

# What drives twin inventions? Evidence from the EU

Bello, M., Castellani, D., Damioli, G., Marin, G., Montresor, S., Ravanos, P.

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### Contact information

Name: Michela Bello

Address: European Commission, Joint Research Centre, Via E. Fermi 2749, TP 361, Ispra (VA), I-21027, Italy

Email: [michela.bello@ec.europa.eu](mailto:michela.bello@ec.europa.eu)

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## **Abstract**

The twin transition —integrating green and digital transformations—has emerged as a strategic priority for achieving smart, sustainable, and inclusive economic growth. As the twin transition hinges on innovation at the green–digital interface, identifying the drivers of twin-technology (TT) development is critical for policymakers seeking to accelerate this progress. By identifying key factors influencing TT, policymakers can design targeted interventions to foster digital-enabled green innovation, leverage synergies between the two transitions, and advance environmental and climate objectives. Such insights also enable optimized resource allocation, prioritisation of investments, and the creation of a supportive business environment to scale TT.

This study analyses the determinants of TT development within the European Union (EU), employing a multi-layered innovation systems framework, which considers firm-specific, technological, sectoral, and regional dimensions. Drawing on a matched patent–applicant-level dataset, the analysis explores how geographical, sectoral, technological, and firm-level factors influence the extent to which the development of new green technologies draws on digital technological knowledge, thereby generating TT, operationalized as the likelihood that green patents cite digital prior art.

Our analysis reveals that firm- and regional-level characteristics have the highest explanatory power in explaining the propensity to develop green technologies that build on prior art digital knowledge.

At the firm level, foreign ownership facilitates TT by leveraging heterogeneous knowledge, regulatory and market environments, while a robust digital knowledge base enhances cross-domain recombination. Conversely, entrenched green expertise and cognitive lock-in hinder digital integration, suggesting path dependence in traditional green sectors may impede the development of TT. At the regional level, specialization in digital technologies fosters TT opportunities through local knowledge spillovers, whereas urbanization shows negative effects, reflecting the dual-edged nature of agglomeration economies. Patent-level findings further highlight the heterogeneous role of technological categories.

These results underscore the need for a multi-level approach to TT governance, emphasizing strategies to overcome knowledge silos, foster cross-domain collaboration, and balance urban and peripheral innovation ecosystems. The study offers actionable insights for policymakers aiming to accelerate the twin transition by harmonizing digital and green innovation pathways.

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## **Authors**

Michela Bello, European Commission, Joint Research Centre, Ispra, Italy

Davide Castellani, Henley Business School, University of Reading, UK

Giacomo Damioli, University of Strasbourg, Faculté des sciences économiques et de gestion, Bureau d'Economie Théorique et Appliquée, Strasbourg, France; Centre for the Analysis of Public Policies, University of Modena and Reggio Emilia, Italy

Giovanni Marin, University of Urbino Carlo Bo, Italy; SEEDS (Sustainability Environmental Economics and Dynamics Studies), Italy; FEEM (Fondazione Eni Enrico Mattei), Italy

Sandro Montresor, Department of Economics and Management, University of Trento

Panagiotis Ravanos, European Commission, Joint Research Centre, Ispra, Italy

## 1. Introduction

The twin transition, which combines green and digital transformations, has become a top priority for countries seeking to drive their economies towards smart, sustainable, and inclusive growth (Muench et al., 2022). As the world grapples with the urgent need to mitigate climate change, the opportunities and threats presented by digital technologies have sparked a growing interest in understanding the interplay between these two transitions. Despite a nascent literature exploring the interconnections between green and digital transitions, a significant knowledge gap remains regarding the factors that identify and drive the technological development underpinning the twin transition, that is “twin technologies” (TT) that combine both digital and environmental features and can thus enable and accelerate the implementation of the twin transition across production and consumption patterns. In the limited extant literature produced so far, TT are identified either as digital technologies that support environmental ones in climate change mitigation and adaptation (such as new sensors for monitoring energy consumption), or as environmental technologies enhanced by a digital component (such as smart waste sorting systems) (Nelli et al., 2025). In both cases, TT are retained to descend from inventions that combine green and digital technological knowledge, both of which are thus acknowledged as classifiers in the corresponding patent applications. Accordingly, TT are typically identified by searching for patents in which green and digital codes (The International Patent Classification – IPC – and The Cooperative Patent Classification - CPC) technological classes) and/or related keywords co-occur within the same document (e.g., Aklilu et al., 2025; Jindra and Leusin, 2022; Nelli et al., 2025; Basilico et al., 2024). Nonetheless, this criterion for identifying inventions that are both green and digital overlooks the influence that digital technological knowledge may exert on the development of new environmental technologies. Indeed, this influence could rather manifest as green inventions drawing on prior art digital knowledge. Such technologies may not be fully captured by conventional definitions of 'green & digital' inventions, as they may not feature the co-occurrence of digital and green characteristics, as captured by the technological classes in a patent. Rather, these inventions may be identified by searching for environmental patents that cite prior digital patents (Aklilu et al., 2025).

The emergence of TT represents a niche area that holds significant promise for driving sustainability and environmental benefits. However, this niche requires a distinct set of skills, expertise, and perspectives that may not be readily available in traditional digital or green technology sectors. Studying the factors that drive inventions in TT is essential to understand the unique challenges and opportunities associated with this intersection of digital and green technologies and identify strategies to develop the specialized skills and knowledge needed to support innovation in this area. Ultimately, a deeper understanding of the factors driving TT inventions can help unlock the potential of this niche area and foster the development of innovative solutions that address pressing environmental challenges.

Focusing on the specific subset of TT defined as green patents citing digital patents, this study contributes to the existing literature by identifying factors influencing the development of such technologies. Existing literature on TT has so far largely been confined to descriptive mappings — examining the distribution of twin inventions across firms (Jindra and Leusin, 2022), regions (Basilico et al., 2024), countries, and sectors (Aklilu et al., 2025) — while paying limited attention to the underlying drivers of their emergence. Indeed, when explanatory dimensions of TT are addressed, the focus tends to remain limited to either the relative contribution of their green and digital sub-components (Damioli et al., 2025; Fazio et al., 2025), or to the ways digital innovations are associated to environmental ones (Cicerone et al., 2022; Montresor and Vezzani, 2023; Cattani et al., 2025), rather than on broader enabling conditions for their development. We find that this is an important gap in the literature and policy discussion. This study aims to address this knowledge

gap by investigating the factors that drive the development of TT, with a specific focus on the European Union (EU). As the formation of TT reflects the joint influence of firm capabilities, place-based conditions, sectoral and technological regimes, and cross-domain knowledge relatedness, we claim that the analysis of the TT drivers requires a multi-layered perspective. Specifically, we explore how geographical, sectoral, technological, and firm-specific factors shape the propensity of green patents filed by an EU applicant to cite digital knowledge and, in doing so, give rise to the specific subset of TT under investigation.

Our findings reveal that TT integration is shaped by distinct regional, firm-level and patent-level factors. At the firm level, foreign ownership facilitates TT by leveraging heterogeneous knowledge, regulatory and market environments, while a robust digital knowledge base enhances cross-domain recombination. Conversely, entrenched green expertise hinder digital integration, suggesting path dependence in traditional green sectors may impede the development of TT. Regionally, specialization in digital technologies fosters TT opportunities through local knowledge spillovers, whereas green specialization and urbanization shows negative effects, reflecting the dual-edged nature of agglomeration economies. Patent-level findings further highlight the heterogeneous role of technological categories.

The rest of the document is structured as follow. Section 2 provides a literature review and our contribution to it. Section 3 illustrates the data and presents our empirical strategy. Section 4 presents some descriptive statistics on the characteristics and distributions of twin patents, Section 5 discusses the results, and Section 6 provides concluding remarks.

