

A twin transition or a flagship policy? Emergent constellations and dominant blocks in green and digital technologies

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ABSTRACT

This paper seeks to understand whether what has been labeled the “twin transition”, a flagship EU policy, emerges as a new endogenous technological trajectory involving the convergence of green and digital technologies, or whether this policy is in fact having little impact. Embracing an evolutionary approach to technology, we first identify the set of relevant technologies defined as “green” and then analyze their evolution in terms of the dominant blocks within the green technology sector and their intertwining with digital technologies, drawing on 560,720 patents granted by the US Patent Office from 1976 to 2024. Three dominant blocks emerge as relevant in defining the direction of innovation, namely energy, transport, and production processes. We assess the technological concentration and underlying complexity of the dominant blocks, interpreting this through the construction of counterfactual scenarios. We find hardly any evidence for a pattern of actual endogenous convergence of green and digital technologies in the period under analysis. On the whole, for the time being, the “twin transition” appears to be a flagship policy in name only, rather than an endogenous technological trajectory driving structural change.

1. Introduction

Climate change and climate-related crises number among the most pressing emergencies that human societies are facing. Since the First IPCC Assessment in 1992, it has been acknowledged that human activities are the primary source of the increase in global greenhouse gas (GHG) emissions, which is driving the rise in the average global temperature (IPCC, 1992, 2023). While the primary source of carbon emissions is industrial society, organized on an anthropocentric and capitalist basis, technology has widely been considered as a means to mitigate and even potentially counteract the climate crisis, an approach that is referred to variously as a technological fix or green capitalism (Fox, 2023). In particular, it has been proposed that technology that serves to mitigate climate change might be more effective at reaching that goal if it is coupled with the digital infrastructure. The aspiration for

a coupling between digital and green technologies falls under the heading of the “twin transition”, where “twin” technologies are identified as technological artifacts embedding digital traits and, at the same time, aimed at reducing emissions. Thus defined, the “twin technology” can take the form either of digital technologies employed to support the decarbonization of the economy (e.g., devices monitoring emissions), or of green technologies characterized by digital traits with the aim of increasing emissions reductions (e.g., emission-capturing technologies (Muench et al., 2022)).

The aim of this paper is to understand whether the “twin transition”, promoted as a flagship EU policy, emerges as a new endogenous technological trajectory stemming from the convergence of green and digital technologies, or whether the policy is in fact having negligible effects. Embracing an evolutionary approach to technology (Freeman, 2019) and applying it to the realm in which evidence for the coupled transition

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can potentially be found, we first identify the set of relevant technologies defined as “green”, and then analyze their evolution in terms of constellations of technologies (Freeman and Louçã, 2001)¹ and dominant blocks (Dahmén, 1988).² Our database for studying green technology in its co-occurrences with digital technology draws on 560,720 patents granted by the US Patent Office from 1976 to 2024. Three dominant blocks emerge as relevant in defining the direction of innovative efforts, namely energy, transport, and production processes. We assess the technological concentration and underlying complexity of the dominant blocks, interpreting this through the construction of counterfactual scenarios. We find hardly any evidence of patterns of actual endogenous convergence of green and digital technologies in the period under analysis. On the whole, at least for the time being, the “twin transition” appears to be a flagship policy in name only, rather than an actual endogenous technological trajectory driving structural change.

Our paper contributes to the literature investigating the nature, direction, and expected impacts of the digital and green transitions. The majority of contributions so far have focused on firm performance, capabilities, innovation strategies, and comparative advantage (Cattani et al., 2023; Chatzistamoulou, 2023; Cicerone et al., 2023; George et al., 2021; Montresor and Vezzani, 2023; Rehman et al., 2023; Veugelers et al., 2023). Other contributions have looked at the twin transition as a channel promoting structural change (Fouquet and Hippe, 2022; Mäkitie et al., 2023) or sustainability (Ortega-Gras et al., 2021), or in terms of whether twin technologies are sustainable (Bianchini et al., 2023).

To the best of our knowledge, the extant literature has not devoted attention specifically to the technological nature of the coupled transition. A notable exception is Vermeulen & Pyka (2024), who propose a conceptual framework combining theoretical elements and empirical tools drawn from the economics of innovation to analyze the twin transition. Their analysis, however, privileges expected projections, rather than studying the current and historical trends in the technological trajectory.

Understanding and assessing the extent to which the trajectories of technological development of these two innovation paths are coupled have important implications in many domains. First, it is becoming progressively more urgent to clearly assess the real potential for such solutions, often considered to be an easy technological “fix” for the climate catastrophe: in other words, there is a need to assess the extent to which we can expect the emergence and diffusion of digitally augmented and interconnected devices to mitigate or even abate carbon emissions. Second, investigating the actual directions of innovation efforts via patent information allows us to define the borders of the search space, and identify in which specific industry application innovation efforts in climate-change mitigation technologies are being concentrated. Given the large heterogeneity in carbon emissions across industries (Dosi et al., 2025b), it is important to understand where the best innovators are located. Third, given the results of our study – which differs from ex-ante expectations by indicating that the two trajectories

are detached or coupled at most only in niche technological domains – the potential disruptive nature of the twin transition as fostered by the policy expectations may not align with the expectations of the innovators, at least from the perspective of the patenting firms. The latter in fact appear to be undertaking a path of very selective innovation, mostly in three domains of application, namely transport, energy, and production processes. We find hardly any evidence for a more pervasive trajectory of change. In this respect our findings align with Vermeulen and Pyka (2024) according to whom the path undertaken by innovators is one of an incremental green-tech fix, rather than the desired paradigm shift toward “intelligent and smart decarbonization”. Finally, accounting for the trajectories of innovation domains has important implications for the macroeconomy and processes of structural change therein (Dosi, 2023), in particular concerning whether we should expect any significant transformation from the new technological paradigm, such as a reshuffling of income and value-added across sectors, something which is usual when structural change occurs.

To sum up, the novel contributions of the paper are as follows. First, differing from all the contributions in the extant literature, it investigates the actual technological character of the twin transition, seeking to identify whether the twin transition is really occurring and whether its alleged pervasiveness is actually leading to a structural change in the economy, as is often assumed. Secondly, we ground our empirical analysis on the solid theoretical basis of the evolutionary approach to technological analysis, mobilizing the concepts of constellations of technologies (Freeman and Louçã, 2001), development blocks (Dahmén, 1988) and technological trajectories (Dosi, 1982), and we define a new theoretical construct, the development sub-block, to respond to the need for a more granular analysis with respect to development blocks (see Section 3). Thirdly, by making use of an extensive collection of patent data, exploiting a long-time window and employing the official technological classification systems, we conduct one of the few existing empirical investigations that is able to assess the dynamics and evolution of a complex technological domain supposed to be the leading solution to the environmental crisis. We thus make a connection between the technological and political economy spheres that underpin the energy transition, and we single out how the innovation interests of patenting actors are in fact decoupled from the alleged policy interests. In the end, our results reveal the actual nature of the alleged twin transition as a flagship policy in name only, rather than an ongoing technological process that can be seen as a solution to environmental challenges, as is assumed within the current European policy framework.

The paper is structured as follows: Section 2 provides a literature review; Section 3 outlines the theoretical framework; Section 4 describes the data and the methodology; Section 5 presents and discusses the empirical results; Section 6 concludes.

2. Literature review

2.1. Context and motivation

Twin technologies have in recent years been identified as key to achieving a carbon-neutral economy. Through the dematerialization of the economy and the development of energy-saving devices (e.g., smart grids), the ICT paradigm has lowered the use of energy with respect to previous technological revolutions (Kander et al., 2014). Since the eighties, policy makers and technologists have envisaged the potential for coupling energy-saving and ICT technologies as a means of achieving structural change. Even in the early stages of the ICT revolution, ICT innovations were identified as potentially able to reduce the energy and material intensity of production in other sectors, thus “greening” industrial processes (Faucheux and Nicolai, 2011; Perez, 1983). For instance, Berkhout and Hertin (2004) claim that resource and waste savings are evident in historical patterns since the introduction of the first computers; and Perez (1983) describes the ICT paradigm as a

¹ Freeman and Louçã (2001) refer to constellations of technologies as bundles of innovations emerging by the advancements in science and technology, complementary to changes in organizational, institutional, and economic structures. New industrial dynamics surge from novel constellations of technologies, dominating for a few decades until a new combination emerges. Details are provided in Section 3. The specific definition of constellations of technologies adopted in this paper is reported in Table 1.

² Dahmén (1988) states the concept of development block that “refers to a sequence of complementarities which by a way of structural tensions, i.e. disequilibria, may result in a balanced situation” (Dahmén, 1988 pag. 5). Complementarities in technological, technical, economic, and other related factors are essential elements of a development process to achieve an economic success. When complementary stages are missing, expansive forces may urge from depressive pressures, constituting structural tensions. Details are provided in Section 3. The specific definition adopted in this paper is reported in Table 1.

technology which affords unprecedented material savings, well able to meet the ecological movements' demands.

More recently, [Perez \(2016\)](#) has argued that ICTs represent a technological revolution that can enable a techno-economic paradigm to shift toward a new sustainable economy. The author claims that the ICT paradigm shift is only halfway through, since past technological revolutions have lasted more than 50 years. At the same time, for ICT to be the driver of such structural change, complementary factors are required, in particular institutional changes directed towards long-term State-guided policies.

By the development of green ICTs that can reduce their own energy use, ICT product innovations have become able to lower the emissions of the wider ICT sector as well ([Freitag et al., 2021](#)). However, economic growth and the widespread use of ICTs have also increased energy consumption worldwide ([Kander et al., 2014](#)). Which effect is prevalent is thus far unclear – cloud computing ([Yu et al., 2023](#)) and cryptocurrencies ([Tayebi and Amini, 2024](#)), for example, are contributing enormously to carbon emissions. Studies on the quantitative impact of ICT on CO₂ emissions find that digital technologies increase the domestic level of emissions through the different mechanisms at work; however, technological spillovers onto downstream sectors from resources' efficiency upstream, and the diffusion of efficient ICT services, display a mitigating effect across industries and countries (see, among others, [Sun et al., 2023](#); [Wang et al., 2021](#); [Zhou et al., 2019](#)). [Lange et al. \(2020\)](#) argue that the two effects are mutually interdependent, with ICTs turning out to be unable to decouple economic growth and energy consumption (see also [Berkhout and Hertin, 2004](#)). [Röpke \(2012\)](#) highlights that the potential of ICTs for sustainable transformation depends on co-evolution of a cluster of technologies involving other industries. In sum, according to this literature, ICTs per se cannot be seen as intrinsically energy-saving and green.

By contrast, in another strand of the literature the alleged convergence between digital and green technologies is thought to be a powerful means to pursue sustainability and mitigate climate change. [Cecere et al. \(2014\)](#) argue that the interaction between ICTs and environmental innovation (EI) is grounded in the character of ICTs as general purpose technologies ([Bresnahan and Trajtenberg, 1995](#); [Carlsson, 2004](#); [Rosenberg and Trajtenberg, 2004](#)). The green ICT domain is characterized by technological pervasiveness, being widespread across technological clusters defined by different combinations of green and ICT applications ([Cecere et al., 2014](#)). For example, [Zhou et al. \(2019\)](#) analyze the impact of ICTs on the development of renewable energy technologies in USA, Canada, Germany, UK, Italy, The Netherlands, and Poland, all countries that experienced a strong policy push coupled with public investment towards renewable energy, wireless connectivity, and smart grids between the 1990s and 2010s. The authors find that ICTs have a positive impact on the development of renewable energy technologies both in the short and the long run. Previous studies have been more concerned to assess the firms themselves: for instance, [Antonioli et al. \(2018\)](#) look at ICT and EI impact on productivity; [Corrocher and Ozman \(2020\)](#) analyze the green innovation activity of ICT companies and how it affects their performance, while [Cecere et al. \(2019\)](#) estimate the probability that ICT companies would switch to green ICTs development; [Santoalha et al. \(2021\)](#) find that at the local and regional level digital capabilities improve green specialization more than non-green specialization. More recent studies focus specifically on Machine Learning and Artificial Intelligence (AI) and their ability to reduce emissions in combination with green technologies ([Biggi et al., 2025](#); [Coeckelbergh, 2021](#); [Kaack et al., 2022](#); [Lacoste et al., 2019](#); [Rolnick et al., 2022](#); [Strubell et al., 2020](#)), or on Industry 4.0/Industrial Internet of Things ([Bauer et al., 2021](#); [Beier et al., 2017](#); [Beltrami et al., 2021](#); [Felsberger et al., 2022](#); [Ghobakhloo, 2020](#); [Machado et al., 2020](#)). This stream of literature on EI and ICTs can be considered an early assessment of the so-called twin transition. Only a few studies have investigated the technological dimension of the twin transition; however, the majority examines the potential for digital capabilities and technological

knowledge to enable green innovation and sustainability gains.

2.2. The extant literature on the twin transition

According to the European Union, “*The term ‘twin transitions’ refers not only to two concurrent transformation trends (the green and digital transitions); the term also refers to uniting the two transitions, which could accelerate necessary changes and bring societies closer to the level of transformation needed.*” ([Muench et al. \(2022\)](#), p.7). In this subsection we focus on studies specifically tackling the twin transition.

[Ortega-Gras et al. \(2021\)](#) address the technological dimension of the twin transition by narrowing the focus to a specific definition of twin technologies, the Key Enabling Technologies (KETs) – the main ICTs for Industry 4.0 – and to a specific aspect of the green transition, the Circular Economy. The aim of the analysis is to understand to what extent the EU Policy Framework is fostering the development of KETs as drivers for a Circular Economy transition and in which sectors. The authors draw on several data sources and employ several identification strategies: they define specific keywords by the combination of terms related to KETs, Industry 4.0, Twin Transition, and Circular Economy, seeking to identify the main contributions of the state of the art by the use of databases of scientific papers; they implement text analysis of patent and research projects to select the KETs and the main sectors in which they are used for a Circular Economy; and they rely on several official European information sources to identify the main EU policies on the twin transition and the Circular Economy framework. Patents have also been selected by the use of the International Patent Classification (IPC), focusing on specific IPCs related to Industry 4.0 ICTs.

