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ABSTRACT

A Twin Transition or a Policy Flagship? Emergent Constellations and Dominant Blocks in Green and Digital Technologies

The aim of this paper is to understand whether what has been labelled as "twin transition", at first as a policy flagship, endogenously emerges as a new technological trajectory stemming by the convergence of the green and digital technologies. Embracing an evolutionary approach to technology, we first identify the set of relevant technologies defined as "green", analyse their evolution in terms of dominant blocks within the green technologies and concurrences with digital technologies, drawing on 560,720 granted patents 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 of the dominant blocks and construct counterfactual scenarios. We hardly find evidence of patterns 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 just a policy flagship, rather than an actual endogenous technological trajectory driving structural change.

JEL Classification: O33, Q55, Q58

Keywords: twin transition, policy flagship, technological trajectories

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1 Introduction

Climate change and the related climate crisis are among the most pressing emergencies societies are facing. Since the First IPCC Assessment in 1992, it has been acknowledged human activities to be the primary source of the increase of global greenhouse gas (GHG) emissions, leading to the rise in the average temperature (IPCC (1992), IPCC (2023)). If the primary source of carbon emission is the anthropocentric and capitalist-basis organization of society, technology has been depicted and considered a potential solution to mitigate and potentially counteract such crisis, according to the so called *technology-fix* and *green capitalism* approach (Fox, 2023). In particular, technology that serves to mitigate climate change might be more effective to reach the goal if coupled with digitalised infrastructure. The aspiration of a coupling between digital and green technologies is what has come under the heading of "twin transition". Twin technologies are identified as technological artifacts embedding digital traits and, at the same time, aimed to reduce emissions. The definition goes either in the form of digital technologies, supporting the decarbonization of the economy (e.g., devices monitoring emissions), or in the form of green technologies characterized by digital traits with the aim of improving their emissions' reduction (e.g., emissions' capturing technologies, Muench et al. (2022)).

The aim of this paper is to understand whether what has been labelled as "twin transition", at first as a policy flagship, endogenously emerges as a new technological trajectory stemming by the convergence of the green and digital technologies. Embracing an evolutionary approach to technology (Freeman, 2019) and applying it to the realm of such potential coupled transition, we first identify the set of relevant technologies defined as "green", analyse their evolution in terms of constellations of technologies (Freeman and Louçã, 2001) and dominant blocks (Dahmén, 1988) within the green technologies and co-occurrences with digital technologies, drawing on 560,720 granted patents 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 and construct counterfactual scenarios. We hardly find evidence of patterns 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 just a policy flagship, rather than an actual endogenous technological trajectory driving structural change.

We contribute to the literature investigating the nature, directions and expected impacts of the digital and green transitions. The majority of contributions so far focus on firm performance, capabilities, innovation strategies and comparative advantages (Montresor and Vezzani, 2023; Cicerone et al., 2023; Cattani et al., 2023; Veugelers et al., 2023; Rehman et al., 2023; George et al., 2021; Chatzistamoulou, 2023). Other contributions have looked at the twin transition as a channel promoting structural change (Fouquet and Hippe, 2022; Mäkitie et al., 2023); promoting sustainability (Ortega-Gras et al., 2021), or whether twin technologies are sustainable or not (Bianchini et al., 2023).

To the best of our knowledge, the extant literature has not devoted specific attention to the technological nature of the coupled transition. A notable exception is Vermeulen and Pyka (2024), that propose a conceptual framework conjugating theoretical building blocks and empirical instruments of economics of innovation to analyse the twin transition. Their analysis, however, privileges expected projections, rather than historical and current trends in technological trajectories.

Understanding and assessing the extent to which the trajectories of technological development of these two innovative paths couple or not bear important implications in many domains. First, it becomes progressively more urgent clearly assessing the actual potential of such solutions, often considered to be an easy technological "fix" of the climate catastrophe, in other words the extent to which we can expect the emergence and diffusion of digitally-augmented and interconnected devices to mitigate, or even better, abate carbon emissions. Second, investigating the actual directions of innovative efforts via patent information allows us to define the borders of the search space, and identify in which specific industry-application innovative efforts in climate-change mitigation technologies are concentrating. Given the large heterogeneity in carbon emissions across industries (Dosi et al., 2024), is important to understand where the best of innovators are located. Third –given the results of our study, which differently from ex-ante expectations identify a detachment of the two trajectories, or at most a coupling only in niche technological domains– the potential disruptive nature of the twin transition fostered by the policy expectations may not align with expectations of the innovators, in our setting represented by the patenting firms. The latter in fact appear to undertake a path of very selective innovations, mostly in three application domains, namely: transport, energy and production processes. We hardly find evidence of patterns of pervasiveness of the trajectory. In that, our findings align with Vermeulen and Pyka (2024), according to which the path undertaken by innovators is the one of an incremental green-tech fix, rather than of a paradigm shift, toward "intelligent and smart decarbonization". Finally, accounting for the trajectories of innovative domains has important implications for the macroeconomy and its structural change (Dosi, 2023), in particular whether we should expect or not a transformative capacity from a new technological paradigm, as such able to reshuffle the distribution of income and value added across sectors, as usual when structural change occurs.