## 2. Background literature

### 2.1. The development of twin (green and digital) technologies: a multi-level phenomenon

Although policy attention to the twin transition in Europe dates back at least to the “Green Deal” strategy (EU, 2019), research on its technological dimension – i.e., on TT – remains at an early stage. Interestingly, at this early stage the literature is spanning multiple levels of analysis, investigating which unit of observation – and which of its attributes – matters most for a proper technological understanding of the twin transition. A first sizeable strand adopts a firm-level perspective, on the premise that firms are the primary actors investing in TT, developing and translating them into market applications (see, e.g., the recent collection in Diodato et al., 2023). Drawing on heterogeneous theoretical lenses – predominantly knowledge – and capabilities-based views of the firm – these studies examine the factors that encourage firms to move along the twin transition and shape their ability to do so.

A second, emerging stream investigates the macro (cross-country) and meso (regional) geography of TT, motivated by concerns that—much like its constituent digital and green transitions— the twin transition risks deepening technological disparities and socio-economic inequalities across regions, potentially resulting in a “territorially unjust” transition (Muench et al., 2022). At this level, studies—often grounded in evolutionary-geography frameworks though employing diverse conceptual approaches—analyse place-specific conditions that either foster or hinder the development of actor ecosystems critical for TT innovation, diffusion, and adoption (see Faggian et al., 2025 for a collection of recent contributions).

Finally, a growing line of work operates at the technological level, asking to what extent TT trajectories depend on the properties of the underlying digital and environmental knowledge bases being combined, as well as on the nature of inventive efforts behind them (Nelli et al., 2025; Biggi et al., 2024; Aklilu et al., 2025). The starting point of this stream of literature is that the twin transition is ultimately enabled by the creation of new twin technologies—i.e., recombination of digital and environmental knowledge. Accordingly, following this stream, understanding the twin transition requires investigating how these technologies are developed in technical terms, focusing on their inner properties – like for example their combinative novelty and relatedness, complexity and complementarity, maturity and standardization – rather than only on firm- or place-level correlates.

The parallel development of these streams of research has rendered TT a genuinely multi-level phenomenon, necessitating a multi-level perspective. However, while each level is arguably important and focuses on complementary aspects that jointly shape TT, a critical challenge lies in identifying which level provides the most explanatory power: specifically, which level accounts for the greatest proportion of observed variance in the development of TT, typically proxied by patent-level inventive efforts. This matters for at least two reasons. From a research perspective, clarifying the different explanatory power at different levels of analysis helps prioritize data collection and analytical strategies – whether to focus on technology-level mechanisms, firm-level capabilities and incentives, or place-level drivers, thereby reducing model misspecification and enhancing causal inference. From a policy perspective, pinpointing the leverage point enables policymakers to design more effective instruments – targeting firm capabilities (e.g., skills, digital/green R&D, data infrastructure), technology standards and interoperability (to lower integration costs), or place-based ecosystem supports (e.g., testing facilities, cluster governance). This strengthens both ex-ante targeting and ex-post evaluation of TT interventions.

The call for a multi-level perspective does not end with identifying which level is arguably the most salient. It also requires empirically investigating TT determinants while retaining all levels simultaneously, enabling an evaluation of their relative and joint contributions to the micro-outcome of interest—namely, patent-level inventive efforts in TT. Concretely, the analysis should preserve distinct constructs at each level and examine how they shape TT invention. While each level features multiple relevant aspects, a pragmatic starting point is to prioritize the dimensions consistently flagged as most salient in the literature. Accordingly, our empirical strategy will focus on a set of “usual suspects”—those constructs that recur as first-order drivers in prior firm, regional, and technological studies — while remaining open for extensions.

Even at the risk of being selective and partial, this approach is valuable for three reasons. First, it delivers identifiable estimates of level-specific effects by reducing construct overload and multicollinearity. Second, it enables variance decomposition—i.e., how much of the observed dispersion in TT patenting is accounted for by technology-, firm-, or place-level factors—thus speaking directly to the “most explanatory level” question. Third, it yields actionable guidance for researchers (on where to deepen measurement) and for policymakers (on which levers—standards, capabilities, or ecosystems—are likely to move the needle most).

## **2.2. Level-specific determinants of twin technologies**

### *2.2.1 Firm-level determinants*

As anticipated in the previous section, the literature about the development of TT at the firm level is gaining momentum (Diodato et al., 2023). While individual studies emphasize different factors shaping firms’ innovation capabilities in this context (e.g., Ardito et al., 2021; Ardito, 2023; De Nicolai et al., 2021), some firm-specific characteristics consistently emerge across the literature.

*i) Size.* A first factor is represented by the size of firms that engage in the combination of digital and green innovations. In principle, it could be argued that, like for other breakthrough inventions, larger firms benefit from wider R&D portfolios and specialist teams, which could raise the chance of breaking cognitive traps and discovering new green-digital combinations (Ahuia & Moriss Lampert, 2001). Indeed, TT possibly require higher combinatory efforts and complementarities than green ones in isolation (Barbieri et al., 2020; 2023), which big firms could internalise more easily by benefiting from a higher absorptive capacity (Cohen & Levinthal, 1990). Furthermore, like their companion green innovations (Becker et al., 2013), TT can be capex-heavy and yield scale economics, making easier for large firms to finance and deploy them. On the other hand, as shown in research on cross-functional product development (Henderson & Clark, 1990), smaller firms — with fewer layers — can face lower coordination costs and iterate faster across departments, which is critical for the kind of cross-functional cycles that TT development requires. Moreover, by plugging more flexibly into digital layers — data platforms, APIs, cloud/IoT-as-a-service — SMEs can integrate these with environmental applications while shifting fixed IT costs to pay-as-you-go models, lowering upfront CapEx constraints (OECD, 2021).

Quite interestingly, this ambiguous conceptual framework is reflected in mixed empirical evidence on the topic. On the one hand, some recent studies provide hints about the presence of a large firm TT advantage. Kesidou and Ri (2021) find that firm size turns out to be a significantly positive control in the econometric analysis of the synergies between digital and environmental technologies/practices with respect to UK firms. Kren and Lawless (2024) show that the joint diffusion of digital and climate investment plans among Irish companies is more pervasive among larger ones. Relying on a large sample of firms in developing countries (Ghana, Thailand, and

Vietnam), Menéndez and Lavopa (2025) show that size is among the salient firm characteristics associated with a joint adoption of green and digital technologies. On the other hand, Cecere et al. (2019) show that, in a large sample of German firms, the size advantage observed for ICT innovation is smaller when it comes to green ICT patents. Analysing a large sample of Italian firms, Montresor and Vezzani (2023) find that investments in digital technologies are positively associated with the adoption of sustainable production models and processes. However, this relationship does not differ significantly among micro, small, and medium-sized enterprises, whereas for large firms, a broader spectrum of digital technology investments is required for a positive effect on eco-innovation to materialise. All in all, while theoretically relevant, the extent to which firm size affects the development of the TT, and the mechanisms through which it does so, still require empirical scrutiny.