[Damioli et al. \(2024\)](#) investigate the role of digital and green-science-based research in determining the “twin knowledge” captured by scientific publications. The authors identify green and digital paper contributions by keyword search and flag as twins, including both fields. By addressing scientific quantity, quality, and dissemination according to number of publications, citations, and online visibility, twin knowledge is localized according to authors' affiliations. The paper thus explores to what extent spatial patterns may facilitate the emergence and recombination of green and digital knowledge, and which are the main green and digital subdomains that recombine to determine this twin knowledge. Although they find an increasing diffusion of twin knowledge, no specific spatial pattern emerges. As expected, more, better quality, and wider dissemination of twin knowledge is found in the areas with the strongest green and digital science bases. [Mäkitie et al. \(2023\)](#) provide a description of the possible characterizations of twin technologies and how they may lead to structural changes with respect to their nature as radical or incremental innovations. The analysis is conducted on the literature of climate transition and innovation studies to identify the interconnection between digital innovations and the sustainability transition. However, the authors do not provide an identification of the technological content of twin artifacts. [Fouquet and Hippe \(2022\)](#) adopt an historical perspective with respect to structural change in energy generation, supply and demand, in relation to the diffusion of the ICT paradigm, concluding that they are in fact linked by their energy-saving potentialities. This study draws on historical data since 1850 on energy consumption by energy source and communication intensity (number of letters, telegrams, text messages, emails, time on the telephone, mobile and mobile ‘app’ conversations). [Bianchini et al. \(2023\)](#) aim to analyze the sustainability of the twin transition. They measure the impact of the local development of environmental and digital technologies, proxied by the number of patent applications, on GHG emissions in metropolitan regions. The twin dimension is identified as the interaction between green and digital technologies in the same area: they investigate whether their joint presence has a negative effect on emissions, and whether digital (environmental) technologies help environmental (digital) ones in abating emissions. Green patent applications are selected by the OECD ENV-TECH classification, which draws on the International Patent and

Cooperative Patent Classifications, while keywords are used to select digital patent applications. The localization of technological development is proxied according to the addresses of applicants and inventors of patents by the OECD REGPAT Database and matched with emissions data at the plant level from the European Pollutant Release and Transfer Register (E-PRTR). The authors find that emissions of highly polluting plants decrease in areas with a high local development of environmental technologies; on the contrary, however, the development of digital technologies increases emissions, but when considering the interaction between the two, emissions decrease in the area: this effect, however, is lower than the increase caused by digital technologies. Again, at the regional level, [Fazio et al. \(2025\)](#) explore the regions' transition towards twin paths, assessing digital and green spatial proximity and socio-economic similarity relevant to becoming a "twin innovator region". Using the OECD REGPAT, they localize the green, ICT, and twin "innovative orientation" according to the number of applications of patents in each category in European regions at the NUTS2 level. Twin orientation is identified as mutual development of green and ICT technologies in the same region. The authors find that the probability of becoming a "twin innovation-oriented region" is higher for ICT specialized areas than for green ones – that is, ICT innovators are more likely to develop environmental technologies than green innovators are to develop ICT ones. However, none of the reviewed studies delves into the technological analysis of the twin transition; that is, none looks at its nature, dynamic evolution, or patterns of complementarity with existing knowledge structures, relative to the policy-level definition provided by [Muench et al. \(2022\)](#).

The twin transition has also been investigated at the firm level: for instance, drawing on the Permanent Census of Firms of the Italian National Statistical Office, which asks firms about investments and adoption in green and digital innovations, [Montresor and Vezzani \(2023\)](#) find that digital and in particular AI investments help to deal with the complexity of green innovation; similar evidence is found also by [Cicerone et al. \(2023\)](#) but only for firms already specialized in green innovation. Specifically, [Cicerone et al. \(2023\)](#) analyze the role of AI technological knowledge, proxied by the share of patent applications from the OECD REGPAT database that can be related to the AI domain, in driving green technological specialization, measured as the share of green patents, exploiting the OECD-ENV TECH classification over the total of patents in different European regions. [Cattani et al. \(2023\)](#) investigate to what extent I4.0 technology adoption influences the probability of eco-innovation for firms in urban vis-à-vis rural areas. The authors use the EU's Flash Eurobarometer, a survey which provides information about the adoption of Environmental Innovations and of Industry 4.0 technologies. Although they acknowledge that the definition of Environmental Innovations provided by the survey is quite general, they claim that the latter is apt to comprehend technological advancements in rural areas, which patent data would otherwise exclude. The main results are that, across countries, environmental innovations are mostly developed in rural areas, regardless of the digital capabilities; digital technologies, if developed, do enable eco-innovations but the relationship is stronger in urban areas. [Rehman et al. \(2023\)](#) analyze the effect of investments in Internet of Things, Environmental Management and green Human Resource Management (HRM) techniques, and general product and process technological innovations, on firms' green competitive advantage, discussing the role of the selected innovations as enablers in the achievement of the twin transition. Data is retrieved by a questionnaire administered to managers and from the Lahore Chamber of Commerce & Industry. They find that Internet of Things is an enabler of the twin transition, since it improves companies' green-based comparative advantages; and green HRM positively affects the development of green innovations and helps companies to achieve sustainability goals thanks to both employers' and workers' engagement. Similarly, Environmental Management strategies foster firms' green competitive advantage. The authors claim that all these factors sustain the unfolding of the twin transition. [Veugelers et al.](#)

[\(2023\)](#) compare investments in green and digital technologies of European and US companies after the Covid-19 crisis. They use the EIBIS survey data collecting information about the adoption of digital technologies, and investments in the reduction of emissions and in the management of extreme weather events. Firms that are more digital are willing to invest more in green technologies, especially in energy efficiency. The co-existence of green and digital technologies defines firms as "green and digital twinning". Similarly, several studies start from the policy push by the European Union on the twin transition strategy and examine to what extent digitalization is an enabler and/or a complement of the green transition and the achievement of energy efficiency. The majority of such studies are based on survey data. [Chatzistamoulou \(2023\)](#) uses the EU Flash Eurobarometer, a survey on the adoption of Environmental Innovations and digital technologies. In [Vasconcelos-Garcia and Carrilho-Nunes \(2024\)](#) digital innovation is measured by a Digital Index, obtained by data from the Eurostat EU survey on ICT usage and eCommerce in Enterprises on Internet access, broadband and connectivity, and promotion of e-commerce for individuals, these being subindexes of the European Commission's Digital Economy and Society Index. Foreign Direct Investment data from the World Bank are also used to analyze the impacts of digitalization and internationalization on green innovation, proxied by different indexes retrieved from the Eco-innovation scoreboard. Similarly, [Benedetti et al. \(2023\)](#) monitor the "European Twin Transition" in different European Member States using the Digital Economy and Society Index and related sub-indexes for specific digitalization areas, to explore the impacts on energy efficiency, measured by the Eurostat Energy Productivity Indicator. Overall, all the contributions mentioned find that digital innovation enables the development of environmental technologies and interpret this evidence as a support for a twin transition.

According to our reading, the extant literature either "assumes" the twin transition as given or focuses on the parallel evolution of digital and green innovations at some observational level (such as regions or firms). What is lacking, however, is: first, an investigation of the alleged co-occurrence of the two types of innovations (digital and green) in the conception of technology in itself; second, an analysis of the industry applications that are targeted by such technologies, in order to understand the inherent potential in terms of emission abating; and third, without going into detailed technological analysis and by only referring to green and digital indexes in general, one might conflate policy and technological attributes and fail to make a clear distinction of what impact is measured.

2.3. The use of patent data: strengths and limitations

From our literature review it emerges that the data sources for assessing the nature and scope of the twin transition are multiple, ranging from scientific contributions to dedicated surveys, from patents to investment data. In this paper we rely on a structural analysis on patent data. While this allows us to perform a fine-grained technological characterization, some limitations of patent data are worth recalling. First, not all innovations are patented ([Hall et al., 2001](#); [Pavitt, 1985](#)). Second, patent propensity is industry- and technology-specific: whether defined as product/process or radical/incremental innovations, and given the sector of development and the industry market structure, technologies may be patented or alternatively protected by different Intellectual Property Rights (IPRs) or secrecy regimes ([Arundel and Kabla, 1998](#); [Hall, 2009](#); [Orsenigo and Sterzi, 2010](#); [Pavitt, 1982](#); [Scherer, 1965](#)). Third, larger firms patent more than SMEs ([Audretsch, 1995](#)).

The main strength of patent data, meanwhile, lies in the possibility of analyzing the inner technological nature of innovation, and of studying its dynamics in detail and overtime ([Griliches, 1998](#); [Pavitt, 1985](#)). Indeed, the official classification systems of patents – the International Patent Classification (IPC) and the Cooperative Patent Classification (CPC) – categorize innovative artifacts according to their characteristics,

allowing us to identify both the main technology at work and all relevant combinations between different technologies (such as the “twin” one). Therefore, with respect to the extant literature using other data sources than patents, we believe the empirical strategy adopted in this analysis (see Section 4) is adequate to fill the gap concerning the proper identification of the twin transition’s technological nature.

Moreover, with respect to the extant literature, by using patent data we claim our identification strategy to be more complete and more capable of spotting the “twin technology” dimension. In fact, in Bianchini et al. (2023); Cicerone et al. (2023); Fazio et al. (2025), the green and digital technological dimensions are kept distinct, while twin artifacts are not identified: as such, the concept of a twin transition is conceptualized as the parallel unfolding of the two transformations. In addition, Cicerone et al. (2023) restrict the focus to the role of AI in driving green technological specialization, without encompassing the broader ICT paradigm, and without looking at the historical evolution. Similarly, in Ortega-Gras et al. (2021) the focus is circumscribed to KETs and the Circular Economy framework, rather than addressing the digital and green transformations of the twin transition overall; as a consequence, the keyword search and the IPC selection dramatically restrict the identification of patents.

In contrast, our analysis comprises a wider selection of technologies by exploiting the Cooperative Patent Classification, which distinctively identifies green and digital technologies as well as green technologies with digital traits – that is, ICTs aimed to mitigate and adapt to climate change and ICTs having an impact on different applications for energy reduction. As such, in essence our analysis allows us to single out the dominant blocks and constellations largely related to the transition of the energy, mobility, and production sectors, as we shall see.³ As will become clearer in Section 4, our methodology allows us to investigate the presence of digital traits in green technologies, and to identify a proper technological convergence/divergence rather than simply a parallel evolution.

3. Theoretical framework

According to Dosi (1982), technological paradigms – *sets of procedures that define both the problems and the specific knowledge that must be applied in order for them to be solved* (p. 148) – arise from the mutual exchange between scientific development, institutional and economic factors, and exogenous and discontinuous changes in the system, leading to radical innovations and structural changes. Each paradigm defines clusters of “technological trajectories”, different directions that technological advances may take within the technological paradigm itself. Technical transformations along established trajectories are endogenous changes to the economic system and usually lead to path-dependent incremental innovations (Dosi, 1982, 2023).

Recalling the EU definition introduced above, the “twin transition” refers to the digital and the green transitions considered as concurrent transformations, and the uniting of the two either in digital artifacts that help in the reduction of emissions or in green artifacts with digital technical traits. If the twin transition is a new general trajectory, we would expect the distinct blocks of green and digital technologies to be converging both in time and intensity into a unified technological path. In particular, we define as convergence the increasing coupling of the

³ The Cooperative Patent Classification revises the IPC and adds the category Y defined in fact as “General Tagging of New Technological Developments; General Tagging of Cross-Sectional Technologies Spanning Several Sections of the IPC.” Two subcategories identify exactly twin technologies: Y02D -ICTs aimed to reduce their own energy use and Y04S -Systems integrating technologies related to power network operation, communication, or information technologies for improving the electrical power generation, transmission, distribution, management, or usage, i.e., smart grids. We will use these two categories to analyze the technological characterization of the twin transition. See Section 4.1 for more details.

green technological domains with the digital ones. If this is occurring, the twin transition could be considered an emerging widespread technological trajectory inside the green/digital paradigms. Alternatively, if we detect the presence of sporadic digital applications to green technologies (mainly with the aim of fostering energy saving), the twin transition could be considered – at best – a technological niche. If the twin transition is unfolding as a dominant technological trajectory, it may lead to paths of structural change towards decarbonization (Dosi, 1984, 2023; Vermeulen and Pyka, 2024) according to the expectations emerging from the unfolding of new trajectories; alternatively, if it takes the form of a technological niche, it may be the outcome of the embedded energy-saving heuristics of the ICT paradigm and it would not embody the key technological transformation envisaged by the policy push.

To implement our investigation, we adopt the notion of constellations of technologies and development blocks. Constellations of technologies are technological clusters of new artifacts characterized by complementarity with the emergence of new industries, new infrastructures, services, and organizational innovations, that are crucial for the establishment of a new trajectory path or the development of a new paradigm (Freeman and Louçã, 2001). Autocatalytic connections and interactions across different clusters of technologies may constitute what Dahmén (1988) defines as development blocks (Nuvolari, 2019; Staccioli and Virgillito, 2021). Development blocks are the sum of the relevant technological, technical, economic, and other related factor complementarities and structural tensions. While constellations define the structures of technologies, the development blocks define the interactions among them, including the old and the new emerging ones. An example of structural tension is the “closing of old sources of raw material and energy” (Dahmén (1988), p. 4). We modify the definition of development block to develop two new operational concepts: the *dominant blocks* and the *development sub-blocks*. Their definition stems from the identification of three stages of technological development, defined with respect to the level of aggregation and to their static or dynamic nature. At the first, most aggregate, level, we look at the core technologies of the green transition and define them as dominant blocks. Each dominant block itself emerges as a development block from previous structural tensions, in response to sectoral restructuring to meet environmental goals. Secondly, we look at the relationship across the dominant blocks. At this stage, the definition of constellations of technologies allows us to capture the co-occurrence of clusters of technologies and to grasp whether the digital dimension is part of the technological bundles constituting the main constellations of climate-change-mitigation technologies. Third, at the micro and dynamic level, we look into the constitution of each dominant block and identify the different technological traits that share common patterns of evolution. Such sequences of evolution can be then identified as development sub-blocks within each dominant block. Table 1 selects the key operational concepts used in the empirical analysis. The third column matches the definition with the empirical identification strategy.

In what follows, we summarize the theoretical pillars on which we build the new methodological constructs, as well as the empirical identification strategy:

- **Development blocks:** combination between the complementary parts constituted by technological, technical, economic, organizational, and institutional factors, and the structural tensions shaping a development process; they define the interaction across a constellation of technologies but also the forces driving eventual structural change.
- **Dominant blocks:** core technologies of a multifaceted technological trajectory, in our case the green transition, emerging as a development block from the structural tensions due to the restructuring of sectors to abate GHG emissions.