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 the empirical results and discuss them; finally, Section 6 concludes.

2 Converging or diverging paradigms?

2.1 The energy-saving nature of the ICT paradigm

Twin technologies have been identified as key to achieving a carbon neutral economy in more recent years. By 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)). However, the potential coupling of energy-saving and ICTs technologies was envisaged since the eighties. In fact, even in the early stages of the ICT revolution, ICTs were identified as potential green process innovations able to reduce energy and material intensity of production processes and products in other sectors (Perez (1983); Faucheux and Nicolaï (2011)). For instance, Berkhout and Hertin (2004) claim that resource and waste savings are evident in historical patterns since the introduction of the first computers. Describing the ICT paradigm, Perez (1983) writes:

*"**The new technological style is fundamentally materials-saving**. We consider only a few of its characteristics. It allows unprecedented downsizing of most products, reduces waste, permits production to closer tolerances, controls energy use, eliminates many moving parts, opens the possibility of closed-loop no-waste systems, etc. At the same time, in an indirect way, its full deployment would tend to fulfill many needs with services rather than products, and substitute much physical transportation with telecommunications while drastically diminishing paper consumption. Hence, **many demands of the ecological movement, which are in fact a rejection of the materials-intensive, energy-intensive waning style, can be met with a further diffusion of the applications of microelectronics**".* (Perez (1983), p.373)

More recently, Perez (2016) argues the ICT can represent the technological revolution able to undertake a new techno-economic paradigm shift, toward a new sustainable economy. The author claims that the ICT paradigm is only half way from its development, since the past technological revolutions have lasted more than 50 years. At the same time, for the ICT to be the driver of such a structural change, other factors need to complement its application; in particular institutional changes towards long-term State guided policies.

By the development of ICTs able to reduce their own energy use, ICTs as green product innovations have become able to lower the emissions of the ICT sector as well (Freitag et al. (2021)). However, economic growth and the large use of ICTs has also increased energy consumption worldwide (Kander et al. (2014)); which effect is prevalent is thus unclear, for example nowadays cloud computing (Yu et al., 2023) and cryptocurrencies (Tayebi and Amini, 2024) are enormously contributing to carbon emissions. Studies addressing the quantitative impact of ICT on CO2 emissions, through the different mechanisms at work, find that digital technologies increase the domestic level of emissions; however, technological spillovers from resources efficiency in the upstream sector onto downstream sectors, and the spreading of services display a mitigating effect across industries and countries (see, among others, Zhou et al. (2019); Wang et al. (2021); Sun et al. (2023)). 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)). Røpke (2012) highlights that the potential of ICTs for sustainable transformation needs a co-evolution of a cluster of technologies involving other industries. In sum, according to this revised literature, ICT per se cannot be seen as intrinsically energy-saving and green.

In contrast, the alleged convergence between digital and green technologies is currently thought as a powerful engine to pursue sustainability and mitigate climate change. Cecere et al. (2014) argue that the interaction between ICT with environmental innovation (EI) applies thanks to the characterization of ICTs as general purpose technologies (Bresnahan and Trajtenberg (1995); Rosenberg and Trajtenberg (2004); Carlsson (2004)). The green ICT domain emerges as characterized by a wide technological pervasiveness since it is widespread across technological clusters defined by different combinations of green and ICT applications (Cecere et al. (2014)). For example, Zhou et al. (2019) analyse the impact ICTs have on the development of renewable energy technologies in USA, Canada, Germany, UK, Italy, The Netherlands and Poland, all countries experiencing a strong policy push and public monetary support in renewable energy, wireless spectrum 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 in the long run. Previous studies assess more firms' space: for instance Antonioli et al. (2018) look at ICT and EI impact on productivity; Corrocher and Ozman (2020) analyse the green innovation activity of ICT companies and how it affects their performance while Cecere et al. (2019) estimate the probability for ICT companies to switch to green ICTs development; Santoalha et al. (2021) find local and digital capabilities improve green specialization at the regional level more than non-green one. More recent studies focus specifically on Machine Learning and AI and their ability to reduce emissions and recombination with green technologies (Biggi et al. (2024); Strubell et al. (2020); Lacoste et al. (2019); Coeckelbergh (2021); Kaack et al. (2022); Rolnick et al. (2022)); others on Industry 4.0/Industrial Internet of Things (Beier et al. (2017); Ghobakhloo (2020); Machado et al. (2020); Bauer et al. (2021); Beltrami et al. (2021); Felsberger et al. (2022)).