*ii) Foreign ownership.* Among the factors that recur in firm-level analyses of TT, special attention has been paid to the multinational status of focal firms, proxied by their foreign-ownership share (e.g., Menéndez & Lavopa, 2025; Kren & Lawless, 2024). As is well known, multinational enterprises (MNEs) can leverage the interplay between their multi-location footprints and their integrated organizational networks to search for, absorb, and recombine heterogeneous knowledge to innovate (Gupta & Govindarajan, 2000; Castellani et al., 2022a). This recombination capability is crucial for TT, because TT depend on combining green and digital knowledge bases, which are themselves produced and diffused through international networks and global value chains where MNEs are pivotal players (Bello et al., 2025; Castellani et al., 2022). In addition, MNEs can benefit from their exposure to heterogeneous regulatory and market environments across countries, learning from the most advanced or “lead” markets—typically those with more stringent environmental and digital regulations—and then transferring and adapting such knowledge throughout their global operations (Marin and Zanfei, 2019). Furthermore, foreign ownership typically comes with international managerial practices and governance routines, which can also be expected to raise a firm’s ability to implement and coordinate complementary green-digital investments (Kostova & Roth, 2022). Altogether, these mechanisms make MNEs, and particularly foreign-owned firms, well positioned to originate, adopt, and scale TT.

Although with some nuances, the relevance of foreign ownership in accounting for TT at the firm level is confirmed by some recent empirical analyses. In advanced countries, like Ireland, foreign owned firms have emerged to make investments in digital and climate change plans more frequently than national ones (Kren and Lawless 2024). In developing countries, like Ghana, Thailand, and Vietnam, foreign ownership has been found to significantly predict the firms’ adoption of green technologies, but not of digital ones (Menéndez and Lavopa, 2025). However, in the same context, green and digital technologies have appeared more likely to be jointly used in firms with at least 50% foreign ownership. To the best of our knowledge, no evidence has been obtained so far about the relevance of same TT factor with respect to European firms, which our study will address through focused analysis.

*iii) Digital and green technological capabilities.* A third factor on which the literature has focused is represented by the firm’s technological capabilities, in the digital and green realm. For example, Cecere et al. (2019) show that the propensity to switch from “pure” to “green ICT” technologies is higher among firms operating in low-opportunity technological fields. In Corrocher and Ozman’s (2020), the green innovation of a panel of European ICT firms, is non-linearly influenced by their degree of digital technological diversification. In the analysis of Montresor and Vezzani (2023), the adoption of sustainable production models and processes appears mainly accounted by firms’ investments in AI, as a special kind of digital knowledge. On the other hand, the research carried out

by Aklilu et al. (2025) shows that TT inventions mainly occur in the specific realm of climate change mitigation.

Drawing on these contributions, we can argue that an important dimension of the firms' knowledge base that matters for TT is their endowment of digital and of green technological knowledge. On the one hand, digital-tech capabilities — AI, data analytics, IoT/connectivity, cloud and software engineering — operate as general-purpose technological inputs, which lower the firms' cost of measuring, optimizing and integrating environmental solutions into products and processes (Bresnahan & Trajtenberg, 1995; Lee et al., 2015). On the other hand, green technological capabilities provide the domain-specific problem frames, constraints, and performance targets (e.g., emissions, energy intensity, recyclability) that guide the integration of digital with green layers. Firms with deeper green knowledge bases are more likely to generate eco-innovations and to combine external science/partners effectively, especially when policy signals are strong (Barbieri et al., 2020; Ghisetti et al., 2005). In the TT context, in which green capabilities complement digital ones, a suitable endowment of both turns out to be a crucial enabling factor (Menéndez & Lavopa, 2025).

### *2.2.2. Country- and region-level determinants*

An important aspect that the literature about the TT has been showing is that the development and adoption of these technologies is marked by an idiosyncratic geography (Faggian et al., 2025). TT appear unevenly distributed across regions, underscoring the significance of regional contexts as critical enablers—or constraints—in shaping the trajectory of the twin transition.

To start with, this appears evident at the country level. On the one hand, recent literature suggests that the technological combination of the green and the digital transition can be quite widespread. For example, Benedetti et al. (2023) show that higher levels of digitalisation are associated with stronger energy productivity growth across 26 European countries. More specifically addressing the technological side of the twin transition, Vasconcelos-Garcia and Carrilho-Nunes (2024) find that, alongside FDI net inflows, various dimensions of the last digital revolution — namely broadband and connectivity, digital inclusion, and the Digital Single Market — are positively correlated with a synthetic indicator of eco-innovation performance among EU countries. On the other hand, despite these cross-country regularities, the development of TT appears geographically polarised. A recent OECD study on the geography of TT (Aklilu et al., 2025) — proxied by patents in which green and digital knowledge co-occur — finds the top five countries (China, the US, Japan, Korea, and Germany) account for 85% of all international twin patent applications over the period 2016–2020: a share significantly higher than their share of all technologies (79%) (ibidem). Furthermore, countries differ greatly in the kind of TT in which they specialise.

While relevant, this country-based evidence hides further elements of geographical differentiation at the sub-national level. Both within (see, for example, Fazio et al., 2025) and outside the EU (see, for example, Zhang & Du, 2023, on China), countries comprise regions with extremely different TT capabilities, making a regional level of analysis a more suitable lens of investigation. Once more, also at this level, various factors have emerged that either enable or hamper the development of TT, stimulating specific foci in the extant literature. Among these, two kinds of factors appear particularly salient across the available studies.

i) *Digital and green regional knowledge base.* Following one of the main tenets of evolutionary economic geography, regions' capacity to develop new technologies largely depends on the characteristics of their knowledge base, i.e. the set of technologies they master from a cognitive

point of view (Boschma & Frenken, 2006). Operationally, this is usually captured by whether and to what extent a region is specialised in a certain technological domain — for instance, by developing a regional share of specific patent classes that is higher than its overall share of total patents (Balland, 2016). Referring to TT, the regional endowment of green and digital technologies—as measured by their relative technological specialisations—represents the most relevant aspect of the knowledge base to consider.

Several studies have already explored this twofold specialisation dimension, though so far only partially and indirectly: that is, by focusing on the green-tech specialisation of regions and by connecting it to some local digital dimensions. For example, using a patent-based panel (1981–2013) of 240 European regions, Montresor & Quatraro (2022) find that regional Key Enabling Technologies (KETs), which include some digital technologies, facilitate the transition towards specialisation in sustainable technologies. Cicerone et al. (2022) show that AI knowledge at the NUTS-3 level supports specialisation in green technologies—but only when its applications can build on pre-existing green-tech capabilities; in the absence of such a base, AI may hinder green specialisation. Similarly, Santoalha et al. (2021) find that digital skills in the local workforce are a strong predictor of EU regions' capacity to specialise in new green technologies, with a stronger effect than in non-green domains.

While these contributions are highly relevant, the analysis of the development of TT requires a different perspective—one that considers the extent to which the regional specialisation in green and digital technologies affects the capacity to generate TT. As far as green specialisation is concerned, one might expect that regions with a strong green-technological base are better positioned to link green and digital domains, for instance by being able to embed digital knowledge in pre-existing green technologies. However, this cannot be taken for granted. A strong focus on established green technologies may lead to path dependence and cognitive lock-in, constraining the region's ability to explore and integrate new digital knowledge from the digital domain. In other words, excessive green specialisation may reinforce existing non-digitally informed green-tech trajectories, rather than favouring new cross-digital green-tech recombination (Tödtling, F., & Grillitsch, 2015). As far as digital specialisation is concerned, one could similarly expect that regions mastering digital technologies might be better able to make them functional to the green-tech transition and to the development of TT. Yet, again, this expectation is not automatic. Being specialised in digital domains does not necessarily imply possessing the right type of digital technologies (e.g. enabling, data-intensive, energy-efficient) or absorptive capacity in environmentally oriented sectors (Tödtling, F., & Grillitsch, 2015). In some cases, digital specialisation may even be biased towards ICTs unrelated—or potentially detrimental—to sustainability goals.

