Regions facing the "twin transition": combining regional green and digital innovations

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Abstract

Merging the green transition with the digital transformation of economic systems in the "twin transition" has become a primary focus for policymakers. In spite of this increased attention, limited is the literature on how the determinants and impacts of combining green and digital innovations vary across regions. This Special Issue aims to fill this gap. It comprises eight papers that address a broad spectrum of topics, including: the regional endowment of scientific knowledge and technologies for the twin transition, its application in specific key domains (like the circular economy and electric mobility), policy measures and institutional settings.

1. Background and aim of the Special Issue

The "twin transition," which is expected to combine the green transition with the digital transformation of economic systems, is now a key focus for policymakers worldwide (Terzi et al., 2023). Discussions at policy forums increasingly focus on what was described as "the Sweet Spot" in a preparation document for the UN COP27: the spot where "Digital amplifies Sustainability" through the "greening OF and BY" digital technologies (Blüm, 2022). This is particularly evident in Europe, where the concept has evolved over time: initially a "soft" green-digital combination aimed at addressing simultaneously sustainability and competitiveness challenges in the New EU Industrial Strategy (EC, 2020), it has now become a "strong" combination designed to make the two transitions mutually supportive in the NextGenerationEU package after Covid-19.

This burgeoning policy debate has recently sparked the emergence of a new wave of studies, which appears to address another instance of "policy running ahead of theory"

(Foray et al., 2011), and “ahead of evidence” as well (Kovacic et al., 2024). On the theoretical side, early studies on the environmental role of the previous generation of Information Technologies (IT) have already provided important insights into the mechanisms through which IT can be made greener — for example, by using alternative raw materials and more energy-efficient IT operating plants — and used more for green purposes, such as employing IT to manage pollution and waste (see Faucheux and Nicolaï, 2011). However, the new suite of digital technologies encompassed under the umbrella of “Industry 4.0” (Cefis et al., 2023; Martinelli et al., 2022)—including AI, Big Data, IoT, additive manufacturing, and robotics—possess distinct and varied features. These are associated to the nature of General Purpose Technology (GPT) they heterogeneously reveal, and to their enabling role including the capacity for "Inventions of the Methods of Inventing." These characteristics necessitate a new conceptual analysis of their environmental sustainability implications. On the empirical side, the evidence regarding the extent to which these new digital technologies can be - and actually are - developed, produced, and adopted by firms to improve their environmental impact and to introduce new green technologies and business practices remains limited, fragmented, and inconclusive. This evidence is in fact mixed and includes both supportive cases (e.g., Montresor and Vezzani, 2023) and less supportive ones (e.g., Veugelers et al., 2023).

To fill these conceptual and empirical gaps, scientific journals have recently called for special issues on the topic of the twin transition, aimed at “demystify” the concept and provide implications for practice and policy. This is for example the case of the special issues recently assembled by *Industry and Innovation* (Diodato et al., 2023) and *Technology and Society* (Gerli et al., 2023). Thanks to these collections, as well as other recent research published in various journals across different fields (e.g., Benedetti et al., 2023; Chen et al., 2023; Collini & Hausemer, 2023), our understanding of the twin transition has significantly expanded. This is especially true regarding the corporate innovation strategies, investments and organizational changes through which firms can implement and contribute to the twin transition, the role of policy in assisting their implementation, and the socio-economic implications of these efforts. While a comprehensive review of these studies is beyond the scope of this Editorial, their findings reveal that the twin transition is not a uniform or monolithic process. Instead, it is characterized by significant variations and complexities. For instance: some digital technologies, such as AI, play a more significant role than others; access to and development of digital technologies for green purposes vary significantly

across firms (e.g., of different sizes) and industries (e.g., differing in technological intensity); the positive environmental impact of these technologies varies across different dimensions (e.g., energy/resource efficiency versus pollution and waste management); their environmental benefits are also influenced by the environmental footprint associated with their production and usage. These insights underscore the heterogeneous nature of the twin transition and highlight the need for nuanced approaches to foster effective and inclusive adoption of digital and green innovations.

Despite these significant advancements in understanding the twin transition, a critical yet underexplored dimension pertains to how its determinants and impacts are distributed across different regions—essentially, the *regional geography of this twin transition*. Indeed, while a few recent studies have adopted a regional perspective on the phenomenon and demonstrated regional disparities in both the capabilities for the twin transition and it environmental impacts (e.g., Santoalha et al., 2021; Cicerone et al., 2023; Bianchini et al., 2023), our understanding of the spatial and territorial dimensions of the twin transition remains incomplete. Important questions remain unanswered, underscoring the need for further investigation.