Table 1
Synoptic Table identifying the key conceptual categories.

| Terminology | Definition | Empirical Identification |
|--|--|--|
| Dominant blocks | Core technologies of the green transition | Distribution of patents by aggregation of CPCs at four digits within the Y02 macro-categories. They are: (i) reduction of GHG emissions related to energy generation, transmission, or distribution (CPC-Y02E); (ii) mitigation technologies related to transportation (CPC-Y02T) and (iii) mitigation technologies in production or processing of goods (Y02P). |
| Constellations of technologies | Clustering of different technologies establishing a new technological trajectory | Analysis of the co-occurrences (i) at the aggregate level across the Y02 macro-categories – CPCs at 4 digits – and (ii) at the micro and dynamic level across all CPCs associated with patents within each dominant block. |
| Development sub-blocks | Aggregation of the constellations of technologies within the dominant blocks on the basis of common patterns of evolution of their technical traits. | Identification of similar patterns in the dynamics of the co-occurrent CPCs over time within each dominant block. |
| Twin transition as a widespread technological trajectory | Digital and green technologies converge pervasively and in a timely fashion into a unique and new global trajectory. | Pervasive and constant co-occurrence between digital and green macro-categories at the aggregate level and of digital technological patterns within the green dominant blocks at the micro level. |

- Constellations of technologies: clustering of different technologies which contribute to the establishment of the same technological trajectory; they define the structure of technological innovation.
- Development sub-blocks: aggregation of the constellations of technologies within the dominant blocks on the basis of common patterns of evolution of their technical traits.
- Convergence: increasing coupling of dominant blocks into a common technological path. If pervasive, this can translate into a new technological trajectory.
- Technological trajectory: direction undertaken by a new technological paradigm, leading to structural changes in production activities, and organizational and institutional settings. If recognized as a new technological trajectory, the twin transition may be key for a structural process of decarbonization.

4. Data and methodology

4.1. Data

In order to identify the nature of the technologies of interest, we use patent data retrieved by PatentsView. We collected 560,720 patents granted from the United States Patent Office (USPTO) in the period from 1976 to 2024.⁴ We choose the USPTO as it allows a direct link with PatentsView and it embeds full texts. To identify green and digital

attributes, we use the Cooperative Patent Classification (CPC), which aims to assess to which technological field each patent pertains.⁵ We select all patents that are classified by the following CPC classes (three digits) and macro-categories (four digits): (i) class Y02, that groups *technologies or applications for mitigation or adaptation against climate change*; (ii) macro-category Y02D, *climate change mitigation in information and communication technologies, i.e. ICTs aiming at the reduction of their own energy use*; and (iii) the class Y04, *information and communication technologies having an impact on other technology areas* that are concentrated in the macro-category Y04S, *systems integrating technologies related to power network operation, communication or information technologies for improving the electrical power generation, transmission, distribution, management, or usage (e.g. smart grids)*. The identification via the tagging scheme “Y02-Y04S” draws on the study of Angelucci et al. (2018) (among other applications of the scheme, see Caldarola et al., 2024; Favot et al., 2023; Hötte and Jee, 2022; Rughi et al., 2025). The identification via Y02 is straightforward by definition – mitigation and adaptation technologies against climate change – while the macro-category Y04S is included since it is widely interconnected with Y02 technologies. According to the authors, two thirds of the classification codes of Y04S are also present in the Y02 macro-categories. Class Y02 is thus our green category, while the Y02D and Y04S classifications fall into the definition of twin technologies. 557,297 patents are classified as mitigation and adaptation technologies against climate change (Y02), of which 58,748 are classified as ICTs aimed to reduce their own energy use (Y02D), while 16,498 of Y02 patents are also classified as ICTs for improving electrical power generation, transmission, distribution, management, or usage (Y04S). 3,423 patents are only classified as ICTs for improving the electrical power generation, transmission, distribution, management, or usage (Y04S, not contemporaneously Y02). Each patent is associated with different CPCs since the technological content may relate to several areas. To identify the main macro-categories within the green technological domain, we look at the CPC Y02 at four digits. Each one relates to the application of technologies for the reduction of emissions in a specific sector. Table 2 provides a description of all macro-categories of interest. Table A1 in the Appendix presents three patent examples, one for each technological domain we are investigating, i.e., green and the two identifications of twin.

4.2. Methodology

We first map the key mitigation technologies against climate change by adopting a descriptive characterization of the main underlying technological patterns over time, focusing on the behavior of the digital dimension. Secondly, we analyze the nature and the concentration of the identified technological patterns by the construction of different alternatives of a concentration index. Drivers of changes in the nature of technologies are also addressed by the comparison across counterfactual scenarios.

4.2.1. Technological identification

Green and twin technologies are identified as follows. Key technologies of the green domain are identified among patents of seven CPC macro-categories at four digits of the CPC class Y02 (Y02A, Y02B, Y02C, Y02E, Y02P, Y02T, Y02W), twin technologies are identified by the two macro-categories Y02D and Y04S (see Table 2 for the definitions). Overall, nine macro-categories are under study, seven of the green domain, two of the twin categorization.

We compute the number of patents by macro-category by year $P_{j,t}$ and the share for each macro-category of CPC over the total number of

⁴ The first granted date is January 6, 2024, the last is March 3, 2024, the last release available at the moment of the analysis.

⁵ The Cooperative Patent Classification is a harmonized classification between the European Patent Office (EPO) and the USPTO building on the International Patent Classification (IPC). Sources: International Patent Classification; Cooperative Patent Classification.

Table 2
Main CPCs at four digits of the patent selection and description. Source: [Cooperative Patent Classification - Table](#).

| CPC | Definition | Additional specifications | Green & Twin |
|------|---|---|--------------|
| Y02A | Technologies for adaptation to climate change. | Technologies that allow adapting to the adverse effects of climate change in human, industrial (including agriculture and livestock) and economic activities. | GREEN |
| Y02B | Climate change mitigation technologies related to buildings, e.g., housing, house appliances, or related end-user applications. | | GREEN |
| Y02C | Capture, storage, sequestration, or disposal of GHG. | | GREEN |
| Y02D | Climate change mitigation in information and communication technologies, i.e., ICTs aiming at the reduction of their own energy use. This macro-category covers information and communication technologies. | [ICT] whose purpose is to minimize the use of energy during the operation of the involved ICT equipment. | TWIN |
| Y04S | Systems integrating technologies related to power network operation, ICT for improving electrical power generation, transmission, distribution, management, or usage (e.g., smart grids). | | TWIN |
| Y02E | Reduction of GHG emissions related to energy generation, transmission, or distribution. | | GREEN |
| Y02T | Mitigation technologies related to transportation | | GREEN |
| Y02P | Climate change mitigation technologies in the production or processing of Goods. | This macro-category covers climate change mitigation technologies in any kind of industrial processing or production activity, including the agroalimentary industry, agriculture, fishing, ranching, and the like. | GREEN |
| Y02W | Mitigation technologies related to wastewater treatment or waste management. | | GREEN |

patents granted in year $t = 1976, \dots, 2024$ (Eq. 1):

$$\delta_{j,t} = \frac{P_{j,t}}{\sum_{j \in J} P_{j,t}} \quad (1)$$

with $j \in J, J = (Y02A, Y02B, Y02C, Y02D, Y04S, Y02E, Y02P, Y02T, Y02W)$ and $|J| = 9$. The macro-categories with the highest number and share of patents across years are identified as the dominant blocks. We then concentrate the analysis on the dominant blocks identified among the seven green macro-categories and their interconnections with the two digital macro-categories Y02D and Y04S.

The other green macro-categories are analyzed only in relation to the dominant blocks, and we do not focus on their technological characterization per se. In fact, given that they are not key in the green technological domain, they are not relevant in the definition of the twin transition as a possible pervasive technological trajectory either.

To classify the twin trajectory, we identify the main constellations of technologies and look at the possible convergence between technologies of the green dominant blocks and the ICT domain, ICTs aimed to reduce their own energy use (Y02D), and systems integrating technologies related to power network operation, ICTs for improving the electrical

power generation, transmission, distribution, management, or usage (Y04S). Firstly, at the aggregate level, we compute the co-occurrence matrix $C \in \mathbb{N}^{9 \times 9}$ with columns that count the number of patents P_{ij} in which each pair of CPC i, j of the nine macro-categories at four digits co-occurs:

$$C = \sum_{i \in J} \sum_{j \in J} P_{ij} \quad (2)$$

where $P_{ij} = \sum_{k=1}^K C_{ijk} C_{j,i,k}$, $C_{ij} = 1$ if $cpc = i$ co-occurs with $cpc = j$; with k the number of patents in which $C_{ij} = 1$ with $i, j \in J$ and $C_{ij} = C_{j,i}$ (symmetric matrix) and $|J| = 9$.⁶ This allows us to identify the main constellations of technologies and understand whether the digital dimension, captured by the co-occurrence of Y02D and Y04S, enters such a bundle of technologies. Given that more CPCs can be assigned to the same patent, the total number of co-occurrences will be higher than the total number of patents (see Fig. 3a). We then provide a second co-occurrence matrix (see Fig. 3b), $CW \in \mathbb{N}^{9 \times 9}$ where we normalize the co-occurrences by weighing for the inverse of the number of patents P_j for each of the nine macro-categories:

$$CW = \sum_{i \in J} \sum_{j \in J} PW_{ij} \quad (3)$$

with $PW_{ij} = \frac{\sum_{k=1}^K C_{ijk} C_{j,i,k}}{P_j}$ and $|J| = 9$.

Lastly, we provide a co-occurrence matrix for each decade (see Fig. 4). The previous specifications consider patents for the entire period (1976–2024); however, the development of technologies might be uneven across time and macro-categories, especially for twin technologies. We expect green ICTs to be developed more recently in time, thus a low co-occurrence with the green macro-categories could be due to the time factor.

Secondly, we analyze the underlying technological patterns by looking at the co-occurrence of the associated technical fields over time within each dominant block. Associated technical fields are labeled by the CPCs assigned to each patent. The purpose is to detect the possible co-occurrence of the digital dimension captured by the CPCs Y02D and Y04S within the technological dynamics of the green dominant blocks. By so doing, we identify constellations of technologies at the micro level as well, and the aggregation by common behavior in co-occurrence defines different development sub-blocks.⁷

Each dominant block is identified by one macro-category of CPC at four digits B out of the nine macro-categories under study. For each dominant block, we look at all the other CPCs $j = I, \dots, Q$ that have been assigned to the patents of the dominant block in the same year t . We compute the share of the number of times each CPC has been assigned with respect to the co-occurrences of all CPCs within the dominant block. We define the vector $s^B \in \mathbb{N}^{1 \times Q}$:

$$s^B = \sum_{j=1}^Q S_{j,t}^B \quad (4)$$

where $S_{j,t}^B = \frac{CPC_{j,t}^B}{\sum_{j=1}^Q CPC_{j,t}^B}$ with CPC_j^B is the sum of co-occurrences of $cpc = j$ with the dominant block identified by $cpc = B$ over the sum of all co-occurrent CPCs $j = I, \dots, Q$ assigned to the patents within the dominant block B , not only the macro-categories of interest.

⁶ Co-occurrence matrices are mostly used in patent data analysis to investigate citations patterns, here we adapt the same methodology to count the co-occurrence of CPCs across patents instead of citations. See among others [Breschi et al. \(2003\)](#); [Verspagen \(2007\)](#); [Yang et al. \(2015\)](#); [Zhong and Verspagen \(2016\)](#) for an application to energy efficiency technological trajectories.

⁷ See [Table 1](#) to recall the definition of dominant blocks, constellations of technologies, and development sub-blocks.

To identify the development sub-blocks, we look at the common patterns of constellations of technologies within the dominant blocks at a micro and dynamic level, highlighting their behavior across time. The temporal analysis of the co-occurrence in terms of time and intensity allows us to characterize the existence and the nature of the twin transition, whether as widespread or rather as a localized niche (see previous Section). After computing the frequency of co-occurrence of the CPCs within each dominant block, we compute a four-year window simple rolling mean (RM) for each $cpc = j$ and of the average of the overall frequencies:

$$RM_{j,t} = \frac{1}{k} \sum_{\tau=t-k+1}^t S_{j,\tau}^B \quad (5)$$

$$RM_{\mu,t} = \frac{1}{k} \sum_{\tau=t-k+1}^t \left(\frac{1}{Q} \sum_{j=1}^Q S_{j,\tau}^B \right) \quad (6)$$

with $k = 5$ and $t = 1980, \dots, 2024$. We compute the rolling mean of the average of overall frequencies in order to select the most relevant CPCs. We select the CPCs above the mean at least for one period, i.e., $RM_{j,t} > RM_{\mu,t}$ for $t \geq 1$. We also select the twin CPCs Y02D and Y04S, despite their value with respect to the average to detect the possible convergence with the green CPCs, both the co-occurring ones and the green CPC of the dominant blocks. All CPCs whose frequency is always below the mean, except for the twin macro-categories Y02D and Y04S, are then discarded. We want to focus on the key technical traits comprising the dominant blocks to identify the possible convergence between the green and digital domains constituting twin patterns.

Common technological patterns with respect to the average allow us to aggregate the different technical traits in development sub-blocks. The relevance of co-occurrence with respect to the average and of all other technical fields co-occurring within each dominant block signals the possible convergence of the green and the digital technological domains and allows us to characterize it with respect to time and intensity. If relevant convergence along time is found to be common to all green dominant blocks, we may declare the twin transition to be a widespread technological trajectory.

4.2.2. Nature of technology and drivers of change

To capture the nature and the complexity of the technologies of interest, we compute the concentration index, for which we employ the Herfindahl-Hirschman Index (HHI) (Herfindahl, 1997; Hirschmann, 1945; Rhoades, 1993). Usually used to measure market structure and competition, the HHI index is an efficient concentration index that allows us to account for the composition of each dominant block of the green domain (for a discussion about the extension of the use of concentration measures to different domains and related limitations, see Ukav, 2017). With respect to the development sub-blocks analysis that provides evidence for the long-term and substitution patterns of the various constellations of technologies underpinning each block, the HHI index accounts for the relevance of each underlying technological domain over time. The baseline index is constructed on the frequencies of all co-occurrent CPCs for each block:

$$HHI_t^B = \sum_{j=1}^Q \left(S_{j,t}^B \right)^2 \quad (7)$$

$t=1976, \dots, 2024$ where $S_{j,t}^B$ is the share for each CPC in each year t (Eq. 4) with respect to all other CPCs co-occurring that year in each dominant block B ; $j = 1, \dots, Q$ are the selected CPCs. CPCs are not aggregated for each patent, and we count how many times each CPC occurs irrespective of whether it is in the same patent or several. The HHI ranges between $[1/Q, 1]$: the more the index converges to 1, the higher the concentration, thus the more relevant specific technical fields (CPCs) are involved in constructing the technologies of interest. Conversely, the lower the

index, the higher the degree of diversification of the underlying dominant blocks.