2.2 The twin transition in the current literature

Adopting the definition of 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).

Ortega-Gras et al. (2021) address the technological dimension of the twin transition by narrowing the focus on a specific definition of twin technologies. They look specifically at Key Enabling Technologies (KETs) and Industry 4.0 ICTs applied to achieve a Circular Economy setting in patent texts. The authors analyse in which sectors KETs for Circular Economy are adopted and provide a review of the EU policies in action, advancing the twin transition by supporting KETs. Damioli et al. (2024) investigate the role of digital and green knowledge in determining "twin knowledge" looking at scientific publications. The authors explore 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 twin knowledge. Mäkitie et al. (2023) provide a description of possible characterizations of twin technologies and how they may lead to structural changes. However, the authors do not provide an identification of the technological contents 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 and conclude that they are in fact linked by their energy-saving potentialities. Bianchini et al. (2023) analyse the impact of environmental and digital technologies on GHG emissions at the regional level. The aim is to assess the sustainability of the twin transition, defined as the co-occurrence of distinct environmental and digital innovations measured by patent applications in green and digital fields at the regional level. Still at the regional level, Fazio et al. (2024) explore the transitions of regions towards twin innovation and the role of ICT vs green innovation orientation, spatial proximity and socio-economic similarity of the probability to become a "twin innovator region". Nevertheless, none of the cited studies delve into the definition and composition of twin.

Twin transition has also been investigated at the firm level. For instance, Montresor and Vezzani (2023) find that digital and in particular AI investments help to deal with the complexity of green innovation; this evidence is found also by Cicerone et al. (2023) but only for firms already specialized in green innovation; Cattani et al. (2023) investigate to what extent I4.0 technologies' adoption influences the probability to eco-innovate for firms in urban vis-à-vis rural areas; Rehman et al. (2023) analyze the effect of twin investments on firms' comparative advantages; Veugelers et al. (2023) compare investments in twin technologies of EU and US companies after the Covid-19 crisis and they find that firms that are more digital are willing to invest more in green technologies, especially in energy efficiency. Similarly, several studies start from the emphasis put forward by the European Union for the twin transition strategy and they examine to what extent digitalization is an enabler and/or a complement of the green transition and energy efficiency (Chatzistamoulou (2023), Vasconcelos-Garcia and Carrilho-Nunes (2024), Benedetti et al. (2023)).

According to our reading, the extant literature either "assumes" the twin transition or focus on the co-occurrence at some observational levels (such as regions or firms) of digital and green innovations. However, what is lacking is first, the investigation of the alleged co-occurrence of the two types of innovations (digital and green) in the conception of technology in itself; second, the industry applications that are targeted by such technologies, in order to understand the inherent potential in terms of emission abating.

3 Implications of an evolutionary assessment of the twin transition

According to Dosi (1982), a new technological paradigm is defined as *"an outlook, a set of procedures, a definition of the relevant problems and of the specific knowledge related to their solution"* (p.148). Technological paradigms stem from the mutual exchange across 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 undertake 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); Dosi (2023)).

Recalling the EU definition introduced above, the twin transition refers to the digital and the green transitions as concurrent transformations, and the uniting of the two in digital artifacts either helping the reduction of emissions or contemplating green artifacts with digital technical traits. If the twin transition was a new general trajectory, we would expect the two distinct blocks of green and digital technologies converging both in time and intensity into a unified technological path. In particular, we define as *convergence* the increasing coupling of the green technological domains with the digital ones. If such was the case, 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 to foster 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); Dosi (2023); Vermeulen and Pyka (2024)), according to the expectations emerging from the unfolding of new trajectories; alternatively, if in the form of 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 supported 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 functional and 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 balance between technological, technical, economic and related factors complementarities and structural tensions. Indeed, while constellations define structures of technologies, development blocks define 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 modulate the *development block* definition to identify *dominant blocks.* Three identification stages of technological development are defined with respect to the level of aggregation and with respect to static or dynamic patterns (see also Table 1).