This is particularly so with respect to the *green and digital innovations* that govern the twin transition on which we focus in this special issue, alongside the diverse policies necessary to foster their development in front of notable innovation market and innovation system failures. Emerging research highlights that the green transition largely depends on the development and adoption of innovative environmental technologies aimed at reducing carbon emissions (Acemoglu et al., 2016; Aghion et al., 2016; IEA, 2020). These green technologies are developed in a highly path-dependent manner, particularly across regions, relying heavily on existing local capabilities to develop "related" technologies (Montresor & Quatraro, 2020; Santoalha & Boschma, 2021; Santoalha et al., 2021). As a result, the geographic distribution of environmental technologies is quite uneven, posing a challenge for policymakers to ensure a "just" and equitable green transition across territories (Rodríguez-Pose & Bartalucci, 2024). Similarly, the emergence of the Industry 4.0 paradigm, associated with the digital transformation, involves the innovative development of new digital technologies of which regions also exhibit varying capacities to develop (Corradini et al., 2021), determining digital gaps across regions that also require policy attention. Combining these aspects, the regional geography of the twin transition can be viewed primarily through the lens of innovation geography, as mainly dependent on regions' ability

to innovate and develop technologies that are both digital and green, and which can also be expected to generate disparities across regions in their development and in their economic impact (Maucorps et al., 2023).

Against this background, the aim of this Special Issue is to present a collection of new papers that enhance our understanding of the opportunities, challenges and implications presented by the combination of green and digital innovations for regions advancing through the twin transition. Consistent with the scope of the contributions and the debates typically featured on Regional Studies, this Special Issue aims to gather and showcase research papers underscoring that: business and institutional actors involved in driving the twin transition are regionally embedded; the competencies and knowledge necessary to facilitate this transition are specific to particular locations; policies at various levels of governance are required to acknowledge these specificities and offer place-sensitive recommendations, rejecting the "one-size-fits-all" approach.

As detailed further in the next section, the papers in this collection aim to advance the regional analysis of the innovation aspect of the twin transition beyond its nascent stages, and to tackle novel research questions that have received limited attention in existing literature. Which is the role of the scientific knowledge base that regions would require to develop new twin technologies? Does the geography of the twin transition technologies mirror that of its underlying green and/or digital ones? How do regions differ in the unfolding of the twin transition in “critical” environmental sectors, like that of electric vehicles and of the circular economy? What is the emission impact of digitalisation at the local level and how does it vary across regions? How do regional and national policies interact among them in supporting the twin transition? How do policies for the twin transition interconnect across national and supernational levels of governance, such as those entailed by the EU?

Still in line with the aims of the journal, the papers of the Special Issue tackle these and other research questions by using a combination of diverse theoretical frameworks, empirical approaches, and heterogeneous methodologies, and by leveraging novel primary and secondary data. These features, along with the variety of domains and aspects along which the twin transition is addressed, represent an important value added of the present collection, which we are confident could be useful to academic scholars and policy makers with an interest in the topic.

2. Synopsis of the Special Issue and its main contents

The Special Issue (SI) comprises eight papers, each addressing various regional aspects of the twin transition. These papers employ diverse perspectives, methodologies, and empirical contexts to explore the multifaceted nature of this transition. While most of these papers (by Cattani et al., 2024, Castellacci & Santoalha, 2024, Damioli et al., 2024, Fazio et al., 2024, Fusillo et al., Zhang & Du, 2024, in this Volume) examine the regional innovation processes that drive and characterise the twin transition and derive policy implications from their analyses, others (Brueck & Losacker, 2024, and Gao, 2024 in this Volume) specifically focus on the policy initiatives implemented to support the twin transition. The former employ quantitative methodologies and various econometric tools on newly assembled secondary data, while the latter adopt a qualitative approach, utilizing textual and conceptual analyses of policy documents.

Consistently with the special attention and recommendations the twin transition has received in Europe (see Section 1), and reflecting the focus emphasized in the call for this Special Issue, nearly all the papers (by Cattani et al., 2024, Damioli et al., 2024, Fazio et al., 2024, Gao, 2024, and Fusillo et al., 2024 in this Volume) conduct their analyses in the context of European regions. However, the Special Issue also includes two papers that examines the twin transition in Chinese regions and cities (Brueck & Losacker, 2024, Zhang & Du, 2024, in this Volume), where significant green-digital policy initiatives, such as China's East–West Computing Resources Transmission Project (EWCRT Project) (Xie et al., 2024), have recently been implemented. Additionally, it includes a paper that also covers regions located in Canada and the US (Castellacci & Santoalha, 2024, in this Volume), highlighting systematic regularities and heterogeneities also going beyond Europe.