To detect whether the digital CPCs are key in driving the concentration dynamics, we analyze different counterfactual scenarios on the variation of alternative HHI indexes. Although we adopt a more simplified methodology, here we refer to the work of Rossi-Hansberg et al. (2021), who analyze the concentration dynamics of the US national market.⁸ We calculate different specifications of the HHI with respect to the exclusion of the top CPCs with the highest share of co-occurrence and of the digital CPCs Y02D and Y04S, and we compare the variation in the concentration patterns with respect to the baseline HHI computed with all the co-occurring CPCs. We obtain three indexes calculated on the shares of (i) all CPCs, the total HHI; (ii) the top CPCs, co-occurring above average at least for one period ($RM_{j,t} > RM_{\mu,t}$ for $t \geq 1$, see Section 4.2.1), with/without Y02D and Y04S; (iii) the bottom CPCs, that are always below the average of co-occurrence ($RM_{j,t} < RM_{\mu,t} \forall t$), with/without Y02D and Y04S. The exclusion of the digital CPCs Y02D and Y04S allows us to understand whether the digital dimension drives the concentration dynamics, and so to address our question about the pervasiveness of the twin transition. We compare the variation of the different HHI specifications with the variation of the total HHI for each dominant block B at time t , with respect to the first time period (1976):

$$HHI_{c,t,1976}^B = \frac{HHI_{c,t}^B - HHIC_{c,1976}^B}{HHI_{c,1976}^B} = \frac{\sum_{j=1}^Q \left(S_{j,t}^B \right)^2 - \sum_{j=1}^Q \left(S_{j,1976}^B \right)^2}{\sum_{j=1}^Q \left(S_{j,1976}^B \right)^2} \quad (8)$$

For $t=1977, \dots, 2024$ where c is the “counterfactual” specification. Table 3 summarizes all indexes used for the empirical analysis, Table 4 summarizes all possible scenarios.

5. Empirical analysis and results

5.1. Identification of the twin transition: macro-level structural analysis

Fig. 1a shows the number of patents granted at the USPTO from 1976 to 2024, each of which has been assigned at least one of the nine macro-categories of the CPC under study. Fig. 1b shows the annual frequency by CPC macro-category (Eq. 1). We identify three dominant blocks, both in terms of number of patents and of annual share: technologies for the reduction of GHG emissions in energy generation, transmission, and distribution (Y02E, in yellow); mitigation technologies in transportation (Y02T, in light blue); and in production or processing of goods (Y02P, in purple). Since the 2000s we see the emergence especially of ICTs aiming at the reduction of their own energy use (Y02D, in dark green), while SITs (systems integrating technologies) for power network operations (Y04S, in pink) are less relevant in terms of number and frequency of patents.

Now that the dominant blocks are identified, we focus on these three technological domains (Y02E, Y02T, Y02P), excluding the other four green macro-categories (Y02A, Y02B, Y02C, and Y02W) from the main analysis (see Section 4.2 for clarification). Following Rughi et al. (2025), we account for the underlying patterns and life cycle stages of the technologies of interest by computing the temporal growth of patenting activity for each macro-category, weighted by the share of patents in each CPC macro-category over the total number of patents of the previous year. The weighing procedure is done to control for the life cycle of

⁸ To understand the role of the top firms' market power in driving concentration, Rossi-Hansberg et al. (2021) compare alternative HHI specifications excluding sales of the top firms and looking at the entry of new establishments of these firms in local markets, to account for entry and exit mechanisms at the local level. Similarly, our “markets” are the dominant blocks and our “market sales” are the shares of co-occurrence of top CPCs.

Table 3
Indexes for the empirical analysis

| Index | Identification | Aggregation Level |
|--|--|-------------------|
| $P_{j,t}$ & $\delta_{j,t}$: Number/share of patents by CPC macro-category | Dominant Block | Macro-level |
| $C \in N^{9 \times 9}$: Co-occurrence matrix | Main constellations of technologies and of the twin transition as aggregate convergence of green and digital technologies | Macro-level |
| $s^B \in N^{1 \times Q}$: Vector of co-occurrences within each dominant block | Main constellations of technologies and of the twin transition as micro and dynamic convergence of green and digital technologies over time. | Micro and dynamic |
| $RM_{j,t}$ and $RM_{\mu,t}$: Rolling mean of the share of co-occurrences and of their average | Development sub-blocks and the twin transition as convergence of green and digital technologies over time. | Micro and dynamic |
| $HHI^{t,B}$: Herfindahl-Hirschman Index | Nature and complexity of the dominant blocks. | Micro and dynamic |
| $\Delta HHI_{c,t,1976}^B$: HHI variation | Relevance of the digital CPCs in the concentration dynamics and assessment of the twin transition as general technological trajectory. | Micro and dynamic |

Table 4
Scenarios by different constructions of the HHI.

| Scenarios | Description |
|-------------------|---|
| Baseline Scenario | No distinction of which CPCs drive concentration. |
| Scenario 1 | Role of the top and digital CPCs in driving concentration dynamics with respect to the Baseline scenario (Top CPCs, Y02D and Y04S). |
| Scenario 2 | The exclusion of Y02D and Y04S signals the role of the digital CPCs vis-à-vis the role of the top CPCs in driving the concentration dynamics and pervasiveness of the twin transition (Top CPCs without Y02D and Y04S). |
| Scenario 3 | Role of the bottom CPCs and digital CPCs with respect to the Baseline scenario (Bottom CPCs with Y02D and Y04S). |
| Scenario 4 | The exclusion of Y02D and Y04S signals the role of the digital CPCs vis-à-vis the role of the bottom CPCs in driving the concentration dynamics and pervasiveness of the twin transition (Bottom CPCs without Y02D and Y04S). |

different technologies, given their heterogeneous rates of maturity. We first compute the growth rate of patenting activity by year within each CPC macro-category j :

$$G_{j,t} = \frac{P_{j,t} - P_{j,t-1}}{P_{j,t-1}} \quad (9)$$

Then, we compute the frequency for each CPC macro-category per year, namely the share of patents of each CPC over the total number of patents P_t by year:

$$S_{j,t} = \frac{P_{j,t}}{P_t} \quad (10)$$

The product of the growth rate per year and the lagged value of the share provides for the weighted share of patenting activity by CPC per year:

$$W_{j,t} = G_{j,t} * S_{j,t-1} \quad (11)$$

Lastly, we apply a 5-year rolling mean to smooth volatility and compute the cumulative growth shown in Fig. 2. We focus on the dominant blocks and on the twin macro-categories. The patenting activity of the dominant blocks is increasing the most, although digital technologies are following the same trend. The cumulative growth rate

of patents in ICTs to reduce their own energy use (Y02D, in dark green) is higher than for SITs for power network operations (Y04S, in pink).

The growth rate for patents in energy generation (Y02E) is negative with respect to the previous year for the first decades, while after 2010 it has the greatest increase, surpassing patenting in transportation (Y02T), which shows the highest growth rate for the first three decades.

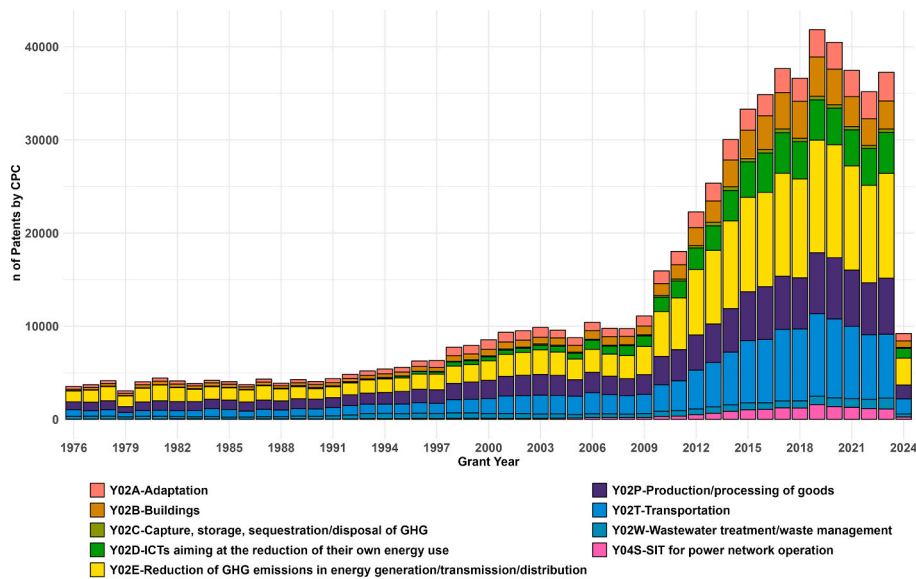
In order to identify the main constellations of technologies of the green domain at the aggregate level and to provide for a first assessment of the characterization of the twin transition, we look at the aggregate convergence between green and twin technologies. We compute the co-occurrence of each pair of the nine macro-categories of interest (Eq. 2) in Fig. 3a. The main diagonal shows the number of patents in each macro-category in descending order from the left corner. Out of the diagonal, the matrix is composed by C_{ij} , the number of patents in which $cpc = i$ and $cpc = j$ occur. The total number of co-occurrences is higher than the total number of patents since each patent can be assigned to several CPCs, and thus the same patent can be counted more than once for each different pair of co-occurrences of $cpc = i$ with $cpc = j$ (see Section 4.2). The dominant blocks Y02E, Y02T, and Y02P are co-occurring the most among them. Despite the number of patents in Y02D being high, this digital category does not co-occur with the dominant blocks, while Y04S co-occurs with technologies for the reduction of GHG emissions in energy (Y02E) and mainly with buildings (Y02B). Fig. 3b shows the normalized co-occurrence matrix with respect to the shares of total number of patents in each macro-category (Eq. 3). Patterns are confirmed: despite the fact that the co-occurrence with Y02E for patents in Y04S is high (34.85 %), Y04S co-occurs only for 2.94 % in patents of Y02E. Similarly, for Y02T, which represents 19.61 % of co-occurrent patents within Y04S while Y04S accounts only for 2.48 % of patents in Y02T. Y02D instead is marginal in the co-occurrence with the dominant blocks, and the dominant blocks are not co-occurring within the Y02D macro-category. Overall, the level of “contamination” of “supposed twin” technologies with the green dominant blocks turns out to be extremely limited. Fig. 4 disaggregates co-occurrences by decades to see whether time trends are detectable. The above results are actually robust to time disaggregation for both twin categories Y02D and Y04S. The increase in patenting in ICTs aimed at reducing their own energy use (Y02D) is evident across time but still does not co-occur with the dominant blocks of technologies of the green transition (even in recent years). If anything, with regard to Y04S, a weak increasing time trend in the above-discussed co-occurrences can be singled out. This first evidence suggests the lack of a convergent twin trajectory in the main technological bundle of the green constellations of technologies.

5.2. Identification of the twin transition: micro-level analysis

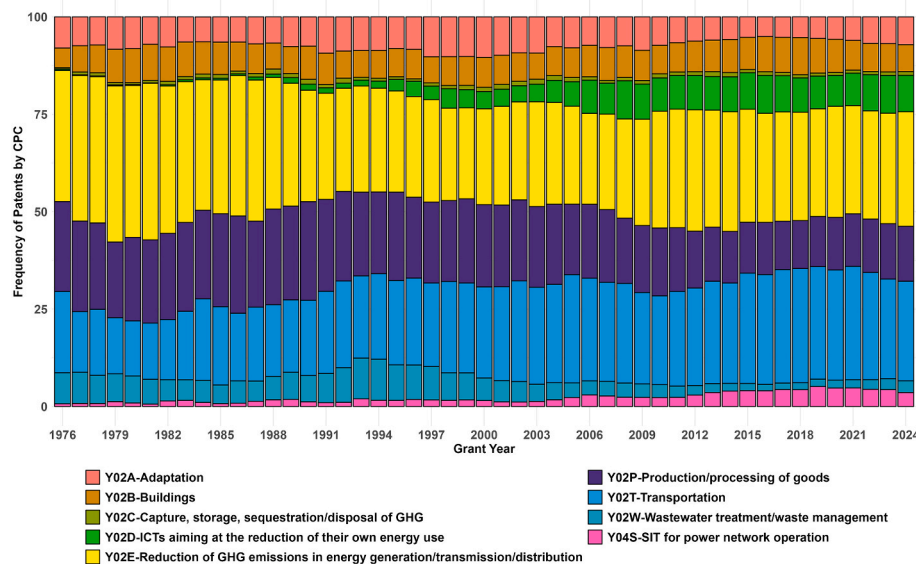
To understand to what extent the twin transition might constitute a new technological trajectory characterized by the convergence of green and digital technologies, in this sub-section we look at the identification of constellations of technologies at the micro and dynamic level, delving into the technological patterns of the three green dominant blocks, Y02E, Y02T, and Y02P.⁹

In more detail, we analyze the temporal dynamics of the CPCs co-occurring with the patents within each dominant block: energy, transportation, and production or processing of goods. We select all patents assigned to each of the dominant blocks, we compute the share of co-occurrence of all other CPCs by year (Eq. 4) and we apply a rolling mean in order to detect the underlying trends of co-occurrences (Eq. 5). We compute the average of the shares of all CPCs and apply a rolling mean as well (Eq. 6) and we look at which CPC appears above the

⁹ Four green macro-categories Y02A, Y02B, Y02C, and Y02W are not singled out for the analysis since they do not emerge as relevant in the distribution of number of patents by macro-category. See Fig. 1a and Section 4.2 for further details.



a: Absolute number of patents by macro-category over time



b: Distribution of the share of patents by macro-category by year.

Fig. 1. Identification of the dominant blocks.

average at least for one period, paying particular attention to the twin CPCs: Y02D and Y04S. The top panels in Figs. 5, 7 and 9 show the constellations of technologies aggregated by color for their common patterns. Within each dominant block, two opposite trends can be identified by aggregation of common technological patterns of the constellations of technologies: the decreasing trend is shown in red, while the increasing one is in blue. Such aggregation identifies a sequence that we define as a development sub-block (see Table 1) that drives the dynamics of each green dominant block. The decreasing development sub-block is the aggregation of all constellations of technologies that were co-occurring the most in the first years of the time period but then begin decreasing over time, losing relevance in constituting the specialization of the technologies of the dominant block (in red). On the other hand, other constellations of technologies acquire relevance over time in influencing the dominant block. This development sub-block is the aggregation of constellations of technologies

increasing in their co-occurrence over time (in blue). In line with the establishment of the ICT paradigm, it comes as no surprise that the electric/electronics and energy-related technologies are common to the rising development sub-blocks of all three dominant blocks. The second panel below zooms on the patterns of Y02D and Y04S. The dashed yellow line shows the rolling mean of the average (Eq. 6). The definitions of all CPC labels in the figures can be found in Table A2 in the Appendix.

Secondly, we analyze the alternative HHI indexes specifications (Eq. 7) and test the counterfactual scenarios (Eq. 8), to understand whether the twin dimension is part of the constellations of technologies driving the changes in the nature of each dominant block.¹⁰ The proposed analysis allows us to detect to what extent the digital dimension enters

¹⁰ See Table 4 for a summary of all Scenarios.