At the first, most aggregate and static level, we look at the core technologies of the green transition and we define them as *dominant blocks.* Each dominant block emerges itself as a development block from previous structural tensions, in particular to respond to sectoral restructuring to meet environmental objectives. 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 we 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.

4 Data and Methodology

4.1 Data

In order to identify the nature of technologies of interest, we use patent data, retrieved by PatentsView. We have collected 560,720 granted patents from the US Patent Office (USPTO) since 1976 to 2024.[1] We choose the USPTO as it allows a direct link with PatentsView and embeds full texts.

To identify green and digital attributes, we use the Cooperative Patent Classification (CPC), that has the aim to assess to which technological field each patent pertains.[2] We select all patents that are classified by the following CPC classes (three digits) and sub-classes (four digits): (i) class Y02, that groups *technologies or applications for mitigation or adaptation against climate change*; (ii) sub-class 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 concentrates in the sub-class Y04S, *systems integrating technologies related to power network operation, ICT for improving the electrical power generation, transmission, distribution, management or usage (e.g. smart grids).* The class Y02 is thus our green category, while 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 the 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 macro-categories of Y02 at four digits. Each one relates to the application of technologies for the reduction of emissions in a specific sector. Table A1 in the Appendix provides a description of all macro-categories of interest.

4.2 Methodology

We first map the key technologies mitigating climate change by adopting a descriptive characterization of the main underlying technological patterns over time, focusing on the behaviour of the digital dimension. Secondly, we analyse the nature and 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

[1] The first granted date is January the 6th 2024, the last is March the 3rd 2024, the last release available at the moment of the analysis.

[2] The CPC is an harmonized classification between European Patent Office (EPO) and the USPTO building on the International Patent Classification (IPC). Sources: International Patent Classification; Cooperative Patent Classification

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 the CPC sub-classes at four digits of the CPC class Y02. We look at the highest number of patents in the distribution by sub-classes. The main macro-categories are defined as *dominant blocks*. To identify the twin trajectory, we 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 operations, ICTs for improving the electrical power generation, transmission, distribution, management or usage (Y04S). Firstly, at the aggregate level, we compute the co-occurrences by the use of co-occurrence matrices that count the number of patents P in which each pair of the CPC macro-categories at four digits co-occurs:

$$C_{i,j} = \sum P_{cpc_i,cpc_j} \tag{1}$$

with $i \neq j$ and where $cpc_{i,j}$ are the four digits macro-categories of Y02 and Y04S. 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 bundle of technologies. Secondly, we analyse 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 labelled 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. In so doing, we identify constellations of technologies at the micro level as well and the aggregation by common behaviour in co-occurrence defines different development sub-blocks.

Co-occurrences for each CPC $cpc = 1, .., N$ assigned to patents in dominant block B (all CPCs, not only the four digits macro categories of Y02 and Y04S as in the aggregate and static identification) in year t are computed as the share:

$$S_{cpc,B,t} = \frac{\sum cpc_{B,t}}{\sum_{cpc=1}^{N} cpc_{B,t}} \tag{2}$$

by counting how many times each CPC is associated to at least one patent within each dominant block over the total number of associated CPCs across patents of the dominant block along 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 as a 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 the moving average of the mean of the overall frequencies and the moving average for each CPC. We select the CPCs above the mean at least for one period and the CPCs related to the digital dimension, Y04S and Y02D. Common technological patterns with respect to the mean allows to aggregate the different technical traits in development sub-blocks. The relevance of co-occurrence with respect to the mean 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 its characterization with respect to time and intensity. If relevant and common in all green dominant blocks, we may identify the twin transition as a widespread technological trajectory.

Table 1 provides a synoptic table that matches the theoretical (see Section 3) and the methodological identification strategies. Table 2 presents three patent examples, one for each technological domain we are investigating, i.e. green and twin. The Table shows the CPC and the technological domain, the title and an extraction from the patent text. The text extraction has been selected on the basis of some key words with respect to climate change mitigation functions as *energy saving, environment, carbon free, clean energy, reduce power*.

