders is regarded as a critical driver of sustainable innovation, particularly for complex technologies (Cova et al., 2023). However, some scholars suggest that collaboration also poses the risk of stifling innovation by potentially constraining diversification (Boschma & Iammarino, 2009). In light of these considerations, we adopt an exploratory approach to investigate the impact of collaboration on the regional development of SG technologies, with a specific focus on distinguishing between intra- and inter-regional collaboration. This approach is motivated by two objectives. First, it allows us to explore whether collaborations influence a region's internal capacity to innovate in SG technology. Second, we aim to ascertain whether these two forms of collaboration play distinct roles in shaping the trajectory of smart grid technology development.

Therefore, this paper empirically examines the role of digital technology capacity, green technology capacity, and collaboration in developing SG technologies in 287 European regions from 1978 to 2019, using data from the OECD-REGPAT and Eurostat databases. Our findings indicate that digital technology has a positive and significant effect on the knowledge productivity of SG technologies in regions, and when concerning the knowledge recombination, digital technology positively affects SG capacity only if combined with green technology. Finally, we found that only intra-regional collaboration increases a region's capacity to establish SG skills.

By analyzing these drivers, the study aims to offer insights into effective strategies for fostering technological development in SG innovations at regional and EU levels. These insights help policymakers set rules, policies, and incentives tailored to support regions in seizing opportunities presented by SG technology development. Additionally, our findings have broader implications for advancing sustainability objectives by encouraging the adoption of SG technologies and identifying key factors that foster their development. Finally, this analysis highlights the role of SG technologies as a bridge between digital transformation and sustainability, serving as a crucial conduit for achieving the twin transition.

The paper is structured as follows: Section 2 reviews literature on regional development of SG technology, introducing the concept of SG technology, and examining the roles of green technology, digital technology, and collaboration at the regional level, and proposes research hypotheses. Section 3 defines the methodology and related variables. Section 4 presents the results. Finally, Section 5 discusses the findings, limitations, and future research.

2. Literature review and hypothesis

Our research builds upon established literature concerning regional innovation and collaborative networks, with a specific focus on investigating the underlying drivers of regional capacity of producing new technology. We aim to contribute to this body of knowledge by delving into how the adoption of digital and green technologies, as well as regional collaborations, influences the degree of specialization in SG technology within EU regions. In the subsequent sections, we provide a comprehensive review of pertinent literature and propose our research hypothesis. Firstly, we delve into the comparative importance of digital versus green technologies in driving regional innovation capacity (Section 2.1). Secondly, we explore the synergistic effects of combining digital and green technologies (Section 2.2). Lastly, we introduce the concept of collaborations within and cross regions and evaluate their impact on SG development (Section 2.3).

2.1 Green technology, digital technology and development of SG technology

The introduction of green and digital technologies triggers significant shifts in regional environments, impacting various aspects such as technological progress, market dynamics, workforce availability, training infrastructure, and the development of essential infrastructure (Santoalha et al., 2021). These technologies may exert diverse influences on a region's ability to innovate and diversify its economic activities. When analyzing the impact of regional technological capacity on regional innovation capacity, it becomes essential to understand how the knowledge influences the way regions cultivate new industries, expand existing ones, and more importantly, adapt to emerging sustainability and technological trends.

Existing literature predominantly focuses on examining how green technology drives green diversification and presents its significance in comprehending the regional diversification process. For instance, van den Berge and Weterings (2014) noted that the likelihood of EU regions developing new green technologies hinges on the existing technological landscape in related fields within the region. Similarly, Tanner (2016) explored the impact of technological relatedness on the emergence of the fuel cell industry in European NUTS-2 regions, concluding that such emergence is propelled by connections with other green technologies. Furthermore, Cicerone et al. (2023) proposed that regions' specialization in green technology stems from their established capabilities in developing green technologies.

Through utilizing green technology, regions can broaden their energy sources, transitioning from conventional fossil fuels to cleaner and more environmentally sustainable alternatives (Singh et al., 2020). Green technology plays an essential role in integrating renewable energy sources such as solar, wind, and hydroelectric power into emerging technologies, thus extending this integration to SG systems. This transition not only diminishes reliance on non-renewable energy but also promotes regional diversification by enhancing the capabilities and scope of SG technology. Therefore, we posit our first hypothesis as follows:

H1: Regions with greater digital technology capacity are more likely to develop SG technology.