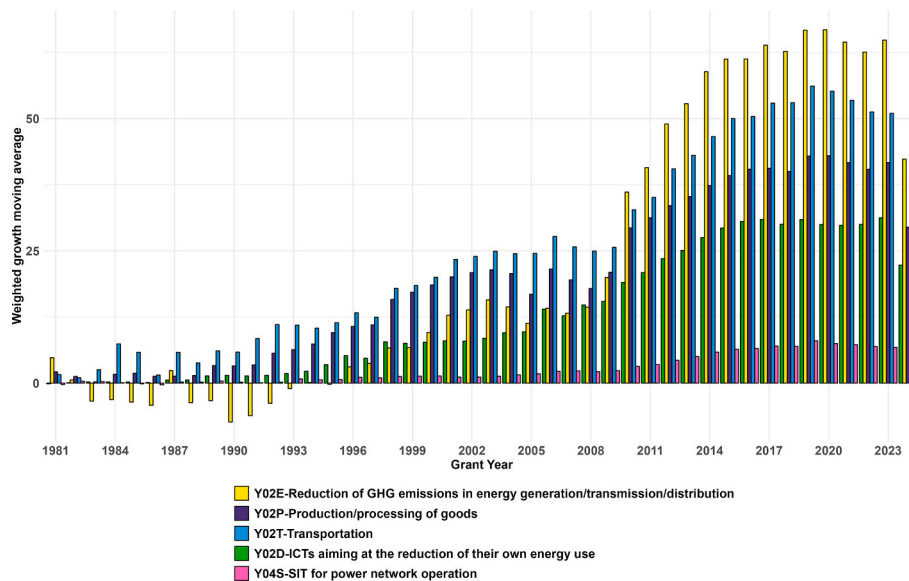


Fig. 2. Rolling mean of the cumulative weighted growth of patenting activity by macro-category.

into the technological nature of the key technologies of the green transition and to identify the nature of the alleged twin transition as a technological trajectory (either widespread or localized, see Section 3). We show the analysis for each dominant block separately.

5.2.1. Energy

Fig. 5a shows the technological patterns for the technical fields (CPCs) that relate to patents in the reduction of GHG emissions in energy generation, distribution, and transmission. In blue (red), we show all those technical fields that in 2024 have a value that is higher (lower) than in 1980 (first year is 1976, we apply a rolling mean of 5 years to smooth the series). The labels are sorted in descending order of co-occurrence in 2024. We see that electric means of energy conversion as batteries (H01M) is the most relevant technical field. A shift from renewable, nuclear energy sources technologies and buildings (F24S-solar heating; G21C-nuclear; Y02B- buildings) to electric means such as circuits arrangements for energy supply (H02J) and propulsion of electrically propelled vehicles (B60L) is evident. Despite the decrease (in red) in the co-occurrence in mitigation technologies against climate change in the production or processing of goods (Y02P), the trend is stable. Although Y04S and Y02D have grown in co-occurrence over time (in blue in the top panel), we can see from Fig. 5b that the co-occurrence is below average and is negligible for Y02D. The co-occurrence of Y04S has been small but positive and increasing since the first years.

Fig. 6a shows the alternative HHIs for the development block Y02E. It reveals the Y02E block to be highly complex, even considering only the top and the digital CPCs (in blue, Scenario 1), since it reaches 0.3 points, with 1 being the maximum concentration. Excluding Y02D and Y04S does not change the pattern (in red, Scenario 2). The overall HHI (light blue, Baseline Scenario) shows a lower concentration since the majority of CPCs have a low co-occurrence share. Considering only the bottom and the digital CPCs (in yellow, Scenario 3), CPCs that are always below average, flattens the HHI. Excluding the digital dimension does not change the patterns (in purple, Scenario 4).

Fig. 6b compares the variation of the different specifications of the HHI with respect to the first year of the time period. The counterfactual scenarios are based on the comparison of the HHI specifications excluding the top and the digital CPCs, with respect to the variation of the total HHI, the Baseline Scenario (light blue). Excluding the top CPCs, the bottom HHI (yellow) results in different upswing phases of the variation. The variation of the index is constantly decreasing, which is the opposite of the total HHI with all CPCs (light blue) and the top and

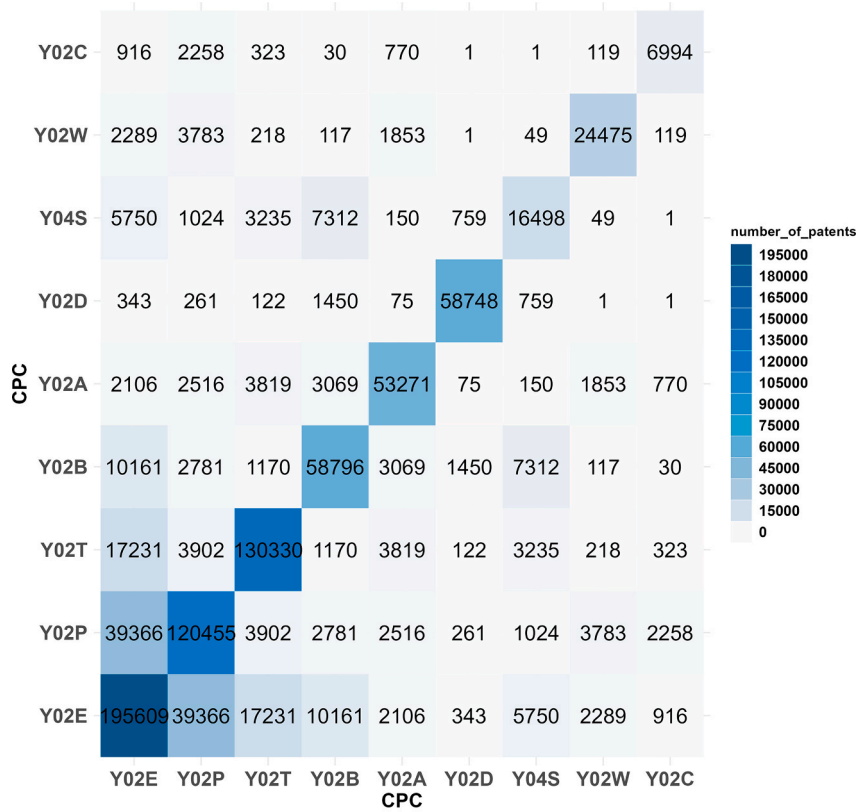
digital CPCs (blue).

This outcome suggests that the top CPCs drive the concentration dynamics. By removing the digital CPCs (red), the variation doesn't change, highlighting the fact that despite their marginal increase in co-occurrence over time (especially Y04S, see Fig. 5), they are not key in driving the concentration patterns (Scenario 2). This is also true even when excluding the digital dimension from the HHI with the bottom CPCs (purple, Scenario 4). The counterfactual scenarios suggest the concentration patterns to be driven by the top CPCs and the irrelevant role of Y02D and Y04S. Recall that concentration here stands for complexity, because the dominant block is prevalently populated by technological fields.

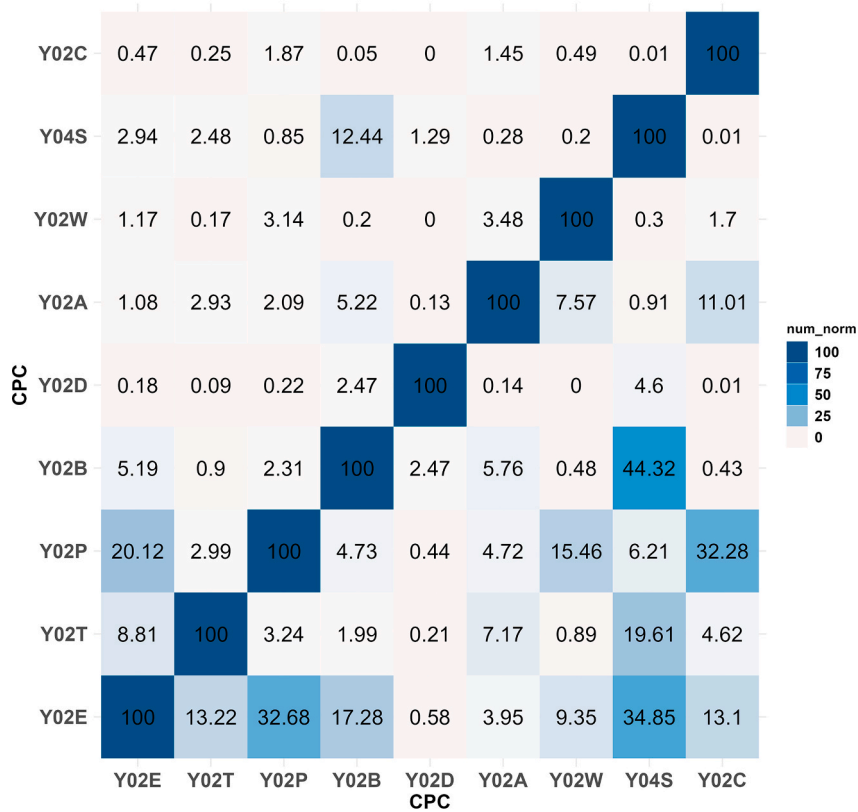
5.2.2. Transportation

The second dominant block of the green technological domain is mitigation technologies in transportation. From Fig. 7a we can see that (not surprisingly) there is a shift from engine and combustion engineering (F01M-supplying combustion engines in general with combustible mixtures; F01P-internal combustion piston engines) towards electric propulsion of vehicles (B60L-propulsion of electrically propelled vehicles; B60W-control systems specially adapted for hybrid vehicles; H01M-batteries). The supposed "twin" dimension is marginal for Y04S and negligible for Y02D; in fact, they are far below average (see Fig. 7b) despite both increasing in co-occurrence over time (in blue in Fig. 7a, the top panel of Fig. 7).

Fig. 8a compares the different HHI specifications for Y02T. The HHI computed with the top and digital CPCs (blue, Scenario 1) mirrors the trend of the HHI with all CPCs (light blue, Baseline Scenario), and although the number of CPCs composing it is much lower, the concentration is still very low, reaching a maximum of 0.125, suggesting high complexity of the Y02T block. Concentration increases in the latter years, highlighting the top CPCs as gaining more shares, while when looking at the HHI with only bottom and digital CPCs (yellow, Scenario 3) the concentration decreases. Removing the digital shares does not change concentration levels, neither from the top HHI (red, Scenario 2) nor from the bottom HHI (purple, Scenario 4). Looking at Fig. 8b we see that the variation of the HHI with all CPCs (Baseline Scenario) and top and digital CPCs (Scenario 1) is decreasing and becoming negative over time. When comparing the counterfactual variations with the Baseline variation (light blue), it is particularly evident that the HHI with bottom CPCs with (yellow, Scenario 3) and without (purple, Scenario 4) digital CPCs, have different upswing phases. The variation for the HHI index



a: Absolute number of co-occurrences across macro-categories.



b: Share of co-occurrences across macro-categories.

Fig. 3. Identification of macro constellations of technologies.



Fig. 4. Co-occurrence matrix across macro-categories by decade.

with bottom CPCs behaves exactly the opposite with respect to the Baseline Scenario and Scenario 1 with top and digital CPCs, confirming the counterfactual result according to which top CPCs drive the changes in concentration (Scenario 1). This outcome holds also when digital CPCs are excluded (red, Scenario 2), highlighting the role of the top CPCs and not of Y02D and Y04S.

Overall, the supposed “twin” technologies seem to play a negligible role in the evolution of green technologies aimed to mitigate against climate change in transportation.

5.2.3. Production and processing of goods

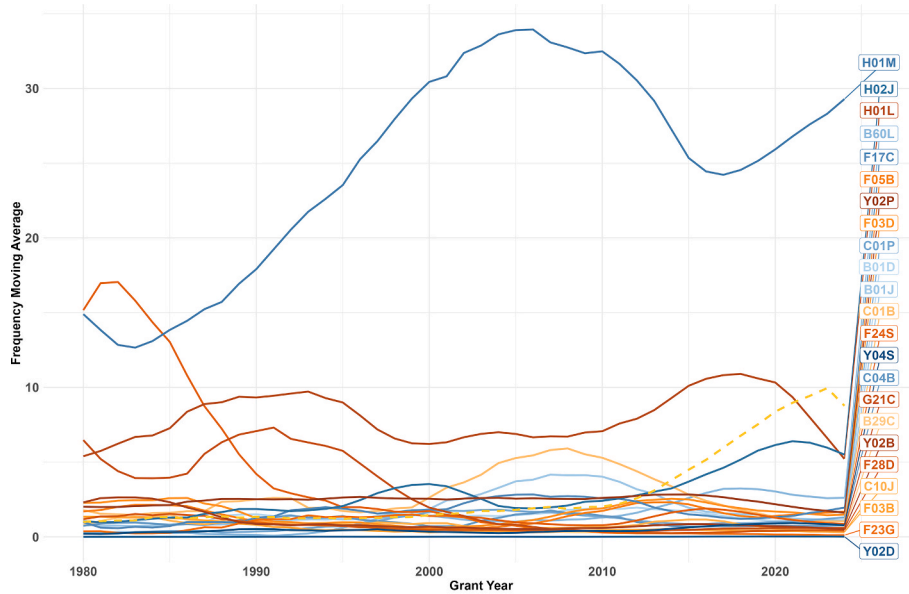
Mitigation technologies against climate change in production or processing of goods (Y02P) constitute the third dominant block. Fig. 9a highlights a shift from a knowledge base of chemical compounds and processes (C10G-cracking hydrocarbon oils; C22B-production, refining of metals) towards reduction in energy in the manufacturing process (Y02E-technologies for reduction of GHG emission in energy generation, distribution, and transmission; H01M-batteries; G05B-control systems). Co-occurrence of semiconductor devices (H01L) increases, reaching a maximum in 2005 and then decreasing below average, but still co-occurring at higher shares than at the beginning of the period; Y02E follows a similar trend. Despite the increase over time of co-occurrence in Y02D and Y04S (in blue in the top panel), it is still around zero and starts quite late in time (close to zero and always below the yellow – average – line in the bottom panel Fig. 9b). Still, they are below average and co-occur less than other technical fields whose shares have decreased from the beginning of the period (in red, e.g., B01J, B01D, C22B).