4.2.2 Nature of technology and drivers of change

To capture the nature and the complexity of the technologies of interest, we compute a concentration index, a Herfindahl-Hirschman Index (HHI) (Hirschmann (1945); Herfindahl (1997); 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 building 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:

$$HHI_{B,t} = \sum_{\substack{cpc=1, \\ t=1976-2024}}^{N} \left(S_{cpc,B,t}\right)^2 \tag{3}$$

where $S_{cpc,B,t} = \frac{\sum cpc_{B,t}}{\sum_{n=1}^{N} cpc_{n,B,t}}$ is the share for each CPC in each year t (Equation 2) with respect to all other CPCs co-occurring that year in each dominant block B; $cpc = 1, .., N$ are the selected CPCs. CPCs are not aggregated for each patent, we count how many times each CPC occurs despite whether in the same patent or more. The HHI ranges between $[1/N, 1]$: the more the index converges to 1, the higher the concentration, thus the more relevant specific technical fields (CPCs) are in building the technologies of interest. At the opposite, the higher will be the degree of diversification of the underlying dominant blocks.

To detect whether the digital CPCs are key in driving the concentration dynamics, we analyse different counterfactual scenarios on the variation of alternative HHI indexes. With a more simplified methodology, we refer to the work of Rossi-Hansberg et al. (2021) who analyse the concentration dynamics of the US national market.[3] We calculate different specifications of the HHI with respect to the exclusion of the top

[3] To understand the role of the top firms' market power in driving concentration, they compare alternative HHI specifications excluding sales of the top firms and looking at the entry of new establishments of these firms in local

Terminology	**Definition**	**Identification**
Dominant blocks	Key technologies among the technological macro-categories for mitigation or adaptation against climate change	Distribution of patents by aggregation of CPCs at four digits within the Y02 macro-class. They are: (i) reduction of GHG emissions related to energy generation, transmission or distribution (CPC-Y02E); mitigation technologies related to transportation (CPC-Y02T) and in production or processing of goods (Y02P).
Constellations of technologies	Clustering of the most relevant technologies - dominant blocks - within the green domain at the aggregate level and in shaping technological patterns at the micro level within the dominant blocks	Analysis of the co-occurrences (i) at the aggregate and static level across the Y02 macro-categories -CPCs at 4 digits- and (ii) at the micro and dynamic level across all CPCs associated to patents within each dominant block.
Development sub-blocks	Development sub-blocks of the dominant blocks: aggregation of the different constellations of technologies according to technological patterns over time shaping the evolution within each dominant block.	Identification of similar patterns in the dynamics of the co-occurrent CPCs over time within each dominant block.
Twin transition/technologies as a *widespread technological trajectory*	EU definition of the twin transition where pervasively digital and green technologies converge 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

Table 1: Synoptic Table identifying the key conceptual categories.

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****"*
Y04S ("supposed" 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 ("supposed" 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 2: Patent examples

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 counterfactual 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 (see Section 4.2.1), with/without Y02D and Y04S; (iii) the bottom CPCs, that are always below the average of co-occurrence, with/without Y02D and Y04S. For each alternative, we then compute the HHI excluding the digital CPCs Y02D and Y04S. 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):

$$\Delta HHI_{c,B,t,1976} = \frac{HHI_{c,B,t} - HHI_{c,B,1976}}{HHI_{c,B,1976}} = \frac{\sum_{\substack{cpc=1,\\ t=1977-2024}}^{N} \left(S_{cpc,B,t}\right)^2 - \sum_{cpc=1}^{N} \left(S_{cpc,B,1976}\right)^2}{\sum_{cpc=1}^{N} \left(S_{cpc,B,1976}\right)^2} \tag{4}$$

where c is the "counterfactual" specification among (i) all CPCs, (ii) top CPCs with and without Y02D/Y04S, (iii) bottom CPCs with and without Y02D/Y04S. The counterfactual HHIs allow us to understand whether the digital dimension drives the concentration dynamics, and in that to address our question about the pervasiveness or not of the twin transition.