The literature on regional innovation capacity has extensively explored the influence of different digital technologies, including Artificial Intelligence (AI) and Key Enabling Technologies, in stimulating regional diversification (Cicerone et al., 2023; Montresor & Quatraro, 2017, 2020). However, many studies have primarily concentrated on analyzing the relatedness to various types of digital technologies in relation to diversification, rather than comprehensively examining the overall knowledge portfolio of digital technologies at the regional level.

Santoalha et al. (2021) argue that Information and Communication Technologies (ICTs) possess two properties crucial for regional technological advancement. First, ICTs foster complementarities across diverse domains, suggesting their applicability in sectors beyond their original domain. By using knowledge from various industrial fields, digital skills can boost regions' recombinant innovations, facilitating the emergence of new green technological specializations (Frenken et al., 2012). Second, ICTs enable forward-complementarities between inventions and applications (Santoalha et al., 2021. This suggests that advancements in digital technologies can stimulate further innovations and developments in other areas, thereby enabling diversification. Consequently, we propose that new digital technologies can help generate novel applications and solutions within smart grid systems.

Furthermore, digital technologies undergo continuous evolution driven by scientific advancements, resulting in cost reductions and an expanded potential for application (Zhao & Qian, 2023). This evolutionary process is crucial for fostering regional innovation within SG systems. Digital technologies possess the capability to enhance productivity by automating production processes, improving equipment operation efficiency, and reducing production costs (Antonioli et al., 2018; Frank et al., 2019; van Klyton et al., 2020). These benefits may be also applied to the efficiency of SG systems. Additionally, as digital technologies progress, they become increasingly cost-effective, thus being more accessible to regions which seek to expand their technological capabilities. Consequently, this technology empowers regions to pursue their energy diversification goals more effectively, irrespective of their financial circumstances.

Moreover, we expect digital technology to play a significant role in regional diversification owing to its technological capabilities within EU regions. Digital technology enhances the knowledge base and multidisciplinary skills of workers (Castellacci et al., 2020), thereby expanding the existing knowledge pool and facilitating knowledge exchange across different domains. This interdisciplinary knowledge exchange enables the integration of various digitalization techniques, resulting in the development of innovative solutions and therefore promoting diversification. We hypothesize that a varied array of digital technologies at the regional level facilitates the emergence of innovative solutions in SG technologies. Therefore, we suppose that:

H2: Regions with greater green technology capacity are more likely to develop SG technology.

2.2 The combination of digital technology, green technology and development of SG technology

Previous literature emphasizes the importance of considering both green and digital technologies in regional diversification efforts, drawing on patent data at the regional level to highlight how integrating pre-existing technologies supports regional diversification. For instance, studies by Colombelli, Krafft, & Quatraro (2014) and Boschma, Balland, & Kogler (2015) detect how the emergence of new technologies through the recombination of pre-existing ones fosters regional diversification. Montresor & Quatraro (2020) investigate deeper into this aspect, emphasizing the significance of recombining various forms of knowledge. They found that the relatedness to pre-existing green and non-green knowledge enhances regions' capacity to specialize in new green technologies, with non-green technology exerting a more pronounced effect. New green technologies often depend on non-green ones, emphasizing the importance of recombining distant knowledge (Perruchas et al., 2020). Interestingly, Zeppini & van den Bergh (2011) provide a tangible example of this phenomenon using hybrid cars, illustrating how new green technologies often arise from the fusion of green and non-green knowledge within regions. Hence, existing research underscores the importance of considering both green and non-green knowledge for the emergence of new technological outputs.

Relying solely on either green or digital knowledge may lead to an incomplete understanding of diversification processes. This limitation arises from the potential absence of one type of technology necessary for new inventions, highlighting the significance of integrating both technological domains. SG technologies often combine green and digital technologies, giving rise to innovative specializations. Digital solutions enhance green technologies by optimizing energy usage, mitigating greenhouse gas emissions, and reducing energy costs. Similarly, green technologies imbue digital systems with sustainability principles (Talat et al., 2019). Therefore, we propose that:

H3: Regions possessing capacity in both digital and green technologies are more likely to develop SG technology.