Fig. 10a shows the different specifications of the HHI. The Y02P block is also very complex, with the HHI reaching a maximum of 0.1 in contrast to the maximum concentration of 1. When computing the HHI with the top CPCs and including Y02D and Y04S (blue, Scenario 1), concentration is higher and shows opposite behavior with respect to the Baseline HHI computed with all CPCs (light blue). The HHI has increased since 2010, while the Baseline HHI decreases. This pattern is

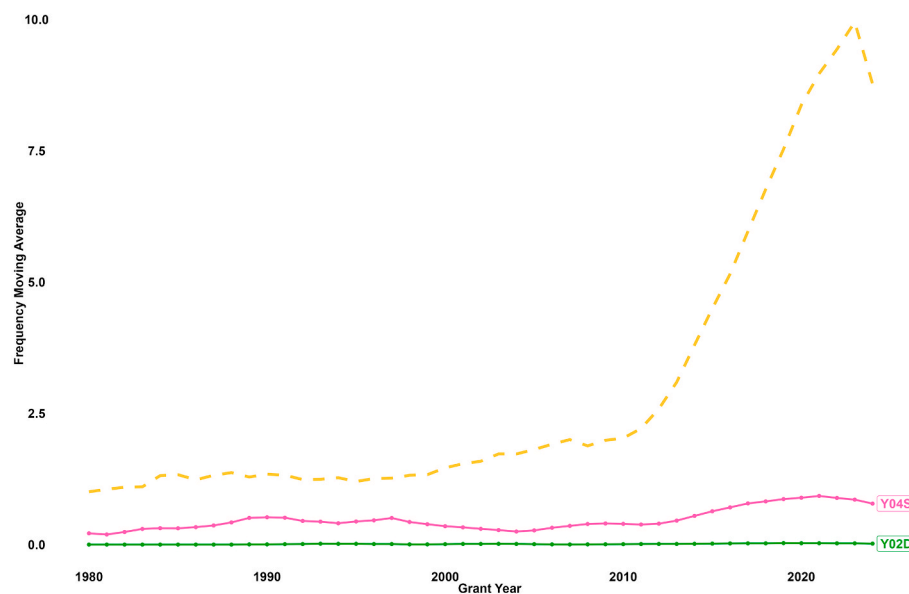
confirmed by looking at the variation in Fig. 10b, highlighting that the top CPCs are gaining shares (Scenario 1), and the variation is mainly positive after 2015. At the same time, both in the HHI and in the variation excluding the digital dimension (red, Scenario 2), the concentration decreases more than for the other dominant blocks Y02E and Y02T (see Figs. 6a and 8a). The counterfactual scenario is also informative for this dominant block, since the HHI specification excluding the top CPCs, i.e., the HHI with the bottom and digital CPCs (yellow, Scenario 3), have different upswing phases with respect to the HHI including all CPCs (light blue, Baseline Scenario). The counterfactual is robust to the exclusion of the digital CPCs (purple, Scenario 4). The variation has been positive and steep in the last years. The variation of the HHI with top and digital CPCs (blue, Scenario 1) shows different upswing phases than the Baseline Scenario and has the same steep increase in the last years. Nevertheless, excluding Y02D and Y04S does not change the concentration patterns, suggesting the top CPCs drive concentration (Scenario 2) and, among the bottom CPCs, there are other CPCs increasing co-occurrence and driving the final upswing phase (Scenario 4). Despite the increase in concentration both in the bottom and the top CPCs specification, the fact that there are more bottom CPCs may drive down the concentration when computed with all CPCs (following Ukav (2017), the smaller the share of each technological domain, the less it counts, and if there is a large number of technological domains with equal volumes, the HHI approximates 0).

Also looking at Fig. 9, we can see that despite several CPCs in 2024 still have a higher share than in 1976, they are decreasing over time and more CPCs that were above average are declining, H01M being the main CPC keeping its top position.

Regardless of the different upswing phases in the variation of the indexes, excluding top CPCs confirms the counterfactual exercise. The exclusion of the digital CPCs Y02D and Y04S does not change the scenarios, highlighting that they are not driving concentration dynamics. This is also true when considering only bottom CPCs with similar shares of Y02D and Y04S. The digital dimension does not emerge as relevant in explaining the concentration patterns of the mitigation technologies in



a: CPCs co-occurring above the mean for at least one period, Y02D and Y04S.



b: Co-occurrence of the twin CPCs (Y02D and Y04S). Mean in yellow.

Fig. 5. Rolling mean of five years of the co-occurrent CPCs in technologies for reduction in GHG emissions in energy generation, distribution, and transmission (Y02E).

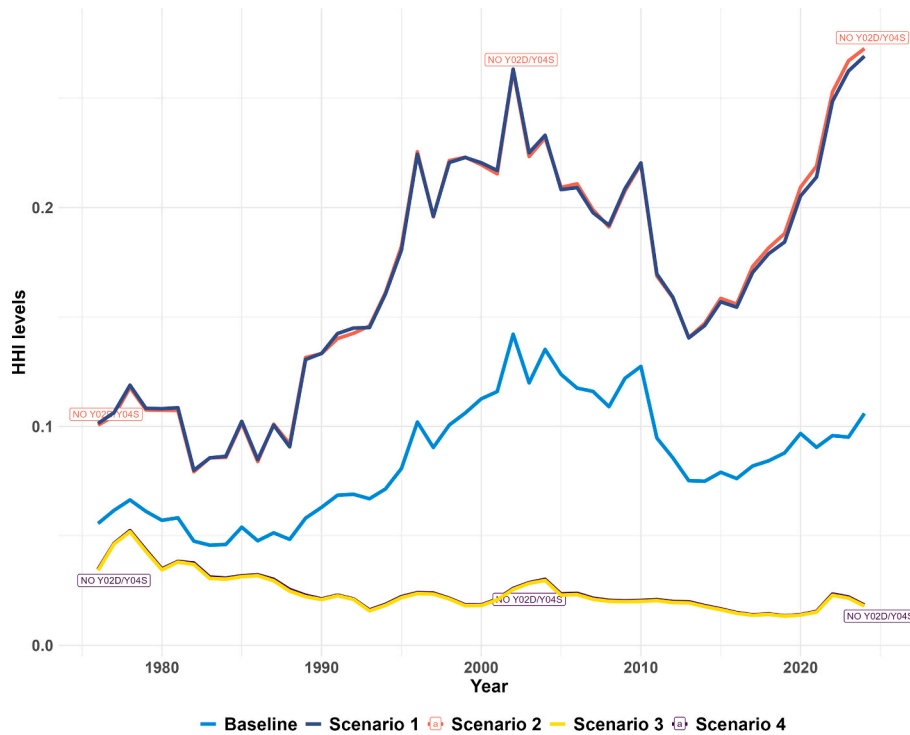
the production and processing of goods, just as in transportation and in energy. The counterfactual scenarios suggest that the supposed “twin” transition is neither timely nor intense and thus is not reflective of the beginnings of a pervasive and widespread trajectory.

5.3. Discussion: where are the twins?

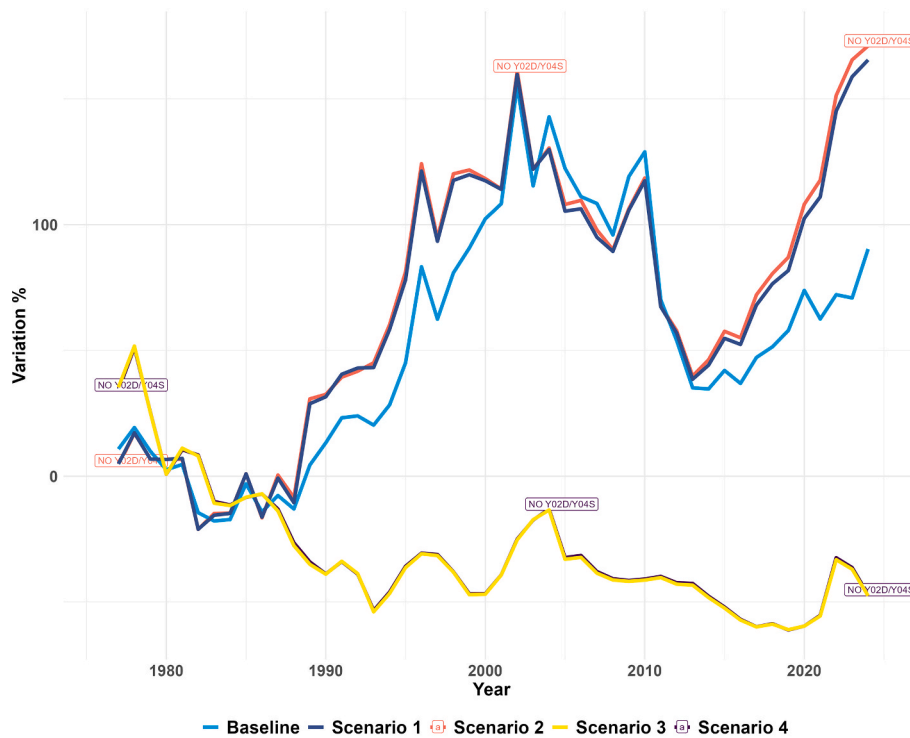
Overall, all dominant blocks show a common shift towards electrification, while the digital dimension emerges as marginal if not negligible. On the one hand, the digital dimension is not relevant when considering the composition of the bundle of technologies identified as the main constellations within the green domain at the aggregate level (see Fig. 3a). At the same time, it does not emerge as relevant in the

evolution of technological patterns within the technologies of the green domain, energy, transport, and production or processing of goods, at the micro and dynamic level (see Figs. 5, 7 and 9).

All in all, we note the absence as well as the non-emergence of co-occurrences within the digital blocks. Despite the general increase in patenting activity, ICTs do not relevantly co-occur with the technologies of the green dominant blocks, although to a different extent between Y04S and Y02D. In fact, Y04S co-occurs more, even if it remains below average, since it relates to ICTs having an impact on other areas such as systems integrating technologies for power network operations. This is especially true for the technologies related to the energy sector (Y02E) and is more obvious in the last decade. This may be the outcome of the evolution of the energy-saving heuristics embedded in the ICT



a: HHI with all co-occurrent CPCs and counterfactual specifications.



b: Baseline variation of the HHI with all co-occurrent CPCs and counterfactual specifications.

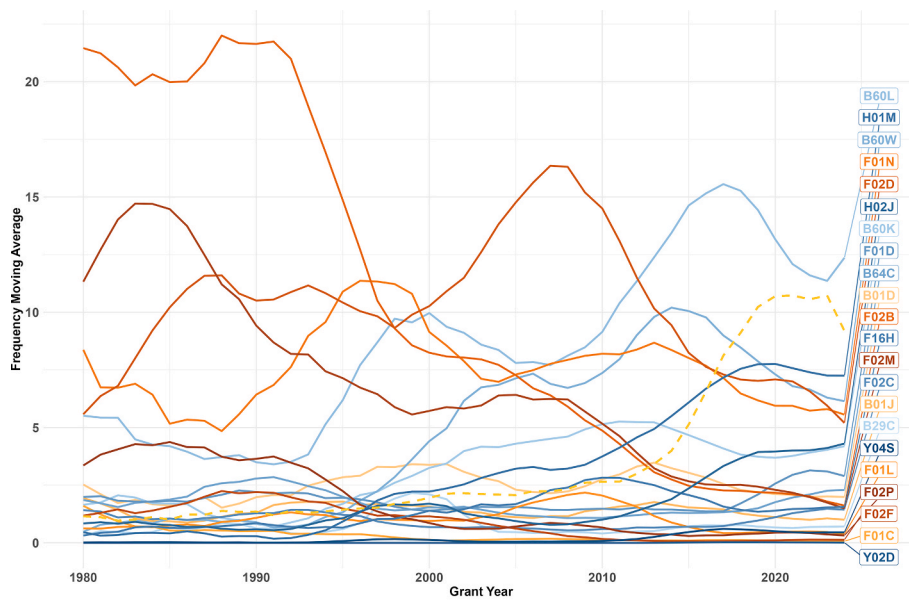
Figure 6: HHI and counterfactual scenarios for Y02E.

Fig. 6. HHI and counterfactual scenarios for Y02E.

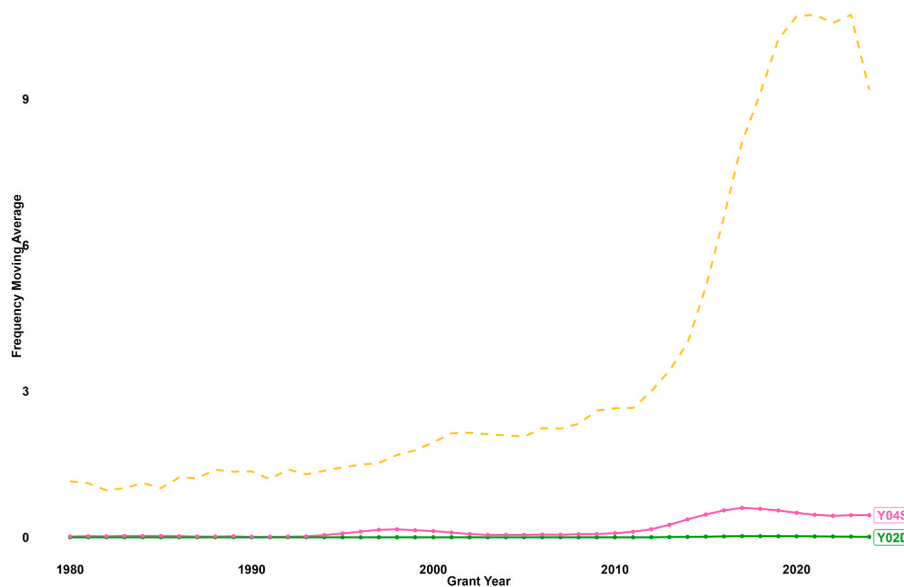
paradigm. However, we cannot identify a convergence of the green and ICT trajectories into a unique twin trajectory since the co-occurrence of Y02D is negligible both at the aggregate and at the micro level, while with regard to Y04S it is scattered in time and intensity across the three

dominant blocks; therefore, no common patterns are detectable. In addition, their co-occurrence generally turns out to be not significant in affecting concentration dynamics in the three dominant blocks.

Overall, the twin transition cannot confidently be considered as a



a: CPCs co-occurring above the mean for at least one period, Y02D and Y04S.



b: Co-occurrence of the twin CPCs (Y02D and Y04S). Mean in yellow.

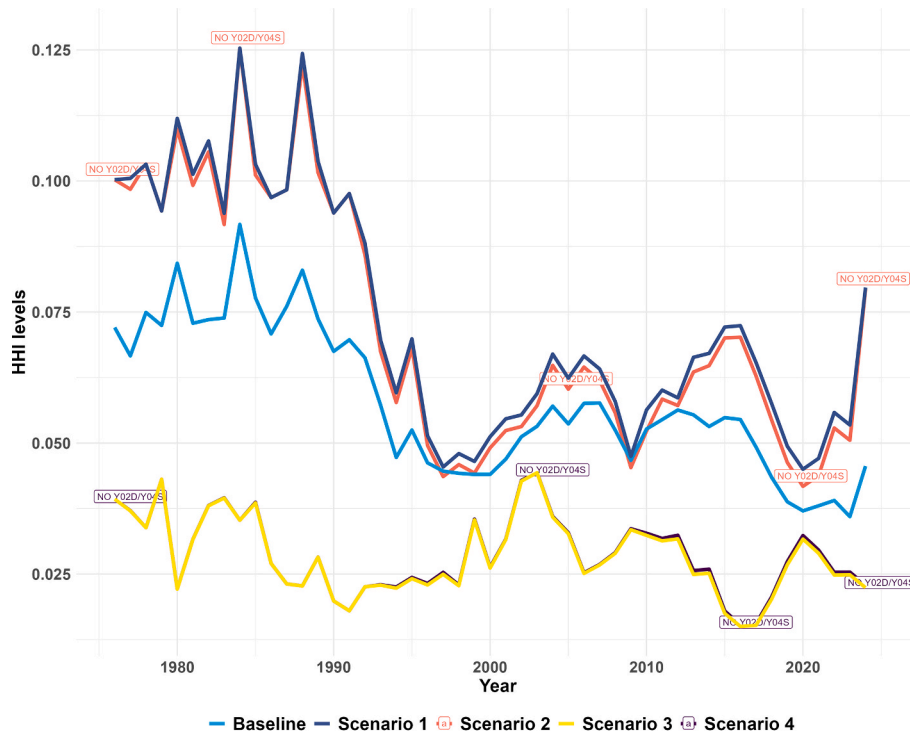
Fig. 7. Rolling mean of five years of the co-occurrent CPCs in mitigation technologies in transportation (Y02T).