5 Empirical analysis and results

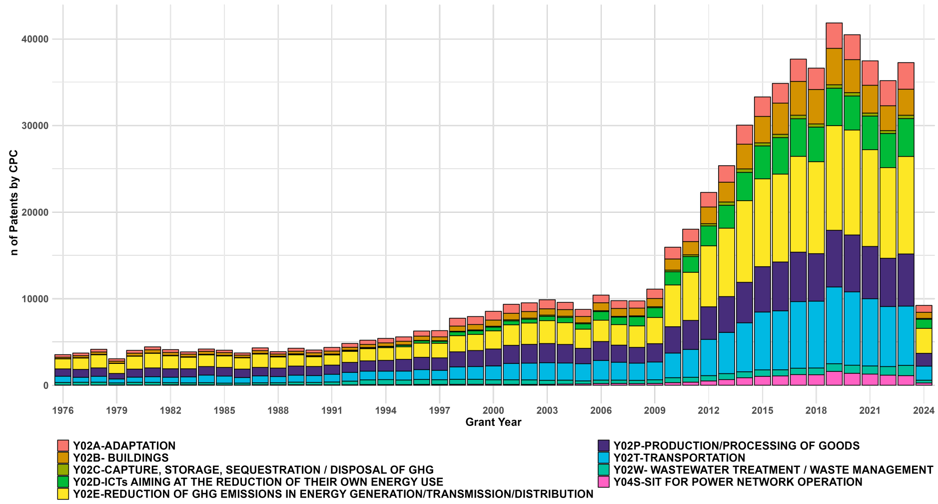
5.1 Descriptive statistics

Figure 1a shows the number of granted patents at the USPTO from 1976 to 2024, to which it has been assigned one of the sub-classes of CPC within the Y02 class and Y04S sub-class. Figure 1b shows the annual frequency by CPC sub-class. Both in terms of number of patents and of annual share we identify three dominant blocks: 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). ICTs technologies emerge since the 2000s, especially ICTs aiming at the reduction of their own energy use (Y02D), while SITs for power network operations (Y04S) are less relevant in terms of number and frequency of patents.

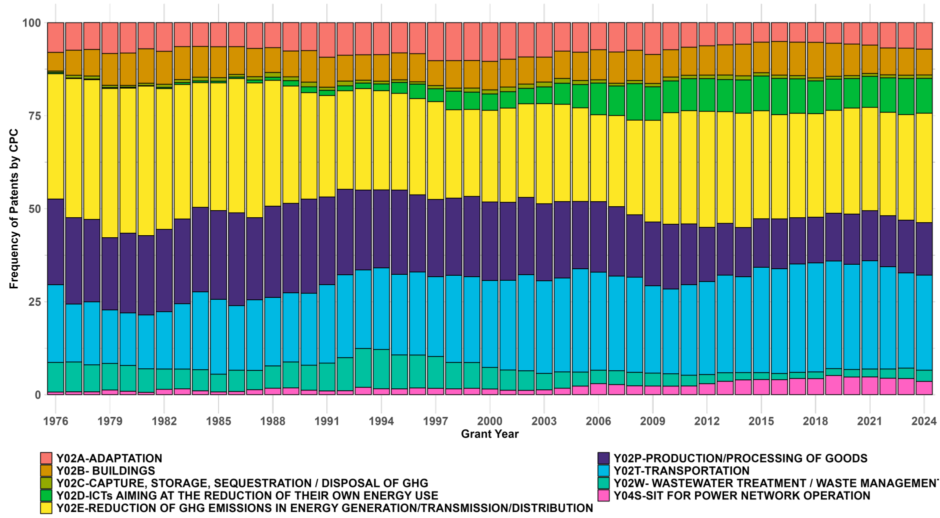
Following Rughi et al. (2025), we account for the underlying patterns and stages of life cycles of the technologies of interest by computing the temporal growth of patenting activity for each sub-class, weighted by the share of patents in each CPC sub-class overall the total number of patents of the previous year. The weighting procedure is done to control for the life cycle of different technologies, given their heterogeneous maturity. We first compute the growth rate of patenting activity by year within each CPC subclass:

$$G_{cpc,t} = \frac{n_{cpc,t} - n_{cpc,t-1}}{n_{cpc,t-1}} \tag{5}$$

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.



(a) Absolute number of patents by Y02 macro-categories and Y04S over time



(b) Distribution of the share of patents by Y02 macro-categories and Y04S by year

Figure 1: Identification of the dominant blocks.

then we compute the frequency for each CPC subclass per year, namely the share of patents of each CPC over the total number of climate change mitigation and adaptation patents (Y02) of the year:

$$S_{cpc,t} = \frac{n_{cpc,t}}{\sum_{cpc=1}^{i} n_{cpc,t}} \tag{6}$$

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

$$W_{cpc,t} = G_{cpc,t} * S_{cpc,t-1} \tag{7}$$

Lastly we apply a 5 year rolling average to smooth volatility and compute the cumulative growth shown in Figure 2. 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 that shows the highest growth rate for the first three decades.