2.3 Collaborations with other regions

Collaborative innovation plays a significant role in achieving sustainability goals by integrating resources across locations, organizations, and individuals. This collaborative process entails continuous communication and interaction activities among participants, fostering knowledge sharing and interactive learning. While existing literature primarily focuses on understanding the drivers of environmental collaborations and their performance outcomes (De Noni et al., 2018; Cova et al., 2023), there is a notable gap in exploring the characteristics and patterns of collaborative innovation on regional capacity of twin transition in the context of European regions. To address this gap, it is imperative to gain a deeper understanding of the strategies and motivations guiding regions' collaborations with other EU counterparts. For instance, regions deficient in certain expertise may seek collaborations with others to access resources and strengthen their abilities in advancing SG technology.

Moreover, as highlighted in economic geography literature, both intra-regional collaboration (Neffke et al., 2011) and inter-regional collaboration (Kogler et al., 2023) should be further investigated. Existing evidence shows the beneficial effects of intra- and inter-regional collaboration on innovation performance (De Noni et al., 2018). Collaboration acts complementarily, suggesting that along with internal capabilities, external linkages enhance regional capabilities in developing new technologies by accessing diverse knowledge (Balland & Boschma, 2021).

It is necessary to indicate that a region's ability to foster innovation through intra-collaborations is significantly fostered by the ease of knowledge exchange facilitated by spatial proximity. This concept, often referred to as spatial externalities, reflects the benefits of co-location within the same region. Co-locating these competencies implies increased opportunities for knowledge sharing and collaboration, thus providing a compelling rationale for their integration. Existing literature elucidates the advantages derived from such proximity, emphasizing the synergy and efficiency that arise when complementary competencies coexist within close proximity (le Duc & Gammeltoft, 2023).

Moreover, inter-regional collaborations are believed to compensate for internal capability gaps and minimize knowledge disparities (De Noni et al., 2018; Kogler et al., 2023). Fusillo et al. (2023) explore the relationship between a region's participation in the global network of embodied R&D and technological diversification, finding that regions enhance their ability to diversify into technologies less cognitively related to pre-existing ones. Externally oriented inventor collaboration networks can also compensate for the lacking skills within a region (Whittle et al., 2020) and facilitate diversification into unrelated technologies (Kogler et al., 2023). In so doing, such collaborations facilitate knowledge transfer and exchange, ultimately creating opportunities for recombining knowledge and enhancing region's capacity to generate new technology. Based on these arguments, we suppose that collaborations serve as a bridge connecting different locations and knowledge sources, thereby supporting developing SG technology. Therefore, we propose that:

H4: Regional intra-collaborations contribute to the development of SG technologies.

H5: Regional inter-collaborations contribute to the development of SG technologies.

3. Methodology

This study examines the regional development of SG technology by investigating the influence of green technology, digital technology within the regional knowledge space, and intra- and inter-technological collaborations in European regions. The sample comprises 287 regions across 30 countries, including the European Union, Norway, Switzerland, and the UK. The regional level is defined using NUTS2 (Nomenclature of Territorial Units for Statistics). To assess the technological capacity of green and digital technologies, patent data is utilized, as it reflects the regions' knowledge and capability levels. The distinction between green and digital patents registered at the European Patent Office (EPO) is detailed in Section 3.1.2. Despite the acknowledged limitations in measuring technological knowledge through patents (Griliches, 1990), they are considered a reliable proxy for assessing technological development at the regional level (Balland et al., 2019).

Collaborations are defined as a collaborative network of inventors engaged in the development of SG technologies, measured through co-patenting activities using patent data. Consistent with previous research (De Noni, 2017, 2018), patent-based metrics are employed to indicate technological collaboration activities. Patent data is sourced from the OECD-REGPAT database (version January 2024), encompassing all patent information to the EPO from 1977 to 2023.

The analysis focuses on the period from 1978 to 2019, as patent application information for the years 2020, 2021, and 2022 is incomplete. These patent data are regionalized based on the inventors' addresses. Additionally, social and economic data from Eurostat is collected to define control variables, such as human capital and population density. The final panel dataset is constructed by merging patent data from OECD-REGPAT and Eurostat, covering the time period from 1978 to 2019.

3.1 Variables

3.1.1 Dependent variables

SG technology (SGT). This study aims to investigate the influence of regional capabilities in green and digital technologies, as well as regional collaborations, on the development of a region's capacity to enhance the competitiveness of SG technologies. To do so, we employ the number of patents related to SG generated in a region as an indicator of the regional capacity to generate new technological knowledge pertinent to SG technologies. A higher capacity indicates a greater ability of a region to innovate and create new SG technologies. To identify SG technologies, we utilize Cooperative Patent Classification (CPC). Specifically, SG-related patent data is classified under the Y04S CPC class (Angelucci et al., 2018). Consequently, the Y04S patents are regionalized at the NUTS-2 level based on the investor's address. In summary, the development SG is represented as the logarithmic transformation of the integer number of SG-related patents per region and year.