“widespread technological trajectory”. If anything, it can be (partially) detected as a “localized niche” within the green technologies related to the energy sector.

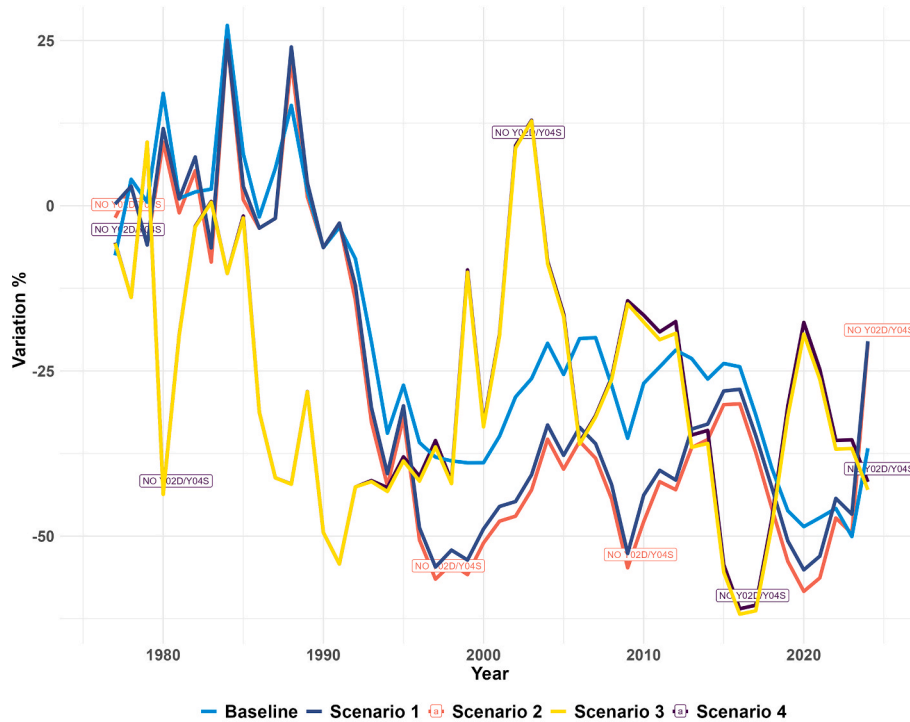
Interestingly, patenting activity is higher in Y02D than in Y04S, but Y04S co-occurs more with the green dominant blocks. Therefore, even from this perspective, we may infer that the ICT paradigm is not developing in the suggested “twin” direction since it is resulting in more patents of ICTs as green products rather than of ICTs that may help other sectors to become sustainable.

This interpretation is also supported when looking at top applicants behind twin transition and green patents. 13.66 % of applications are for patents in green technologies as well as in twin applications. Fig. 11 shows the share of patents for each dominant block Y02E, Y02T, Y02P, and twin applications Y02D and Y04S for the top twenty firms by

patenting activity. The firms are ordered by numbers of patents. We detect an overlap only for ICTs having an impact on other areas, i.e., systems integrating technologies for power network operations (Y04S), while only ICTs firms seek patents in ICTs aimed to reduce their own energy use (Y02D). For instance, the top applicant is Toyota and only 0.25 % of Toyota’s patents are ICTs aimed to reduce their own energy use (Y02D), while 2.20 % are in Y04S. Research in twin applications that are concentrated in the Y04S twin category appears as a complementary activity by giant conglomerates such as General Electrics in the energy sector; Toyota, Honda, and Mitsubishi in the automotive industry; and Siemens in the manufacturing of electrical components (mainly batteries). Patenting in Y02D emerges as a product innovation activity of ICT companies (see Section 2) such as Intel, Qualcomm, Samsung Electronics, and IBM. At the same time, ICT companies together with car



a: HHI with all co-occurrent CPCs and counterfactual specifications.

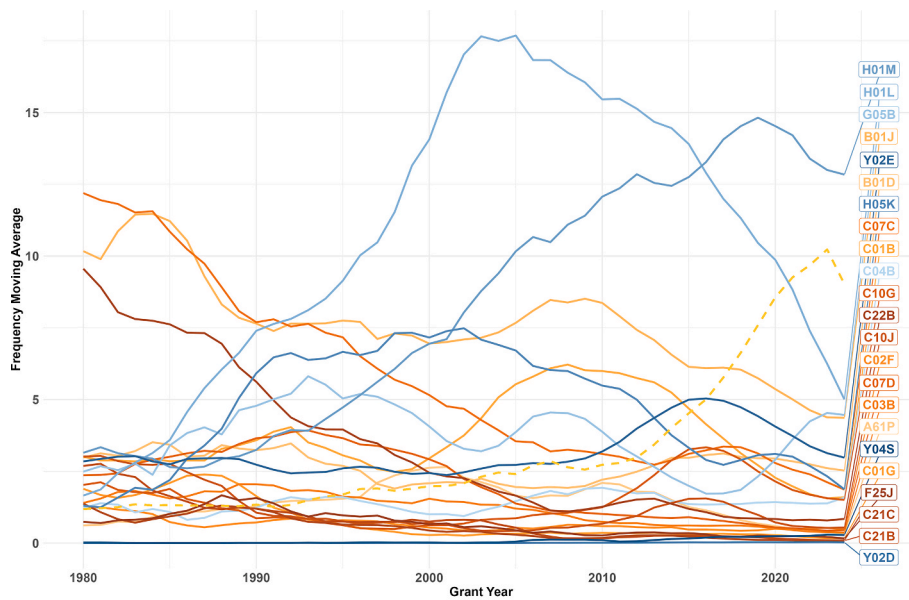


b: Baseline variation of the HHI with all co-occurrent CPCs and counterfactual specifications.

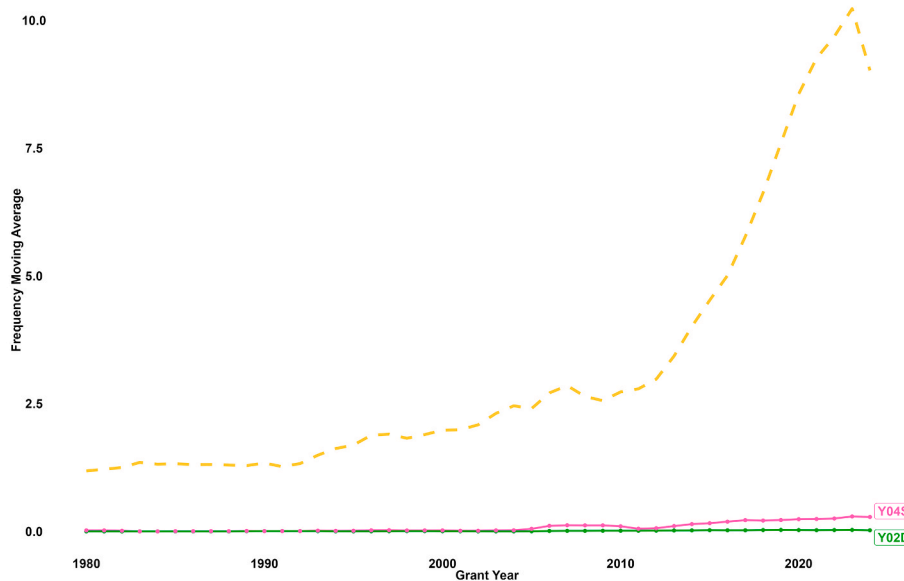
Fig. 8. HHI and counterfactual scenarios for Y02T.

manufacturers are among the top applicants in mitigation and adaptation technologies against climate change, but the patenting activity is mostly concentrated in green ICTs (Y02D, in green in Fig. 11). The other technological category to which patents of ICT firms relate the most is

production and processing of goods (Y02P, in purple), which we may assume to be ICT process innovations for manufacturing. Overall, each company patents the most in the technological category most related to its core industrial activity (Y02T for players in the automotive sector in



a: CPCs Co-occurring above the mean for at least one period, Y02D and Y04S.



b: Co-occurrence of the twin CPCs (Y02D and Y04S). Mean in yellow.

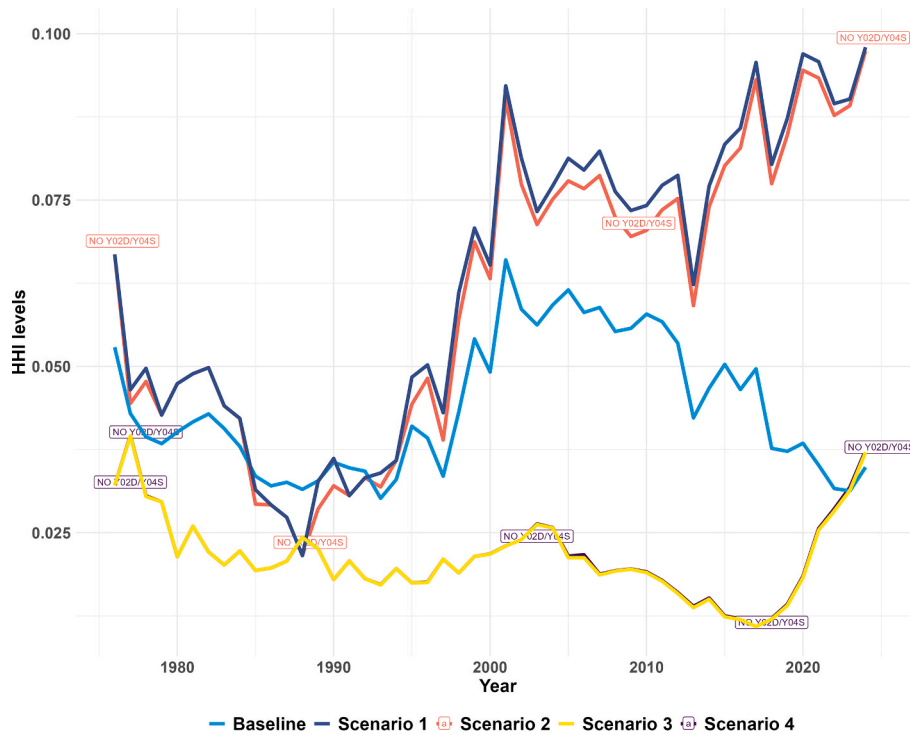
Fig. 9. Rolling mean of five years of the co-occurrent CPCs in mitigation technologies in production and processing of goods (Y02P).

particular). The only ICT firm which shows a more balanced distribution across the main technological categories is Hitachi, whose core industry is Computer Systems Design and Related Services (NAICS 5415), but whose patent portfolio is quite balanced across Y02E, Y02T, Y02P, and Y02D patents. The concentrated patenting activity of ICT players in green ICTs (i.e., CPC Y02D) confirms previous results according to which there is no interweaving between the green and the digital domains, since key innovators in green technologies are not innovating in digital applications. We may infer that ICT companies' innovation in green ICTs is related to the development of the energy-saving heuristics of the ICT paradigm and that Y02D technologies are ICTs becoming greener, while we do not have evidence that green technologies are becoming more digital, which would be required for a twin path. Of course, green ICTs as product innovations of the ICT sector may be

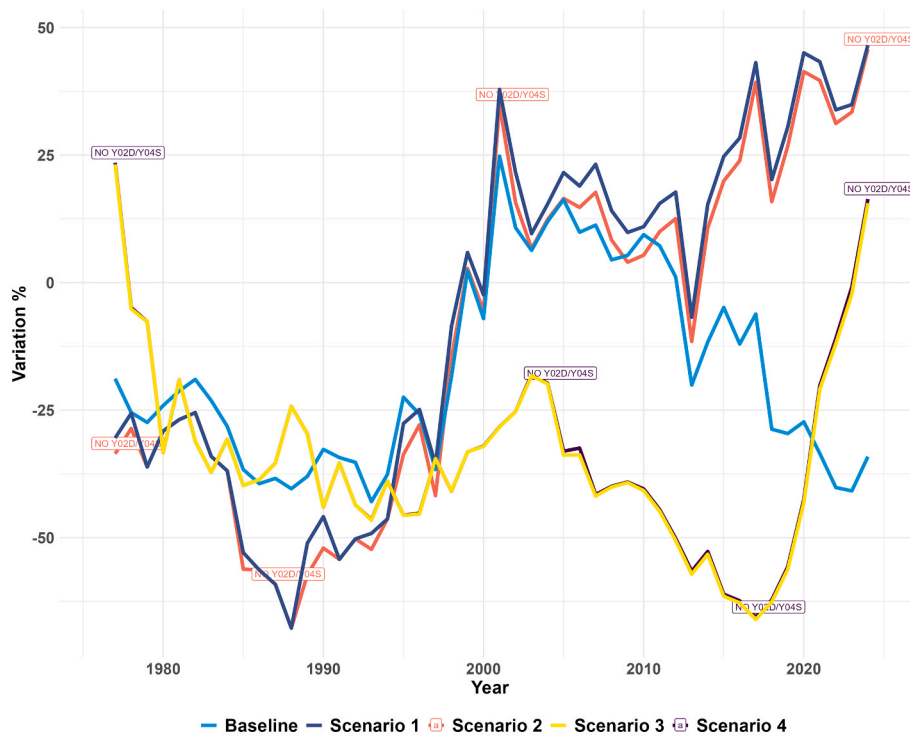
adopted as process innovations to reduce emissions by other firms in different sectors, given the co-occurrence with the Y02P category. This aspect of the investigation is outside the scope of this paper, however, and can be pursued as possible future development of the current analysis.

6. Conclusions and policy implications

The green and the digital transitions are two of the main transformative processes of our economy. Seeking to rise to the climate change emergency, a strong policy push is promoting the convergence of these two transitions into a single one, in which digital technologies are identified as key to reducing emissions, and technologies to reduce emissions become digital. In this paper, we try to detect whether this



a: HHI with all co-occurrent CPCs and counterfactual specifications.



b: Baseline variation of the HHI with all co-occurrent CPCs and counterfactual specifications.