All in all, in line with existing literature, the green and digital composition (i.e., specialisation) of the regional knowledge base can be considered as a contextual factor shaping local TT dynamics. Yet, in the absence of strong theoretical a priori on how these components interact, an empirical investigation becomes a crucial step to ascertain their actual role and complementarity in driving the emergence of TT.

ii) *Agglomeration economies*. Moving beyond knowledge-related factors, a wide set of local socio-economic and institutional conditions can be deemed to affect the development of TT. One may recall the literature on Regional Innovation Systems and on the capacity of its constituent actors and relationships to orient technological trajectories towards green and digital targets, increasingly discussed in transition studies (Cooke, 2010; Truffer & Coenen, 2012). Unfortunately, the number of place-specific factors explicitly examined in TT research remains rather limited. The level of

economic development of the focal regions is usually considered only as a control variable (see the collection in Faggian et al., 2025), while few studies explicitly address other contextual mechanisms.

A notable exception concerns the extent to which the local development of TT can benefit from agglomeration economies. As is well known, through the interplay of matching, sharing, and knowledge-spillover mechanisms, agglomeration economies have been found to grant urban areas a premium in innovation outcomes in general terms (Carlino & Kerr, 2015). This urban advantage has been recently confirmed for the geography of digital technologies as well (Corradini et al., 2021). However, whether this also holds true for the development of green technologies remains more contentious. In one of the few studies on the topic, using data from the French Community Innovation Survey (CIS), Galliano et al. (2022) find that while Marshallian specialization economies (related to factor above) positively affect firms' eco-innovation, Jacobian urbanisation economies—proxied by unrelated variety—tend to negatively affect the breadth of firms' eco-innovations. Moreover, they show that related variety (still aligned with urbanisation economies) is more strongly associated with eco-innovation breadth in rural rather than in urban contexts.

Interestingly, the role of urbanisation economies has also been explored directly within the twin transition framework, by examining whether digital investments facilitate green innovation across urban versus peripheral areas. Using a large sample of European firms from the Eurobarometer 2020, Cattani et al. (2023) find that firms located in rural areas display a relatively higher capacity to eco-innovate, despite their lower digital propensity. However, an urban location amplifies the eco-innovative impact of digital technologies. While this provides a relevant starting point, whether urban agglomeration economies truly facilitate the combination of green and digital knowledge for the unfolding of TT remains far from guaranteed. On the one hand, urban regions are known to exhibit higher combinatorial capabilities and to foster atypical knowledge recombination (Mewes, 2019). On the other hand, urbanisation economies may also act as barriers to the digital alignment of green technologies, while rural or peripheral regions could enjoy specific advantages in this regard. This may happen because peripheral regions, despite their smaller size, often host diversified yet loosely coupled knowledge bases that facilitate cross-domain experimentation outside the dominant technological paradigms of dense urban environments. In addition, lower cognitive and institutional lock-in and stronger community embeddedness can favour the local adaptation of digital solutions to environmental challenges. Such mechanisms resonate with recent evidence on the innovative potential of “thin” or “peripheral” regional innovation systems in sustainability-oriented transitions (Isaksen & Trippl, 2016; Tödtling et al., 2021). Quite interestingly, the role of urbanisation in hampering the development of TT is aligned with recent evidence showing that, even with respect to green patents as such (i.e., non-twin), regional inventive capabilities in the environmental realm correlates negatively with regional population density, usually taken to proxy the same economies (Becker et al., 2025).

### *2.2.3. Technology-level determinants*

In addition to the previous contextual elements, the development of TT is also affected by the nature of the salient technologies that are combined, which are of course heterogeneous (Nelli et al., 2025; Biggi et al., 2024). Focusing on the development of new green technologies that rely on digital prior art knowledge, as we do in our empirical application, it becomes important to investigate the specific environmental domain in which new inventions are fed by digital ones. In the extant literature, this has been examined to a limited extent, by referring to the patent IPC and CPC classes in which green patents are currently classified using standard taxonomies (Haščič and Migotto, 2015). In a recent OECD work, for example, Aklilu et al. (2025) have showed that, while

most environmental inventions are concentrated in climate change mitigation and environmental management, twin transition inventions — still identified through the co-occurrence of green and digital CPC codes and keywords, applied to PCT patents over the period 2005–2020 — happen mostly in climate change mitigation. Indeed, the spectrum of environmental fields to which digitalisation can be functional, and the extent to which combination opportunities are exploited across them, is heterogenous, and requires a sufficiently disaggregated kind of analysis.

By considering the standard OECD-ENVTECH taxonomy of green technologies (Haščič & Migotto, 2015, 2015), we consider the ones related to climate change mitigation and adaptation.

i) *Adaptation to climate change*. Technologies for climate adaptation — such as early-warning systems, precision meteorological models, and climate-resilient agriculture — display a strong cognitive overlap with digital domains, which are related to data analytics, sensing, and simulation. Digital tools are crucial for translating environmental data into actionable adaptation measures.

ii) *Climate change mitigation related to energy-generation and transmission*. Renewable-energy generation and grid management exhibit one of the highest dependencies on digital technologies. Smart-grid systems, predictive maintenance of wind or solar assets, and integration of distributed energy resources all hinge on digital control, AI-based forecasting, and data connectivity. Digitalisation thus underpins both efficiency and system flexibility, especially as electricity networks decarbonise.

iii) *Climate change mitigation related to production and processing of goods*. In manufacturing and process industries, digital tools serve mainly as efficiency and optimisation levers—for example, via process automation, advanced sensors, and digital twins. These technologies contribute to resource and energy efficiency and, ultimately, emission reductions. However, the reliance on digital knowledge here is expected to be more selective, and arguably depending on sectoral readiness and absorptive capacity.

iv) *Climate change mitigation related to buildings*. Energy efficiency in buildings relies heavily on digital monitoring and automation. Smart-metering, building-management systems, and IoT-based control devices constitute the digital backbone of low-carbon buildings.

v) *Climate change mitigation related to waste-management*. In waste management, digital tools increasingly support sorting, tracking, and circular-economy processes. Nonetheless, compared with energy or transport, the connection might be expected to remain less systematic. The role of digital technologies here is predominantly logistical and managerial—e.g., sensor-based sorting or digital traceability—rather than at the technological core of waste treatment.

vi) *Climate change mitigation related to transportation*. Transport decarbonisation has become a paradigmatic “twin” domain. Digitalisation is crucial for electrified, autonomous, and shared mobility systems, providing integration across vehicles, infrastructure, and energy networks. Digital control and AI enable route optimisation, battery-management systems, and vehicle-to-grid communication. Consequently, transport-related green inventions can be expected to exhibit a high digital reliance, especially in automotive electronics and intelligent-transport-system patents.

vii) *Storage of greenhouse gases (GHG)*. Technologies related to carbon capture, utilisation, and storage (CCUS) can be expected to display a moderate digital content. While process optimisation and subsurface monitoring rely on digital modelling and remote-sensing tools, the core of the technology remains physical and chemical. Digital knowledge plays an enabling but peripheral role, for instance in simulation of injection processes or safety monitoring.

viii) *Climate change mitigation related to ICT*. This category represents a direct convergence domain, where digital technologies themselves are designed to reduce carbon emissions—for example, energy-efficient computing, data-centre management, or low-power electronics. Here, the relationship between green and digital knowledge is intrinsic: digital inventions are simultaneously green, and vice versa. The overlap here is therefore arguably maximal, making this domain central to the twin transition.

ix) *Information and communication having an impact on other technologies*. This domain encompasses digital general-purpose technologies (GPTs)—such as AI, IoT, big data, and connectivity—that enable green innovation across all other sectors. These technologies are cross-cutting enablers: their value lies in complementing domain-specific green inventions.