Altogether, the papers in this collection represent a coherent body of heterogeneous studies, which nicely complement each other also in addressing the specific research questions that we will outline in the remaining part of this Section. A successful transition that combines environmental sustainability and digitalisation of the economies rests on the availability of frontier scientific knowledge that can feed into technological progress and innovation. The contribution by Damioli et al. (2024, in this Volume) provides insights in this direction for 287 NUTS 2 regions in 30 European countries over the period 2000-2020. The authors first notice that spatial patterns of twin scientific publications are dynamic and

volatile, and differ from those typically characterising patenting activities. The econometric analysis reveals a "success-breeds-success" dynamics in the generation of twin scientific knowledge, with regions characterised by larger scientific bases in the green and digital domains being those with more (and more visible) twin publications, while the quality of twin science seems to depend more on the green scientific orientation of the region. The authors also provide some insights on the combinations of green and digital subdomains. The most prevalent ones relate to Internet of Things and Artificial Intelligence digital domains with energy and environmental management.

Another work focusing on the generation of knowledge that serves the successful transition towards green and digital innovation is that by Fusillo et al. (2024, in this Volume). The authors focus on the knowledge recombinant capabilities which lead to the generation of circular economy (CE) patents in a dataset of European NUTS2 regions over the period 1985-2015. Their work points to how digital technologies - with data collection, integration and analysis applications - can help achieve higher environmental and material use efficiency. Digital technologies are found to smoothen the relevance of relatedness, allowing regions with limited technological capabilities associated to CE to develop CE-related technologies. This element appears to be of high policy relevance, suggesting a strategy for making CE-ready regions that have limited competencies in the field.

The contribution by Fazio et al. (2024, in this Volume) is concerned with the technological pillars of the twin transition too. It pays particular attention to the combination of ICT and green technologies and the role of spatial spillovers in 259 regions from 28 EU countries between 1977 and 2018. ICT-oriented regions are more successful in the twin transition than green-oriented ones, suggesting the prevalence of ICT-for-green modes of entry into the twin transition. Despite the volatility of regional positioning in the advancements towards the twin transition, low innovative-oriented regions display a certain persistence: an issue to be particularly considered by policy aimed at supporting lagging behind territories. Geographical proximity matters for the twin transition, suggesting the importance of spatial association and clustering of twin innovators.

The paper by Cattani et al. (2024, in this Volume) considers the adoption of green and digital innovations, and particularly the extent to which location in urban vis-à-vis rural context matters for that. Focusing on the adoption of innovation, the authors provide complementary evidence to other works of this SI (Damioli et al., 2024, and Fusillo et al., 2024, in this Volume), which focus on the knowledge-generation pillars of the twin-

transition. More precisely, Cattani et al. shed light on the different agglomeration and location forces that may favour the adoption of green innovations and innovations associated to Industry 4.0 by referring to 14,000 firms across 36 European countries over the period 2016–19. Results point to the higher propensity of rural firms to introduce eco-innovation; their location appears to make them closer to natural resource management and endowment. Urban agglomeration forces instead seem to favour the adoption of Industry 4.0 technologies and use of these as tools for innovating in the green domain. This latter is an element which connects with the role of digital technologies to achieve environmental sustainability, which is discussed by Fazio et al. (2024, in this Volume) in relation to knowledge generation.

Castellacci & Santoalha (2024, in this Volume) dig into another element associated with the adoption of innovation, with great impact on the possibility to achieve a transition towards sustainability. The paper focuses on how digitalisation affects electric mobility. Relevant digital technologies may pertain to the supply side, which foster the production of electric vehicles, the demand side, which relate to proficiency, user experience and connectivity, as well as to communication and diffusion of information. The study makes use of Google trends data for 182 regions in 15 different countries (12 European plus US and Canada) over the period 2010 to 2023. From the results, it seems that digitalisation, especially associated to smart manufacturing and appliances, can drive the uptake of electric mobility despite signs of regional heterogeneity. The effect is stronger in regions with higher GDP per capita, better internet infrastructures, and young and highly educate workforce. The analysis carries implications for policy: digitalisation is a key determinant of the adoption of relevant sustainable behaviours and practices in the mobility sector.

The paper by Zhang & Du (2024, in this Volume) provides an account of the carbon emission impact of digitalisation focusing on Chinese cities. The study is based on 278 prefecture-level cities in China for the period 2005-2017. Results show that an increase in digital industrialisation reduces urban carbon emission per capita. A set of mechanisms are explored, which pertain to green total factor productivity, industrial restructuring, and digital governance. The authors also provide evidence on the moderating effect of emission trading scheme (ETS) policies, pointing to their beneficial role at the national level. The paper sheds light on important regional heterogeneities for both the baseline and the moderation effect analyses.