Fig. 10. HHI and counterfactual scenarios for Y02P.

policy perspective is reflected in the actual and observable technological dynamics. Using patent data and endowed with an evolutionary approach to the study of technologies, we identify the dominant blocks of the green transition and examine to what extent the digital dimension enters the green technological domain. By doing so, we are able to

understand whether there is a convergence between the two technological fields and to what extent a new technological trajectory (either widespread or localized) can be detected. In addition, we look at the nature of the technologies of interest in terms of complexity and the combination of different knowledge sources. We find that the three main

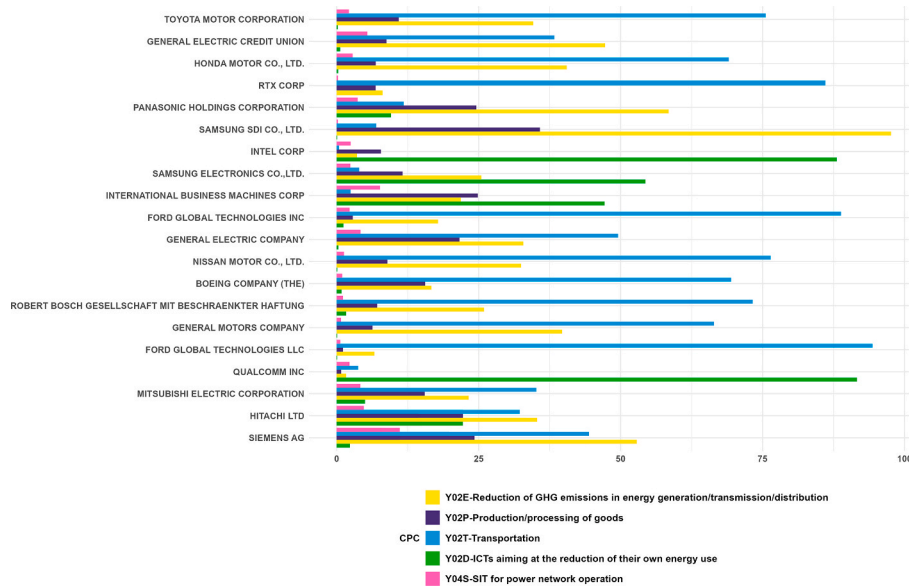


Fig. 11. Share of patents by CPC of the top 20 patenting firms in the green and twin domain. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

dominant blocks within the green technology domain are technologies reducing GHG emissions in energy generation, distribution, and transmission; mitigation technologies in transportation; and mitigation technologies in the production or processing of goods. However, ICTs reducing their own energy use and ICTs having an impact on other technology areas are not a relevant part of the main constellations of technologies in the green technological domain. Moreover, all the technologies of interest emerge as complex, with different rates of knowledge recombination, as measured by the HHI.

Indeed, the convergence between the three dominant blocks and ICTs aimed at reducing their own energy use turns out to be negligible, while it is marginal for ICTs having an impact on other technological areas. Therefore, we can conclude that a general twin transition is not detectable at all, at least as far as patent evidence is concerned. The alleged twin transition emerges – at best – as a localized niche (and scattered both over time and in intensity), limited essentially to the green technologies adopted in the energy sector.

To sum up, as a general conclusion of this study, we can exclude that the twin transition constitutes a widespread technological trajectory. On the whole, and for the time being, the “twin transition” should be considered a flagship policy in name only, with its associated wish-list realized only in some technological niches within the energy sector, and even then, only partially so. Policy makers should be aware of this empirical evidence and – instead of evoking the twin transition as if it were an ongoing process – should promote those institutional changes that are crucial to increase the (at present very weak) match between green transformation and the uptake of digital technologies (Perez, 1983, 2016), if this is to prove relevant in facing up to climate change challenges.

The implications of our study extend beyond its relevance for the policy agenda and raise a deeper challenge concerning the relationship between technology and society, and the more general hope of relying on “endogenous” technological and market solutions to solve human-production-based catastrophes such as the climate crisis. Given the patterns we have surveyed, we do not see any endogenous technological propensity among economic agents towards overall decarbonization. For example, we clearly see the absence of big oil companies as top players in the patenting activity on climate change mitigation technologies (see Fig. 11); by the same token, we do not see any clear emerging shift towards specific technologies, but instead a welter of rather diversified and heterogeneous efforts. Our evidence in fact depicts a

timid incremental path towards technologies meant to mitigate the climate crisis, revealing a lack of bets by private actors on market rewards. The presence of low (or even nonexistent) market rewards is defined in Economics 101 as evidence of market failures; however, beyond market failures, it is clear that the current fragmented and simplistic policy framework is not able to foster the critical innovative efforts needed to bring about a twin transition to address the climate crisis. The politics behind technology generation has to come back to the center of the stage and to the center of the analysis, in particular to avoid evoking expectations that are barely verified in experience. In this context, the main policy implications of this study can be summarized as follows.

For the time being, the “twin transition” remains a flagship policy in name only, scarcely reflected in the actual technological dynamics. Policy makers, who often take the reality of the twin transition for granted, should – on the contrary – be aware that at present the twin transition is barely more than a wish-list. Our study shows that private agents are not spontaneously converging on a twin transition technological trajectory, since market incentives appear insufficient to induce the desired technological patterns; by contrast, market failures dominate the scene. As such, strong policy action is required, and economic agents should be directed towards the twin transition via clear targets on emissions abatement and strong directionality as opposed to simply hoping for more effective technological solutions. Such directional policies should be selective and vertical, whereas our study singles out a prominent lack of coupling in the three most relevant dominant blocks, which are energy, transport, and production processes. If this is the case, policies should be highly tailored in terms of the targeted industries. Some attempts have been made recently in the United States with the Inflation Reduction Act and in Europe with the Green Deal. In addition, national instruments like the National Integrated Energy and Climate Plans represent actual tools to make the energy transition occur. However, the directionality and conditionality premises of industrial policies are still missing. Certainly, “government failures” (such as the well-known substitution and deadweight effects) should be avoided, and for this reason continuous monitoring of the targets should be implemented.

Not only economic policies but also certain managerial implications can also be drawn from our study. The “twin transition” requires deliberate strategic decisions at the company level. In this context, firm-level strategic management should design a dedicated division targeting

the convergence of digital and green innovation at the company level, well beyond traditional R&D. In addition, a better coordination and integration of the relevant divisions within the company (R&D, IT, ESG, etc.) should be pursued.

Finally, the twin transition bears important implications in terms of distributive and environmental justice. An increasing literature (Bez et al., 2024; Cha, 2024; Davies, 2022; Mohai and Saha, 2015) shows that those suffering the most from the disproportionate impact of the climate crisis are those in poor and deprived territories, what Richard Nelson called the ghettos of the world (Dosi et al., 2025a; Nelson, 2011). If those suffering such disproportionate burdens were not prioritized, this would imply the failure by design of the flagship policy. This study shows how even in the process of generating technologies, the big international players and oligopolies turn out to be key players; however, they do not seem to engage in the twin transition spontaneously. If such efforts are conducted only with the intention of increasing profitability, the twin transition will simply represent a marginal market opportunity, lacking any transformative capacity. A strong policy initiative is needed (see above), and it should address the needs of the poor, with a particular emphasis on access to clean water and clean energy.

The main limitation of this paper concerns the well-known shortcomings in using patent data (see Section 2.3 for a detailed discussion of the pros and cons of using patent data). Moreover, we intersect patents with industries, while firm-level microdata could surely be extremely useful to further test the outcomes of our analysis. Finally, the policy and managerial implications discussed above should be treated with caution, since they refer to analyses based on a particular dataset (USPTO), which can be affected by geographical bias. Further studies based on indicators of technological change other than patents, possibly using firm-level data and going beyond US-based data, would therefore be promising research avenues in investigating the true extent of the twin transition.

CRediT authorship contribution statement

Linnea Nelli: Writing – review & editing, Writing – original draft,

Appendix

As a robustness test, for all dominant blocks Y02E, Y02T, and Y02P we check the behavior of the HHI and its variation, when explicitly accounting for the so-called DIGITAL CPCs, according to the definition provided by the WIPO technological classification (see INPI-OST/FhG-ISI Classification of 30 fields; IPC and Technology Concordance Table; for applications see Breschi et al., 2003; OECD, 1994; Wagner, 2006). DIGITAL CPCs include the following fields: measurement, control, computer technology, IT methods for management, digital communication. This implies excluding a total of 47 out of 615 CPCs for Y02E; 45 CPCs out of 544 for Y02T; 47 CPCs out of 621 CPCs for Y02P. Results show that the behavior of the HHI, and its change over time, are completely unaffected when looking at the trend of such codes, while only the overall level of concentration is slightly reduced. This is the inevitable outcome of reducing the number of CPCs. The DIGITAL CPCs of the robustness test are: G01, measuring an testing; G04, horology; G05, controlling, regulating; G06, computing, calculating, counting; G07, checking devices; G08, signaling; G09B, educational or demonstration appliances; appliances for teaching or communication with the blind, deaf, or mute; models, planetaria, globes, maps, diagrams (among which e.g. G09B19/00; teaching or practice apparatus for gun-aiming or gun-laying F41G3/26; G0B19/0053 Computers, e.g. programming; G09B19/0061 geography; G09B 23/186 for digital electronics; for computers, e.g. microprocessors); G09C ciphering or deciphering apparatus for cryptographic or other purposes involving the need for secrecy; G10L, [...] speech recognition, speech of voice processing techniques, speech of audio coding or decoding; G11, information storage; G12 instrument details; G16 ICT specially adapted for specific application fields; H04L, transmission of digital information.

Table A1
Patent examples.

| CPC | Title | Text |
|---|---|--|
| Y02E (Green, not necessarily with digital traits) | Wave power generation device [US10883470B2] | “The ocean accounts for more than 70 % of the earth’s area. The ups and downs, horizontal movement, shaking and rotation of seawater not only have huge amounts of energy, but also have certain laws. They are inexhaustible natural carbon-free clean energy sources [...]. The ups and downs of this wave have potential and kinetic energy, and it seems that it can be used for power generation.” |

(continued on next page)

Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Visualization, Validation. **Maria Enrica Virgillito**: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Marco Vivarelli**: Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

All authors declare that they do not have any conflict of interest to report.

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Table A1 (continued)

| CPC | Title | Text |
|-------------|---|--|
| Y04S (twin) | Electric automobile energy monitoring and swapping network in remote monitoring of cloud computing network [US10894484B2] | “With the deepening of the global energy crisis, as well as serious environment pollution, major automotive enterprises around the world generally recognize that energy saving and emission reduction is the main direction of future automotive technology development [...] it is an important for electric vehicle’s safe operation to monitor and manage the battery swapping station remotely [...]. This invention provides a remote control center, an electric vehicle remote monitoring system, a battery remote monitoring system, a battery swapping system on the chassis of an electric vehicle and an internal main display, which integrates big data and cloud computer technology, the Internet of Things technology, video identification technology, a battery monitoring network system based on multi-type monitoring and electric vehicle energy swapping network.” |
| Y02D (twin) | Extending a battery life of a battery-powered computing device [US10884484B2] | “The systems and techniques described herein enable artificial intelligence (e.g., machine learning) to predict an activity in which a user is currently engaged and automatically (e.g., without human interaction) select or create a profile to reduce power consumption and thereby extend battery life.” |

Table A2

Definitions of the CPCs in the development sub-blocks

| CPC | CPC Definition |
|------|--|
| A61P | MEDICINAL PREPARATIONS |
| B01D | SEPARATION |
| B01J | CHEMICAL/PHYSICAL PROCESSES |
| B29C | SHAPING OF PLASTICS |
| B60K | ARRANGEMENT OF PROPULSION UNITS FOR TRANSMISSIONS IN VEHICLES |
| B60L | PROPULSION OF ELECTRICALLY PROPELLED VEHICLES |
| B60W | CONTROL SYSTEMS FOR HYBRID VEHICLES |
| B64C | AEROPLANES; HELICOPTERS |
| C01B | NON-METALLIC ELEMENTS |
| C01G | COMPOUNDS CONTAINING METALS |
| C03B | MANUFACTURE PROCESSES |
| C07C | ACYCLIC/CARBOCYCLIC COMPOUNDS |
| C07D | HETEROCYCLIC COMPOUNDS |
| C10G | CRACKING HYDROCARBON OILS |
| C21B | MANUFACTURE OF IRON/STEEL |
| C21C | PROCESSING OF PIG-IRON REFINING MANUFACTURE OF WROUGHT IRON/STEEL |
| C22B | PRODUCTION/REFINING OF METALS |
| C25B | ELECTROLYTIC/ELECTROPHORETIC PROCESSES FOR PRODUCTION OF COMPOUNDS/NON-METALS |
| F01C | PISTONS |
| F01D | NON-POSITIVE DISPLACEMENT MACHINES |
| F01L | CYCLICALLY OPERATING VALVES FOR MACHINES/ENGINES |
| F01N | GAS-FLOW SILENCERS |
| F02B | INTERNAL-COMBUSTION PISTON ENGINES |
| F02C | GAS-TURBINE PLANTS |
| F02D | CONTROLLING COMBUSTION ENGINES |
| F02F | CYLINDERS/PISTONS/CASINGS FOR COMBUSTION ENGINES |
| F02M | SUPPLYING COMBUSTION ENGINES WITH COMBUSTIBLE MIXTURES |
| F02P | IGNITION FOR INTERNAL-COMBUSTION ENGINES |
| F03B | MACHINES/ENGINES FOR LIQUIDS |
| F03D | WIND MOTORS |
| F03G | MECHANICAL-POWER PRODUCING DEVICES/MECHANISMS |
| F05B | INDEXING SCHEME FOR WIND/SPRING/WEIGHT/INERTIA LIKE MOTORS |
| F16H | GEARING |
| F24D | DOMESTIC/SPACE-HEATING SYSTEMS; DOMESTIC HOT-WATER SUPPLY SYSTEMS |
| F24S | SOLAR HEAT COLLECTORS/SYSTEMS |
| F28D | HEAT-EXCHANGE APPARATUS |
| G05B | CONTROL SYSTEMS |
| G21C | NUCLEAR REACTORS |
| H01G | CAPACITORS, RECTIFIERS, DETECTORS; SWITCHING, LIGHT/TEMPERATURE-SENSITIVE DEVICES OF ELECTROLYTIC TYPE |
| H01L | SEMICONDUCTOR DEVICES |
| H01M | PROCESSES/MEANS FOR CONVERSION INTO ELECTRICAL ENERGY |
| H02J | CIRCUIT ARRANGEMENTS/SYSTEMS FOR DISTRIBUTING/SUPPLYING ELECTRIC POWER/ENERGY |
| H05K | PRINTED CIRCUITS/MANUFACTURE OF ASSEMBLAGES OF ELECTRICAL COMPONENTS |
| Y02A | ADAPTATION |
| Y02B | BUILDINGS |
| Y02E | REDUCTION OF GHG EMISSIONS IN ENERGY GENERATION/TRANSMISSION/DISTRIBUTION |
| Y02P | PRODUCTION/PROCESSING OF GOODS |
| Y02T | TRANSPORTATION |
| Y02W | WASTEWATER TREATMENT/WASTE MANAGEMENT |

Data availability

Data will be made available on request.

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