In sum, the extent to which green technologies draw upon digital knowledge is expected to vary substantially across technological domains, reflecting differences in their underlying knowledge bases, complementarities, and functional requirements. While some green fields—such as ICT-related mitigation, energy generation, and transport—are inherently digital-intensive, others rely on digital tools only as supporting or enabling inputs. This heterogeneity implies that the drivers of TT cannot be fully captured by a one-size-fits-all approach. Rather, accounting for the distinct digital complementarities of each green domain becomes essential to identify the technology-specific factors that sustain or constrain the emergence of twin inventions. Considering at least these major green domains therefore provides a necessary analytical framework for disentangling how digital capabilities contribute—unevenly but crucially—to the evolution of the twin transition.

### 3. Data sources and methodology

We construct our dataset by combining patent application data from the Moody's Orbis Intellectual Property (IP) and the European Patent Office (EPO)'s Patstat databases with balance sheet information for applicants from the Moody's Orbis Global database.

To identify green technologies, we apply the CPC system, jointly administered by the EPO and the US Patent and Trademark Office (USPTO). Following the literature (De Haas and Popov, 2022), we classify green patents as those falling under the Y02 and Y04 categories. For digital technologies, we adopt the WIPO (2022) mapping of digital general-purpose technologies, which combines keyword-based and CPC-class-based criteria. To this, we add additive manufacturing, identified by the CPC class B3YY, resulting in a total of 2.8 million global digital patents. The majority of these patents are in data and AI, and robotics-related technologies, followed by additive manufacturing and other technologies (**Table 7** in the Annex).

Following our identification approach to TT, we proxy them with green patents that cite at least one digital patent (Aklilu et al., 2025). To avoid usual problems of truncation with patent data, our final sample includes green patent applications filed by EU applicants between 2007 and 2020. We have adopted the applicant's primary address as recorded in the ORBIS database to define its geographical location. To facilitate cross-country comparisons, we focus on applications filed at the EPO, which provides legal protection across 41 European countries (27 EU member states and 14 non-EU countries). This yields a total of 72,762 EPO green patent applications, 3,386 of which (about 5%) are classified as twin patents.

Our econometric analysis aims to identify the factors influencing the likelihood of a green invention to cite at least one digital invention (as opposed to citing only non-digital inventions). Using individual green patent applications as unit of analysis, we proceed in two steps. First, to provide an initial assessment of the relative importance of the different dimensions that may affect the development of TT, we regress the occurrence of a twin patent application (TP) on geographical, sectoral, technological, and firm-specific fixed effects. Specifically, we estimate the following model:

**Equation 1.** First-stage equation

$$TP_{p,i,t,r,c,s,o} = \alpha + \pi_1 R_r + \pi_2 C_c + \pi_3 S_s + \pi_4 T_o + \pi_5 Z_i + \pi_6 Y_t + u_{p,i,t,r,c,s,o}$$

where  $TP_{p,i,t,r,c,s,o}$  is a dummy variable equal to one if the green EPO patent application  $p$  cites a digital patent, and 0 otherwise. Each patent  $p$  is filed at time  $t$  by EPO applicant  $i$ , located in region  $r$  within country  $c$ , and it features technology  $o$  in sector  $s$ .  $R_r$ ,  $C_c$ ,  $T_o$ ,  $S_s$ ,  $Y_t$  and  $Z_i$  are regional, country, technology group, sectoral (at NACE two-digit level), year and firm-fixed effects, respectively. We define technological groups based on the grouping (35 technologies) by Schmoch (2008).

In the second stage of our analysis, we build on the previous results by replacing firm and region fixed effects with vectors of firm and regional covariates. We further enrich the model by including a vector of patent-level covariates, as follows:

**Equation 2.** Second-stage equation with vectors of firm, regional and patent-related covariates

$$TP_{p,i,t,r,c,s,o} = \alpha + X_i' \beta + Z_r' \gamma + W_p' \theta + C_c + S_s + T_o + Y_t + u_{p,i,t,r,c,s,o}$$

where  $X$ ,  $Z$ , and  $W$  refers to our vectors of firm, regional and patent-related covariates, respectively.

Building on existing literature (see Section 2), we first explore the role of firm size — an aspect for which the evidence remains inconclusive — measured as the logarithm of the number of employees associated with the patent applicant (*“Number of employees (in log)”*) in

**Table 1** and **Table 6**).

Furthermore, as the multinational status of the applicant firm might affect the network through which its green inventions can draw on digital ones, we also control for its foreign ownership with a dummy, taking value 1 if a foreign entity holds a majority or all of the shares or ownership of our focal firm, and 0 otherwise (*“Foreign-owned”*).

To capture a firm’s knowledge base—a key determinant identified in prior empirical work (Section 2)—we develop two complementary measures. First, we calculate the firm’s share of digital patents in total patent stock (*“Share of digital patents in total patent stock”*). This metric reflects a firm’s familiarity with digital technologies and, by extension, its capacity to leverage these capabilities in the development of green innovations. Second, we construct the firm’s share of green patents in total patent stock (*“Share of green patents in total patent stock”*) to investigate whether green expertise fosters the integration of digital knowledge in this domain or whether such capabilities risk entrenching path dependence and cognitive lock-in, reinforcing existing non-digital knowledge and limiting the absorption of digitally aligned innovations.

At the regional level, we construct two indicators to measure whether regions are specialised in digital or green technologies (*“Digital specialisation”* and *“Green specialisation”*). These are calculated using a Revealed Technological Advantage (RTA) index, defined as a ratio between one region’s share of digital (green) patents and the corresponding share at the EU level. These indicators capture the relevance of the digital or green technological base for TT development, as emphasized in previous studies (Fazio et al., 2025; Santoalha et al., 2021),

The third and fourth independent variables - *“Population density”* and *“Predominantly urban”* - are sourced from Eurostat at the NUTS-3 level. Population density is calculated as the ratio between the annual average population and the land area of the respective region. Urban predominance is a dummy variable taking the value 1 if more than 50 % of the population live in urban clusters, and 0 otherwise. By incorporating these variables, we aim to assess whether agglomeration facilitates or hinders the integration of green and digital knowledge in TT contexts (Section 2).

The final set of variables in **Equation 2** incorporates patent-level features to identify the defining characteristics of twin patents. First, we control for the specific environmental domain addressed by the digital cited patent, categorized using retained CPC codes: adaptation to climate change, buildings-related mitigation, storage of greenhouse gases, ICT-related mitigation, energy generation and transmission-related mitigation, production and processing of goods-related mitigation, transportation-related mitigation, and waste management-related mitigation (all included as dummy variables). Second, we control for the total number of backward citations in the focal green patent (*“Backward citations”*), as patents with higher citation counts are more likely to incorporate digital knowledge. Summary statistics for these and other key variables in our analysis are provided in

**Table 1.**

We estimate the equations above using an ordinary least squares (OLS) model, thereby assuming a linear probability model (LPM) (see Section 5). We opted for the LPM due to its simplicity and interpretability, particularly for presenting marginal effects in a straightforward manner, while acknowledging its limitations in cases of extreme predicted probabilities. Equation 1 and Equation 2

are estimated on the full sample of green patents. As a robustness check, we also estimate Equation 2 using a reduced sample that excludes green patents classified under the CPC class Y04W (information and communication technologies impacting other technologies) to assess whether our findings are sensitive to this specific category.