3.1.2 Independent variables

Digital technology capacity (DT). The breadth of a region's digital knowledge base reflects its potential for contributing to advancements in SG development. A region with a larger knowledge base in this domain is more likely to drive progress in SG technologies. To identify digital technology capacity, we utilize the "J tag", a novel International Patent Classification (IPC)-based code system for ICT, introduced by the OECD in 2017. The "J tag" encompasses various areas of digital technologies, such as high-speed networks, mobile communication, security, among others. Consequently, we perform a logarithmic transformation on the integer number of patents falling under these IPC codes within each NUTS-2 region per year.

Green technology capacity (GT). Consistent with similar studies (Santoalha et al., 2021), we select environment-related technologies using the detailed classification of OECD ENV-TECH to identify green technology. Our search strategy for green technology revolves around the corresponding groupings of CPC or IPC from the OECD, involving four key elements: environmental management, water-related adaptation technologies, biodiversity protection and ecosystem health, and climate change mitigation. Particularly, the last element is rooted in the CPC "Y02" scheme, which considers various aspects of environment-based technologies, including renewable energy generation, combustion technologies with mitigation potential, and technologies for efficient electrical power generation. While the "Y02" scheme is utilized for this aspect, the remaining three elements are based on the IPC classification. Finally, we computed the logarithmic transformation of the integer number of all the environment-related patents per region and year.

Collaborations. The number of co-patents among inventors within and across regions serves as an indicator of regional connectivity capacity. Specifically, we aim to differentiate between intra-regional and inter-regional collaborations. Intra-regional collaboration (INTRA) occurs when inventors within the same European region collaborate on patents. It is measured as the logarithmic transformation of the number of collaborative patents within the region. According to De Noni et al. (2017), high levels of local collaborations can facilitate knowledge exchange among inventors due to spatial, social, and cultural proximity, thereby increasing collaborative opportunities. Inter-regional collaborations (INTER), on the other hand, refer to collaborative patents involving inventors from different regions, and it is counted by the logarithmic transformation of the number of inter-regional collaborative patents in the EU region.

3.1.3. Control variables

We employ population density (POP.DEN) as a measure of urbanization externalities, calculated as the population per 1,000 inhabitants per square kilometer (population divided by one square kilometer of land) for each region and year. To assess the economic development of each region, we include GDP per capita (GDP.POP), calculated as GDP divided by the population of the region, and the employment rate of the age group 15-64 (EM). Additionally, we considered total patents per capita (PAT.IND) and patents excluding those related to SG, green, and digital technologies (OTHER.PAT) to evaluate the innovation performance of the region. Unlike previous studies that utilized employment shares as a proxy for industrial structure, we control other aspects of the regional economy by considering shares excluding employment share (EX-ES). Furthermore, we include gross fixed capital formation (GFCF), which measures the acquisitions of new or existing fixed assets minus the disposal of fixed assets in a given region and year.

3.2. Model estimation

The analysis is conducted using a panel data econometric model. Specifically, we estimate the models presented in Table 2 using ordinary least squares (OLS) with fixed effects. To ensure the consistency of the OLS estimator, a logarithmic transformation is applied to certain variables to mitigate skewness. We calculate the capacity for producing SG technologies at the regional level by employing fourteen 3-year moving time windows, spanning from 1978 to 2019. Each window covers a period of three years, with the first window ranging from 1978 to 1980, the second from 1981 to 1983, and the last from 2017 to 2019. Also, to enhance the robustness of our estimations, clustered robust standard errors are introduced at the regional level.

Additionally, a one-year lag between independent as well as controls and dependent variables is introduced in our models for two reasons. First, we expect that the process of assimilating external knowledge into invention outputs requires time, and thus, patents represent lagged outputs of this process. Second, incorporating lags helps mitigate endogeneity resulting from reverse causality.