The two remaining papers of the issue shed light on the policy framework that support the unfolding of the twin transition. Gao (2024, in this Volume) focuses on the policy framework of the EU, the context that attracted most of the attention of the contributors of the Special Issue. Given the complexity of the EU scenario, involving many policy areas and organisations, the paper investigates whether the EU has been a coherent policy actor in pursuing the twin transition since the presentation of its New Industrial Strategy in 2019. Two aspects of the coherence concept are considered: the conceptual (related to the framing and policy discourse) and the operational (related to the adoption of policies) one. Two dimensions are taken into consideration: the vertical (between different levels of governance) and the horizontal (between policy areas within the same level of governance) one. Against this background, the article surveys relevant features of the current policy scenario supporting the twin transition within the EU block. Despite the heterogeneity of Member States' attitudes, at the conceptual level the authors find a higher degree of coherence than at the operational level, which is characterised by the fragmentation of the institutional architecture.

The second paper which is concerned with policy is the one by Brueck & Losacker (2024, in this Volume), which allows to gather insights on the policy implemented in China to support the green, digital and twin transitions. This will help the readers to obtain a different view that complements the Special Issue insights obtained mainly on European regions. The authors investigate the multi-level governance of three regional cases – Shanghai, Wuhan, and Hangzhou – by collecting a set of policy documents issued between 2016 and 2022. The paper analyses the alignment between national and regional strategies; the extent to which green and digital transitions are coordinated; the differences across regions. The authors consider three main elements: the aims, the means and the level of abstraction, which focuses on the generality of the interventions. Important differences emerge across the cases analysed, even if the implementation of digital for green solutions (digital applications to obtain environmental benefits) seem to be more important than green for digital (aimed at improving environmental sustainability of digitalisation). The authors also provide a typology of the investigated Chinese regions, depending on the type of implementation: holistic (with the larger alignment between national and regional policies); basic (with relevant adaptations of aims and means associated to lacking capabilities of the regional system); selective (with many aims and means adapted to the local contexts, typically characterised by very specialised systems).

3. Conclusive remarks, policy implications and suggestions for a research agenda

The results of the eight papers of this Special Issue enrich our still scanty knowledge of the twin transition with several nuances about the role of its constituent digital and green technologies, the extent to which they can be and have been actually combined across heterogeneous regional contexts, the nature and effectiveness of the policies that have been implemented for that to happen at different levels of governance.

Six main conclusive remarks can be drawn on the basis of the papers' results. First, there appear to be opportunities for a beneficial environmental effect of digitalisation at the local level, which could pass through its role in efficiency, industrial restructuring and digital governance. Accordingly, digitalisation could actually represent an important leverage for policymakers seeking to improve environmental conditions of their territories. Second, regional scientific foundations and regional scientific capabilities appear crucial in driving the twin transition across regions. Regions with stronger bases in green and digital domains exhibit higher levels of twin scientific publications, reflecting a "success-breeds-success" dynamic where existing strengths contribute to further innovation. Third, confirming the main rationale of the twin transition, the synergies between Information and Communication Technology (ICT) and green technologies play a critical role in its unfolding. ICT-oriented regions demonstrate greater success in integrating green innovations, suggesting that ICT-for-green strategies are effective in driving innovation and fostering regional resilience. Fourth, the kind of regional context that hosts the twin transition matters. In particular, the urban-rural dynamics in innovation adoption appear to matter also when it comes to the combination of green and digital innovations. Rural regions can excel in eco-innovation due to their proximity to natural resources, while urban areas leverage agglomeration effects to adopt Industry 4.0 technologies for green advancements. This dichotomy underscores the need for tailored policy interventions that address local context and promote balanced regional development. Fifth, digital technologies emerge as pivotal enablers of environmental sustainability also and above all in facilitating circular economy practices, suggesting that the circular economy is a domain where the twin transition could have important effects. Indeed, digital technologies enhance material and energy efficiency, allowing regions with otherwise limited technological capabilities to participate in circular economy innovations. This highlights the transformative potential of digital technologies in smoothing the path towards sustainability across diverse regional

contexts. Last, but not least, digitalisation appears to be a key determinant also in sectors that are under the radar of the green transition, like the transportation one. Indeed, digital technologies help promoting sustainable mobility practices, particularly in the adoption of electric vehicles. Regions with robust digital infrastructure and a skilled workforce exhibit higher uptake, highlighting the critical role of digital transformation in advancing sustainable mobility solutions.