**Table 1.** Summary statistics

<b>Variable</b>	<b>Mean</b>	<b>Std. dev.</b>	<b>Min</b>	<b>Max</b>	<b>Obs</b>
<i>Regional level (NUTS 3)</i>					
Green specialization	4.2	3.2	0.0	31.5	68,254
Digital specialization	0.1	0.1	0.0	2.1	68,254
Population density	3.0	5.6	0.0	21.5	67,906
Predominantly urban	0.9	0.3	0.0	1.0	68,266
<i>Applicant level</i>					
Number of employees (in log)	7.2	3.4	0.0	12.9	58,494
Foreign-owned	0.2	0.4	0.0	1.0	69,489
Share of digital patents in total patent stock	0.0	0.1	0.0	1.0	91,232
Share of green patents in total patent stock	0.4	0.3	0.0	1.0	91,370
<i>Patent level</i>					
Twin application	0.0	0.2	0.0	1.0	72,762
Backward citations	6.8	9.9	0.0	382.0	72,761
Adaptation to climate change (Y02A)	0.1	0.3	0.0	1.0	72,762
Buildings-related CC Mitigation (Y02B)	0.1	0.3	0.0	1.0	72,762
Storage of GHG (Y02C)	0.0	0.1	0.0	1.0	72,762
ICT-related CC Mitigation (Y02D)	0.0	0.2	0.0	1.0	72,762
Energy-generation and transmission-related CC Mitigation (Y02E)	0.4	0.5	0.0	1.0	72,762
Production and processing of goods-related CC Mitigation (Y02P)	0.2	0.4	0.0	1.0	72,762
Transportation-related CC Mitigation (Y02T)	0.2	0.4	0.0	1.0	72,762
Waste management-related CC Mitigation (Y02W)	0.1	0.2	0.0	1.0	72,762
Information and communication having an impact on other technologies (Y04W)	0.0	0.2	0.0	1.0	72,762

Note: "CC" stands for climate change.

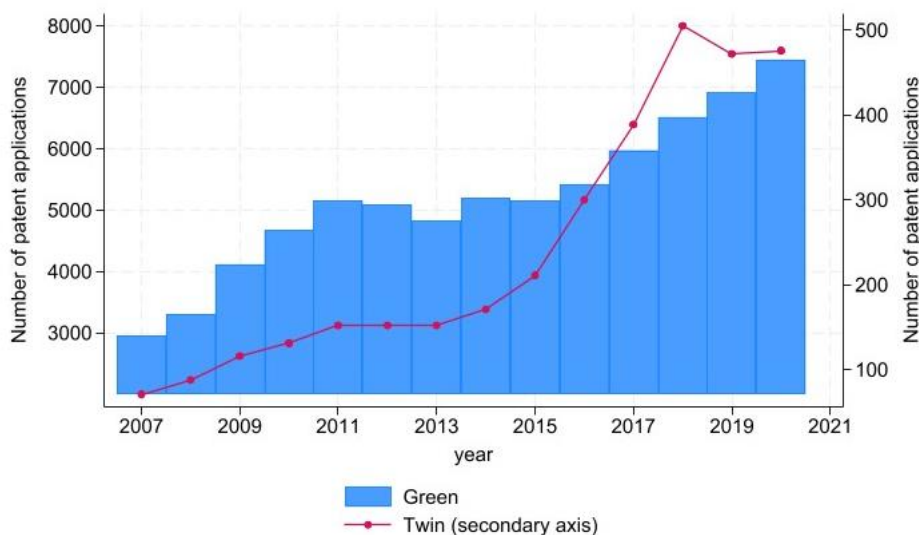
Source: Authors' calculation.

## 4. Descriptive evidence on twin inventions in the EU

This section provides an overview of the distribution of twin inventions in the EU, based on our dataset of green and twin patent applications. The analysis aims to clarify patterns and trends in the development of twin technologies and to identify areas where digital knowledge is being integrated to advance sustainability and environmental benefits.

**Figure 1** illustrates the trend in the number of green and twin patent applications from 2007 to 2020. It highlights a notable rise in the share of twin inventions over the most recent five-year period for which data is available (2015–2020). Consistently with other recent evidence about TT (Aklilu et al. (2025), twin patent applications have exhibited a significantly faster growth rate compared to green patents during the 2014–2018 period, followed by a gradual decline in 2019. This trend overall suggests an accelerating technological convergence between digital and environmental domains. The majority of these twin patents are green patents that cite inventions related to additive manufacturing, followed by technologies in robotics and the data and AI domains (**Table 2**). This seems to suggest that digital technologies enabling design flexibility, real-time data processing, and automation are playing an increasingly central role in shaping the direction of environmentally oriented technological development.

**Figure 1.** Trend in the number of EPO green and twin patent applications (2007-2020)



*Note: This figure refers to EPO patent applications filed by an EU corporate applicant.*

*Source: Authors' calculation based on Moody's ORBIS and EPO's Patstat datasets*

**Table 2.** Distribution of digital patents filed cited in EU green patents by class of digital technology in the cited patents

	Data and AI	Robotics	Additive manufacturing	Others
<b>%</b>	23.3	24.6	75.8	13.1
<b>N</b>	807	852	2624	452

*Note: Percentages exceed 100% as one green patent can cite more than one digital technology class*

*Source: Authors' calculation based on Moody's ORBIS and EPO's Patstat datasets.*

**Table 3** presents the distribution of green and twin patent applications across different green technological groups. The results reveal that green patent applications are predominantly concentrated in the energy-generation and transmission-related climate change mitigation category (39.2%), followed by transportation-related climate change mitigation (24.1%) and production and processing of goods-related climate change mitigation (23.3%). In contrast, twin patent applications are most prevalent in the production and processing of goods-related climate change mitigation category (40.6%), indicating a stronger focus on integrating digital knowledge in manufacturing and industrial processes. The propensity of green patents to cite digital inventions varies significantly across technological groups. The Information and Communication Technologies (ICT) impacting other sectors category exhibits the highest share of twin applications (22.8%), while twin patents accounts for 8.1% of the production and processing of goods-related climate change green patents. These trends align with their sectoral distribution, where twin patent applications are predominantly clustered in information and communication services, machinery and equipment manufacturing, and professional, scientific, and technical activities (**Table 9** in the Annex).

**Table 3.** Distribution of green and twin inventions by green technological group

Technological class	Green		Twin		% Twin out of green
	%	Adj %	%	Adj %	
Adaptation to climate change	9.1	7.5	3.1	2.5	1.6
Buildings-related CC Mitigation	11.6	9.6	14.6	11.9	5.9
Storage of GHG	1.3	1.1	0.1	0.1	0.4
ICT-related CC Mitigation	4	3.3	5.6	4.6	6.5
Energy-generation and transmission-related CC Mitigation	39.2	32.4	23.9	19.5	2.8
Production and processing of goods-related CC Mitigation	23.3	19.3	40.6	33.1	8.1
Transportation-related CC Mitigation	24.1	19.9	17.5	14.3	3.4
Waste management-related CC Mitigation	5	4.1	1.1	0.9	1.0
Information and communication having an impact on other technologies	3.3	2.7	16.2	13.2	22.8
<b>Total</b>	<b>120.9</b>	<b>100.0</b>	<b>122.7</b>	<b>100.0</b>	<b>4.7</b>

Note: "CC" stands for climate change. "Adj %" refers to shares accounting for patents belonging to multiple green tech classes

Source: Authors' calculation based on Moody's ORBIS and EPO's Patstat datasets.

The propensity to develop twin inventions also varies across EU countries, which may be related to factors such as human capital, innovation capacity, research and development investments, and policy frameworks (**Table 4**). Germany is the leading country in terms of the number of green patent applications (31,544), followed by France (12,747) and the Netherlands (4,967). In terms of twin patent applications, Germany also leads with 1,836 applications, followed by France (329) and Denmark (159). The percentage of twin patent applications out of total green patent applications varies across countries, with Germany and Spain having a higher share (5.8% and 6.1%, respectively) compared to other countries.