4. Results

	min	q1	median	q3	max	mean	sd
SGT	0	0	0	0	4.317	0.386	0.718
DT	0	0	1.099	0	7.065	1.538	1.526
GT	0	1.099	2.639	1.099	7.549	2.611	1.771
INTRA	0	0	0	0	6.428	0.723	1.134
INTER	0	2.398	4.159	2.398	8.709	3.941	2.046
POP.DEN	-6.836	-2.647	-2.057	-2.647	2.41	-1.958	1.268
GDP.POP	-6.379	-4.257	-3.893	-4.257	-2.32	-4.033	0.639
GFCF	3.143	5.213	5.351	5.213	7.04	5.339	0.274
OTHER.PAT	0	0.034	0.151	0.034	1.319	0.224	0.242
EX-ES	0.487	0.753	0.816	0.753	0.982	0.809	0.082
EM	0.354	0.852	0.913	0.852	1.738	0.916	0.124

Table 1: Descriptive statistics

	Dependent variable:				
	SGT				
	(1)	(2)	(3)	(4)	(5)
DT		0.034^{*}	-0.270^{***}		

		(0.017)	(0.026)		
GT		0.038	-0.002		
		(0.023)	(0.022)		
INTRA				0.108^{***}	
				(0.022)	
INTER					-0.032
					(0.022)
POP.DEN	0.199	0.185	-0.036	0.133	0.198
	(0.161)	(0.157)	(0.110)	(0.144)	(0.160)
GDP.POP	-0.384^{***}	-0.434^{***}	-0.192^{**}	-0.420^{***}	-0.338^{***}
	(0.117)	(0.115)	(0.092)	(0.111)	(0.118)
GFCF	-0.042	-0.045	0.008	-0.034	-0.028
	(0.059)	(0.058)	(0.046)	(0.057)	(0.059)
OTHER.PAT	2.069^{***}	1.928^{***}	0.720^{***}	1.818^{***}	2.102^{***}
	(0.161)	(0.178)	(0.139)	(0.170)	(0.161)
EX-ES	2.109^{***}	2.070^{***}	0.819^{**}	1.975^{***}	1.996^{***}
	(0.471)	(0.462)	(0.386)	(0.442)	(0.480)
EM	0.363^{*}	0.352^{*}	0.151	0.360^{**}	0.345^{*}
	(0.196)	(0.187)	(0.118)	(0.178)	(0.196)
DT*GT			0.096^{***}		
			(0.007)		
Regions FE	No	No	No	No	No
Time FE	No	No	No	No	No
N.obs	3182	3182	3182	3182	3182
Regions n.	277	277	277	277	277
Years n.	13	13	13	13	13
R^2	0.163	0.167	0.246	0.177	0.164
Adjusted R^2	0.078	0.081	0.169	0.093	0.079
F Statistic	93.930^{***} (df = 6; 2887)	72.130^{***} (df = 8; 2885)	104.788^{***} (df = 9; 2884)	88.483^{***} (df = 7; 2886)	81.033^{***} (df = 7; 2886)
Notes:	*p<0.1; **p<0.05; ***p<0.01				
	Regions-clustered Robust Standard Errors are in parentheses				

Table 2: Regression models' results

Tables 1 present the descriptive statistics of all variables included in our models. The results of the regression models are presented in Table 2. In Model 1, as our baseline model, we solely introduce control variables to analyze their impact on the dependent variable, SGT. The coefficients and signs of the control variables remain consistent across different models. The employment rate and OTHER.PAT is positive and significant coefficients in most models. To explore industrial effects, we introduce the variable EX-ES, which demonstrates a significant and positive effect on SG capacity. However, GDP.POP shows a negative yet significant coefficient across these models.

Moving to Model (2) and Model (3), we find that the coefficients of green technology are not statistically significant, leading to the rejection of Hypothesis 2. However, in Model (2), the coefficient of digital technology is positive and significant ($p<0.1$), indicating that the development of SG technologies benefits from an increasing capacity of digital technology, thereby confirming Hypothesis 1. Subsequently, in Model (3), we introduce both green technology, digital technology, and their interaction term to test Hypothesis 3. The results suggest that a combination of green and digital technologies fosters the development of SG technologies. Specifically, the interaction term is positive and significant ($p<0.01$), while the digital technology term is negative and significant ($p<0.01$), indicating that when digital technology is combined with green technology, it effectively produces SG outputs. This implies that the combined effect of these two technologies is greater than the sum of their individual effects, confirming Hypothesis 3.