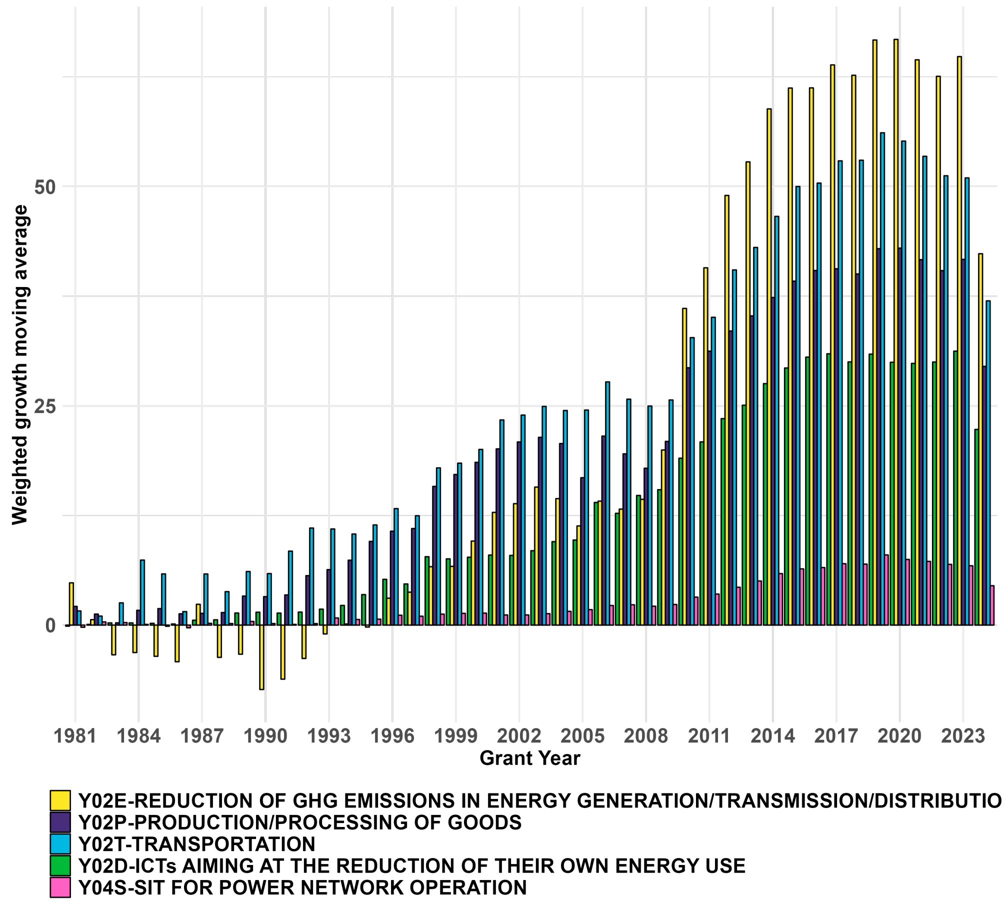


Figure 2: Moving average of the cumulative weighted growth of patenting activity by Y02 subclasses and Y04S