**Table 4.** Distribution of green and twin inventions by country of applicant

EU country	Green (N)	Twin (N)	Twin (% of green)
DE	31,544	1,836	5.8
FR	12,747	329	2.6
NL	4,967	129	2.6
DK	4,615	159	3.4
SE	4,400	210	4.8
IT	3,712	121	3.3
BE	2,411	91	3.8
AT	2,367	94	4.0
FI	2,019	87	4.3
ES	1,939	119	6.1
IE	466	24	5.0
LU	442	8	1.8
Other EU countries	1,093	52	4.8
<b>Total</b>	<b>72,722</b>	<b>3,258</b>	<b>4.5</b>

*Note: Country refers to the country of primary address of the patent applicant. Figures are based on fractional counting.  
Source: Authors' calculation based on Moody's ORBIS and EPO's Patstat datasets.*

## 5. The drivers of twin inventions in the EU

This section presents the results of our econometric analysis, which aims to identify the factors influencing the development of TT in the EU. **Table 5** reports the results from our first-stage estimation using an LPM. The model containing only year, country, and sector fixed effects explains a modest 6.4% of the variance in our dependent variable (Column 6). This suggests that macro-level temporal, national, and industrial differences alone offer a partial explanation for the development of twin technologies. Incorporating regional fixed effects more than doubles this explanatory power, increasing the variance explained to 15.7% and underscoring the importance of sub-national territorial factors. Adding technological class fixed effects slightly improves the fit, slightly raising the adjusted R-squared to 16.7% (Column 9) indicating some relevance of the underlying technological field. The inclusion of firm-level characteristics significantly enhances model fit, with the adjusted R-squared increasing to 27.1%. Overall, our analysis points to a substantial role played by firm-specific characteristics and, to a lesser extent, regional characteristics in explaining the propensity of a green technology to cite digital technologies.

**Table 5.** Drivers of twin inventions: first-stage estimation (Equation 1)

<b>Dep variable: probability of a green invention to cite a digital invention</b>										
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes					Yes				
Industry FE		Yes				Yes	Yes	Yes	Yes	Yes
Region FE			Yes				Yes		Yes	
Tech group FE				Yes					Yes	Yes
Applicant FE					Yes			Yes		Yes
R-squared adjusted	0.026	0.059	0.143	0.032	0.271	0.064	0.157	0.264	0.167	0.271
N	91,436	77,549	68,353	91,436	91,436	77,549	68,049	77,549	68,049	77,549

*Note: Coefficients are estimated using a linear probability model (LPM) via ordinary least squares (OLS). FE denotes fixed effects. Industry fixed effects are defined at the NACE 2-digit level, and regional fixed effects at the NUTS-3 level. Technological group fixed effects follow the 35-technology classification by Schmoch (2008). Source: Authors' calculation.*

Turning to the second stage of our estimation (**Table 6**), our findings show that foreign-owned firms are more likely to develop green technologies that draw on digital prior-art knowledge. This suggests that being part of an MNE increases a firm's exposure to diverse knowledge sources, heterogeneous regulatory and market environments, and established collaboration networks, which may facilitate cross-domain knowledge integration. As expected, firms with a stronger digital knowledge base are more likely to develop the kind of twin patents under investigation. This result suggests that accumulated expertise in digital technologies equips firms with the cognitive and technical capacity to integrate digital solutions into green innovations, facilitating knowledge spillovers and cross-domain learning that underpin the development of twin technologies. By contrast, firms with accumulated green knowledge may face path dependence and cognitive lock-in, reinforcing existing traditional and non-digitally aligned trajectories and limiting their capacity to explore cross-domain recombination essential for twin technologies. A strong focus on established green solutions may risk entrenching siloed, domain-specific knowledge bases, which hinder the integration of novel digital insights into green innovation processes.

Regarding regional drivers, our results show, in line with recent studies about the geography of the TT (e.g. Santohala et al., 2021), that opportunities of developing TT are higher in regions with a specialisation in digital technologies. This may reflect the greater local availability of digital knowledge and competences, which facilitate knowledge spillovers and enable inventors to access and integrate digital knowledge into green technological developments. Conversely, specialisation in green technologies does not seem to facilitate the development of twin technologies. Furthermore, we find that both population density and urban predominance are negatively associated with the integration of digital knowledge in green inventions. The negative association between population density and the development of twin technologies may reflect cognitive lock-in and institutional inertia in densely populated regions. High population density often correlates with entrenched green-tech paradigms, specialized knowledge silos, and limited cross-domain experimentation (Galliano et al., 2022). These factors may hinder the recombination of green and digital knowledge, as dense urban environments prioritize optimization of existing green technologies over exploratory innovation that incorporates digital solutions (Cattani et al., 2023). The negative effect of urban predominance may reflect the rigidities inherent in urban knowledge ecosystems. While urban areas typically benefit from agglomeration economies and dense innovation networks, their entrenched green-tech paradigms and institutionalized systems may resist the integration of disruptive digital knowledge.

Interesting results also emerge from the patent-level regressors. Green inventions categorized under information and communication technologies impacting other technologies (CPC Y04W) exhibit a significantly higher probability of being twin technologies as compared to other green technological classes, with the exclusion of production and processing of goods-related climate change mitigation and buildings-related climate change mitigation. Notably, when Y04W patents are excluded from the sample, the development of twin technologies becomes more likely among inventions in the production and processing of goods-related mitigation category.

Overall, our findings reveal a nuanced interplay between firm, regional, and patent-level factors in shaping twin technology (TT) development. While foreign ownership, digital knowledge bases, and digital regional specialization foster TT, entrenched green expertise, urban rigidity, and population density emerge as key barriers. The conditional role of patent categories further underscores the heterogeneous pathways to integrating green and digital innovations. These results highlight the importance of targeted strategies to overcome knowledge silos and leverage synergies between domains, offering critical insights for policy and future research.

Notably, when introducing firm, region and patent-level regressors, the presence of missing value reduces the estimating sample. As a robustness check, in **Table 10** we provide estimates of our first stage regression (Equation 1) on the (smaller) estimating sample of our second stage (Equation 2). Interestingly, our model's explanatory power increases in the smaller sample. Specifically, the model with year, industry, technology and regional fixed effects explains 21% of the variance, whereas replacing regional fixed effects with firm-level fixed effects increases the explained variance to 35 percent.

**Table 6.** Drivers of twin inventions: second-stage estimation (Equation 2)

<b>Dependent variable: probability of a green invention to cite a digital invention</b>		
	(1)	(2)
<i>Regional characteristics</i>		
Green specialisation	-0.000 (0.001)	-0.000 (0.001)
Digital specialisation	0.277*** (0.018)	0.303*** (0.018)
Population density	-0.001*** (0.000)	-0.003*** (0.000)
Predominantly urban	-0.035*** (0.006)	-0.036*** (0.006)
<i>Firm characteristics</i>		
Number of employees (in log)	-0.001 (0.001)	-0.000 (0.001)
Foreign-owned	0.013*** (0.003)	0.009*** (0.003)
Share of digital patents in total patent stock	0.767*** (0.023)	0.711*** (0.023)
Share of green patents in total patent stock	-0.035*** (0.007)	-0.028*** (0.006)
<i>Patent characteristics</i>		
Backward citations	0.001*** (0.000)	0.001*** (0.000)
Information and communication having an impact on other technologies (Y04W)	[ref. cat.]	
Adaptation to climate change (Y02A)	-0.043*** (0.004)	[ref. cat.]
Buildings-related CC Mitigation (Y02B)	-0.003 (0.006)	-0.026*** (0.005)
Storage of GHG (Y02C)	-0.060*** (0.004)	-0.047*** (0.003)
ICT-related CC Mitigation (Y02D)	-0.093*** (0.010)	-0.028*** (0.009)
Energy-generation and transmission-related CC Mitigation (Y02E)	-0.059*** (0.004)	-0.037*** (0.003)
Production and processing of goods-related CC Mitigation (Y02P)	-0.001 (0.004)	0.023*** (0.003)
Transportation-related CC Mitigation (Y02T)	-0.046*** (0.005)	-0.026*** (0.005)
Waste management-related CC Mitigation (Y02W)	-0.066*** (0.005)	-0.046*** (0.004)
Constant	0.113*** (0.010)	0.077*** (0.009)
Year FE	Yes	Yes
Industry FE (NACE 2-digit)	Yes	Yes
Country FE	Yes	Yes
R-squared adjusted	0.202	0.213
N	42,099	40,782
Green classes	All	Excluding Y04W

Note: OLS estimation. Robust standard errors in parentheses. \*  $p < 0.1$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$ .