As their respective papers have discussed, all these results have important policy implications. At the outset, supporting interdisciplinary research and knowledge exchange platforms can facilitate the generation of twin scientific knowledge, making science policies a crucial ingredient of the twin transition, which has so far received only limited attention. As digital and green technologies do actually appear complementary, policymakers should also foster ICT-for-green strategies, that integrate digital technologies with green innovations. This involves, for example, creating incentives for ICT firms to develop solutions that enhance the sustainability performance of other sectors, such as energy, transport, and agriculture. Also in the domain of the twin transition, the previous and other policies need to be place-specific: not only be adapting to the socio-economic and institutional contexts of the twinning regions, but also to their relative degree of techno-economic development. For example, tailored policies are needed to address the distinct innovation adoption patterns between urban and rural regions also of green and digital innovations. Policy interventions are also recommendable to make digitalisation functional to the improvement of the environmental conditions of territories, as well as for the development of crucial economic sectors, practices and behaviours. Policy frameworks that prioritize local digital transformation initiatives could be also capable of enhancing material and energy efficiency along the route of the circular economy paradigm. And again, by prioritizing investments in digitalisation policy makers could support the widespread adoption of electric mobility solutions and the positive environmental effects this could entail.

As we said, two papers of the Special Issue shed light on the design of policy actions and their institutional setting, highlighting the role of coherence – not only in relation to the conceptualization of actions, but also in relation to their implementation. The integration of different levels associated to the different components of the twin transition implies the need of coordination of actions, but also their possible adaptability to the peculiarities of the regional systems.

Several research avenues may be explored, developing from the insights emerged through the papers featured in the Special Issue. However, here we want to refer to a few, which seem the most significant in terms of academic and policy relevance.

At first, it is noticeable how the Special Issue has *de facto* concentrated the attention on one of the two possible configurations of the green-digital twinning: the extent to which digital solutions can enhance the environmental sustainability of our economies. Still scant, but equally relevant, is the investigation of how digital technologies can (and in some cases, must) be made more environmentally friendly, given the scale of their energy usage, and the policy implications (e.g. Montevecchi et al, 2020). The energy intensity of data centers and the use of "critical" raw materials in developing digital technologies are prime examples of this issue (Valero et al., 2018). In this respect, future studies may seek to shed light on the specificities of this green-for-digital twinning in terms of scientific, technological and innovation pillars.

Second, the Special Issue includes studies deploying a variety of data that can be used to investigate the science, technology and innovation angle of the twin transition. As far as the latter is concerned, data on the actual adoption of both green and digital innovations by firms can be inferred from surveys, as in Cattani et al (2024, in this Volume). Nevertheless, scant are the works that focus on the actual adoption of twin innovation into single products, processes or services. Recent work on the identification of patented digital inventions with an environmental functionality (e.g. Jindra & Leusin,2022) represents an interesting opportunity in this direction. This appear to be a higher class of twinning that may be characterised by different opportunities and challenges for economic agents, and territories alike, which we hope future works may investigate.

Third, the success of the transition towards a successful twinning of environmental sustainability and digitalisation requires changes on both the supply and demand side. While the works featured in this Special Issue have largely explored the former, the contribution by Castellacci and Santoalha (2024, in this Volume) provides some insights on the role of consumers' adoption of electric mobility. Yet, much more light should be shed on how demand influences the twin transition: among the others, local green preferences (as expressed by regional green voting and environmental concerns) (Hoffmann et al., 2022) may be relevant in spurring new entrepreneurial activities (e.g. VC) in the green realm, as well as policy determined procurement schemes (e.g. Ghisetti, 2017), and the role of environmentally aware consumers (Wagner, 2007; Demirel and Kesidou, 2012).

Moving to the directions that will elicit some policy relevant insights, the array of studies included in the Special Issue, has provided ample evidence on the drivers of the twin-transition innovation, but it is equally important to consider the obstacles, barriers and coping strategies characterising such transition. Studies can draw from contributions focused on innovation (D'Este et al. 2012), or eco-innovation, in particular (Marin et al., 2015); these can serve as benchmark to highlight how innovation related to the twin transition may be characterised by specific obstacles that policy should address with dedicated tools.

Finally, as we outlined in the Introduction, the twin transition is a central element of the EU policy actions. The Special Issue features two studies dealing with policy scenarios, integration and coordination (Gao, 2024, Brueck & Losacker, 2024, in this Volume). Yet, scant is the literature that has looked into the actual impact of policy aimed at stimulating the twin transition. We hope that future works can emerge to fill in this gap, based on causal inference tools.

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