Furthermore, Model (4) and Model (5) look at the impact of collaborations. The results of Model (4) indicate that intra-regional collaborations have a positive and significant effect on the regions' capacity to develop new knowledge of SG technologies ($p<0.01$), confirming Hypothesis 4. However, in Model (5), inter-regional collaborations do not exhibit a significant effect on the regions' capacity to develop SG technology, leading to reject Hypothesis 5. This highlights the importance of regions seeking external knowledge that is closely located, rather than exploring related technologies that may be physically distant from the regions.

5. Discussion and conclusions

The aim of this paper is to examine how regional capabilities in green technology, digital technology, as well as intra- and inter-regional collaborations influence the development of SG technology at the regional level. By investigating these factors, we seek to understand how they contribute to the regional capacity for SG patent performance. While previous studies have individually explored the roles of green technology or digital technology in regional innovation performance, none have delved into the knowledge stock level, interplay between these factors or discussed the impact of collaborations on advancing twin transition technologies, such as SG technology.

Through our analysis, we found several key insights that contribute to our understanding of how different factors shape regional capacity in this SG technology. Our research reveals that digital technology plays a crucial role in enhancing the knowledge capacity of regions in developing SG technologies. The positive effect of digital technology on SG knowledge capacity is evident and aligns with expectations based on the widespread recognition of the transformative potential of digitalization in various industries, including those towards to twin transition. Contrary to our initial expectations, our findings suggest that the capacity of green technology alone does not significantly contribute to the technological advancement of SG skills in regions.

Alternatively, we discovered a persistent and reinforced effect of digital technology on SG knowledge capacity when coupled with green technology. This result suggests the importance of achieving an optimal balance between these two technological domains, as their combination synergistically enhances SG capacity at the regional level. Digital technology enhances efficiency and optimizes energy usage within SG systems, while green technologies offer insights for developing environmentally friendly solutions. When these domains integrate, they leverage each other's strengths, resulting in a more enhanced capacity within SG technology.

Furthermore, our analysis delves into the impact of collaboration—both intra-regional and inter-regional—on regional capacity for producing new knowledge in the SG domain. We found that intra-regional collaboration positively influences a region's capacity to generate new knowledge in SG. It stresses the importance of fostering collaboration among stakeholders within a region to apply local expertise and resources effectively. A high level of intra-regional collaboration suggests that the region has developed locally embedded innovation networks to support knowledge production and recombination. In this regard, our results are consistent with the co-location concept, which facilitates knowledge flows and collaboration among inventors due to spatial and cultural proximity. The development of intra-regional connections and collaborations, as a means of accessing external knowledge from other inventors and enhancing the knowledge capability of SG tech, should be encouraged and supported by regional policies.

In contrast, our findings suggest that inter-regional collaboration does not significantly contribute to the capacity of regions to produce new knowledge in the SG domain. This unexpected result challenges conventional assumptions about the benefits of inter-regional collaboration (Lorenzen & Mudambi, 2013). It implies that increasing cross-regional collaborations do not necessarily lead to new inventions. Several factors such as long cognitive or physical distances, time required for knowledge transfer, or the absorptive capacity to understand new knowledge may hinder extensive collaboration across regions.

Our research findings provide valuable insights for policymakers seeking to advance SG technologies for sustainability. We recommend strategies or policies aimed at fostering growth in the twin transition areas covered by both digital and green technology may generate greater effectiveness when considering the combined effects, rather than focusing solely on one aspect. Moreover, our findings underscore the significance of fostering intra-regional collaborative activities to accelerate the development of SG technologies. Therefore, European policies should prioritize support for intra-regional collaboration, enabling better access to external knowledge and maximizing their impact not only on SG technologies but also on other aspects within the twin transition domain. This approach will accelerate progress towards sustainability and digitalization goals.

This study has several limitations. First, our evaluation of digital technology is primarily reliant on ICT-related patents, which may not provide a comprehensive assessment of digital knowledge. Future research should explore alternative measures of digital technology, such as AI, to offer a more nuanced understanding of digital knowledge dynamics. Second, our analysis may not capture certain forms of collaborations that are crucial for understanding regional capacity development. We intend to analyze the collaborations with regions specialized in digital or green technologies, providing deeper insights into collaborative activities. Third, the regionalization of our datasets at the NUTS-2 level may limit the granularity of our analysis. Future research should aim for a more fine-grained investigation by focusing on the NUTS-3 level, allowing for more detailed insights into regional innovation capacity.

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