Source: Authors' calculation.

## 6. Conclusions and policy implications

Understanding the drivers of twin technology development is crucial for policymakers seeking to accelerate the twin transition. By identifying these drivers, policymakers can design targeted interventions and support measures that facilitate the adoption of digital technologies for green innovation, leverage synergies between the two transitions, and ultimately supporting the achievement of environmental and climate goals. Furthermore, knowledge of the drivers of twin technology development can help policymakers optimise resource allocation, prioritize investments, and create a favourable business environment that fosters the growth of twin technologies, thereby maximising the potential for a successful twin transition.

This study aims to shed light on the factors driving the development of twin inventions, which leverage digital technologies to drive sustainability and environmental benefits. Our analysis reveals that firm- and regional-level characteristics have the highest explanatory power in explaining the propensity to develop green technologies that build on prior art digital knowledge.

At the firm level, foreign ownership emerges as a critical enabler, likely due to the firms' exposure to diverse knowledge sources, heterogeneous regulatory and market environments, as well as established collaboration networks. Similarly, a firm's digital knowledge base is strongly associated with TT development, underscoring the importance of cumulative expertise in enabling cross-domain recombination. Conversely, entrenched green knowledge appear to hinder the adoption of digital solutions, suggesting that path dependence in traditional green sectors may act as a barrier to hybrid innovation.

At the regional level, specialization in digital technologies boosts TT opportunities, likely due to the availability of local digital competencies and spillovers, while urbanization exhibits negative effects. These findings align with broader debates about the dual-edged nature of agglomeration economies: while urban areas are hubs of innovation, their rigid structures and entrenched paradigms may resist the disruptive integration of digital and green knowledge. Finally, the patent-level analysis further highlights the conditional role of patent categories underscoring the heterogeneous pathways to integrating green and digital innovations.

These results contribute to the growing literature on the geography and governance of TT by emphasizing the need for multi-level perspective. Policymakers must address cognitive lock-in in green sectors, foster cross-domain collaboration, and leverage the strengths of both urban and peripheral regions to balance specialization and experimentation.

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## List of abbreviations and definitions

<b>Abbreviations</b>	<b>Definitions</b>
AI	Artificial Intelligence
BE	Belgium
CC	Climate Change
CPC	Cooperative Patent Classification
DE	Germany
DK	Denmark
EU	European Union
EPO	European Patent Office
FR	France
ICT	Information and Communication Technologies
IT	Italy
KETs	Key Enabling Technologies
LU	Luxembourg
NL	Netherlands
NUTS	Nomenclature of Territorial Units for Statistics
PCT	Patent Cooperation Treaty
SE	Sweden
TT	Twin Technologies
WIPO	World Intellectual Property Organization

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## Annexes

### Annex 1. Additional tables and charts

**Table 7.** Distribution of digital patents filed by any applicant by digital class

	Data and AI	Robotics	Additive manufacturing	Others
<b>%</b>	44.8	32.6	4.6	22.1
<b>N</b>	1,288,763	937,558	131,205	635,743

Source: Authors' calculation.

**Table 8.** Distribution of EU twin patent applications by digital class and applicant's main sector

Main sector	Data and AI	Robotics	Additive manufacturing	Others
	%			
Manufacturing	10.19	12.39	72.80	4.61
Services	10.21	9.65	72.17	7.97
Other	36.68	47.39	0.78	15.14

Source: Authors' calculation.

**Table 9.** Distribution of green and twin inventions by applicant sector

<b>Sector</b>	<b>Green</b>	<b>Twin</b>	<b>Sectoral share of twin patents in the total (%)</b>
<b>Agriculture and mining</b>			
Agriculture, forestry and fishing	96	2	0
Mining and quarrying	457	-	-
<b>Manufacturing</b>			
Manufacture of food and beverage products	250	2	0
Manufacture of textiles, wearing apparel and leather products	103	3	0
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	51	3	0
Manufacture of paper and paper products	212	1	0
Printing and reproduction of recorded media	19	5	0
Manufacture of coke and refined petroleum products	160	2	0
Manufacture of chemicals and chemical products	4,004	81	2
Manufacture of basic pharmaceutical products and pharmaceutical preparations	1,041	3	0
Manufacture of rubber and plastics products	866	16	0
Manufacture of other non-metallic mineral products	1,137	22	1
Manufacture of basic metals	708	15	0
Manufacture of fabricated metal products, except machinery and equipment	1,214	114	3
Manufacture of computer, electronic and optical products	3,523	201	6
Manufacture of electrical equipment	3,747	242	7
Manufacture of machinery and equipment n.e.c.	8,505	472	14
Manufacture of motor vehicles, trailers and semi-trailers	6,301	162	5
Manufacture of other transport equipment	3,313	115	3
Manufacture of furniture	25	-	-
Other manufacturing	453	15	0
<b>Services</b>			
Repair and installation of machinery and equipment	512	43	1
Electricity, gas, steam and air conditioning supply	2,395	132	4

<b>Sector</b>	<b>Green</b>	<b>Twin</b>	<b>Sectoral share of twin patents in the total (%)</b>
Water supply; sewerage, waste management and remediation activities	39	1	0
Construction	24	-	-
Wholesale and retail trade and repair of motor vehicles and motorcycles	1,939	108	3
Transportation and storage	173	14	0
Accommodation and food service activities	18	2	0
Information and communication	4,365	612	18
Financial and insurance activities	1,854	80	2
Real estate activities	382	10	0
Professional, scientific and technical activities	12,377	478	14
Administrative and support service activities	1,929	74	2
Public administration and defence; compulsory social security	45	13	0
Education	934	24	1
Human health and social work activities	95	2	0
Arts, entertainment and recreation	11	-	-
Other services	819	41	1

*Note: Sector refers to the main economic activity of the patent applicant. Figures are based on fractional counting. As an applicant's sector may vary across years, we assign each firm a permanent 2-digit sector based on the most frequent occurrence.*

*Source: Authors' calculation.*

**Table 10.** Drivers of twin inventions: first-stage estimation based on second-stage estimation sample

<b>Dep variable: probability of a green invention to cite a digital invention</b>										
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes					Yes				
Industry FE		Yes				Yes	Yes	Yes	Yes	Yes
Region FE			Yes				Yes		Yes	
Tech group FE				Yes					Yes	Yes
Applicant FE					Yes			Yes		Yes
R-squared adjusted	0.027	0.062	0.191	0.034	0.345	0.072	0.205	0.343	0.218	0.349
N	42,099	42,099	42,099	42,099	42,099	42,099	42,099	42,099	42,099	42,099

*Note: Coefficients are estimated using a linear probability model (LPM) via ordinary least squares (OLS). FE denotes fixed effects. Industry fixed effects are defined at the NACE 2-digit level, and regional fixed effects at the NUTS-3 level.*

*Technological group fixed effects follow the 35-technology classification by Schmoch (2008).*

*Source: Authors' calculation.*

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