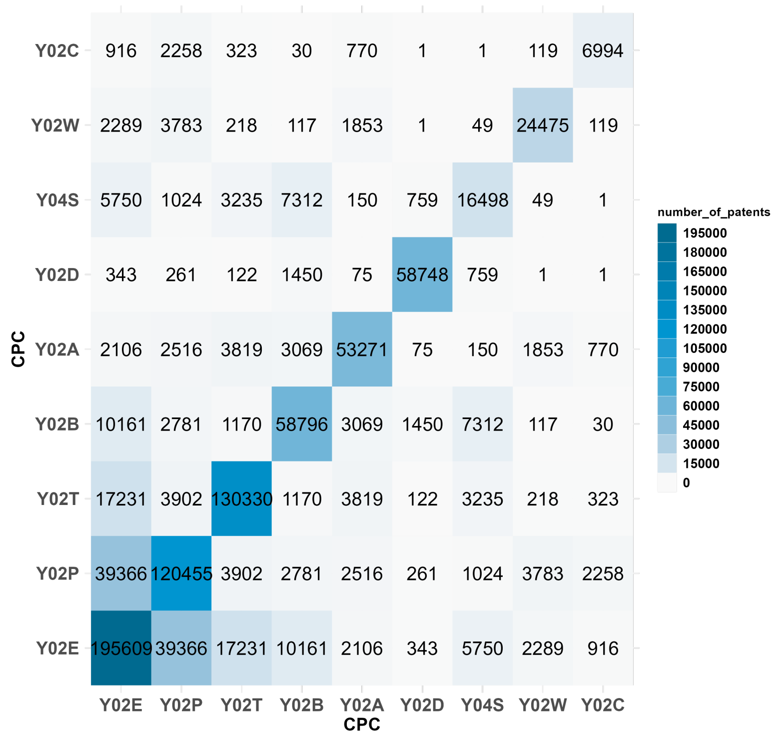
In order to identify the main constellations of technologies of the green domain at the aggregate level and to provide for a first assessment of characterization of the twin transition, we look at the aggregate and static convergence between the green and twin technologies. We compute the co-occurrence of each pair of macro-category within Y02 plus Y04S in Figure 3a. The main diagonal shows the number of patents in each CPC sub-class in descending order from the left corner. Out of the diagonal, the matrix counts how many pairs of CPC_i in rows and CPC_j in columns occur. The dominant blocks Y02E, Y02T and Y02P are co-occurring the most among them. Despite the number of patents in Y02D is 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). Figure 3b shows the normalized co-occurrence matrix with respect to the shares of total number of patents in each subclass. Patterns are confirmed: despite 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 the 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 subclass. Overall, the level of "contamination" of "supposed twin" technologies with the green dominant blocks turns out to be extremely limited. Figure 4 disaggregates co-occurrences by decades to see whether time trends are detectable. The above results are actually robust to time disaggregation for both digital categories Y02D and Y04S. The increase in patenting in ICTs aimed to reduce their own energy use (Y02D) is evident across time, but it still does not co-occur with the dominant blocks of technologies of the green transition (even in recent years). If any, with regard to Y04S, a weak increasing time trend in the above discussed co-occurrences can be single 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 The identification of the twin transition as a possible technological trajectory

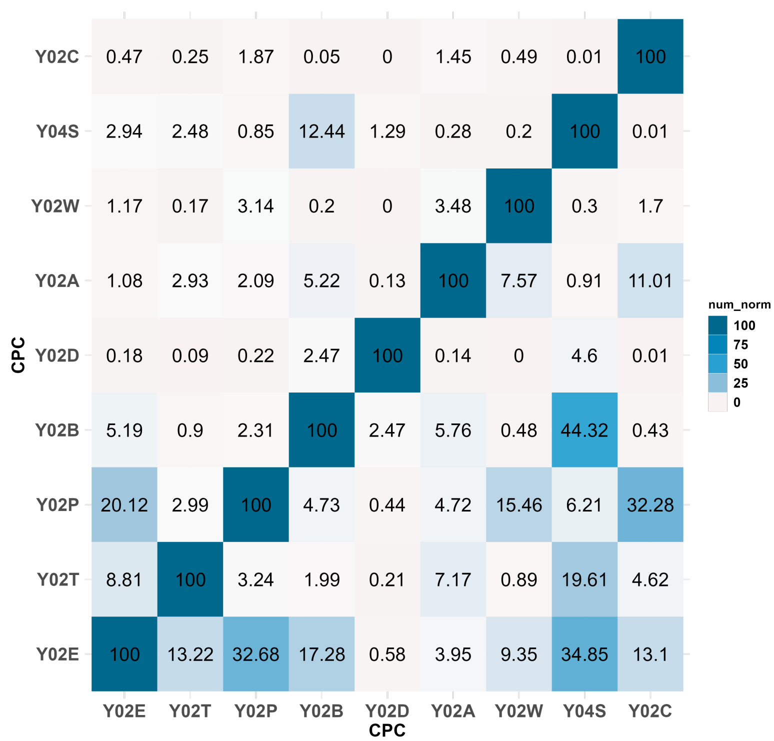
To understand to what extent the twin transition may constitute a new technological trajectory characterised by the convergence of green and digital technologies, in this sub-section we look at the identification of constellations of technologies at the micro and dynamic level, delving into the technological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

In more detail, we analyse 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 block and we compute the rolling mean of the frequency of co-occurrence of all other CPCs by year. We compute the mean and we look at which CPC appears at least for one period above the mean, paying particular attention to the digital CPCs: Y02D and Y04S. The top panel in Figures 5, 7 and 9 show the constellations of technologies aggregated by colour 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: a decreasing (in red) and an increasing one (in blue). Each sequence can be defined as a *development sub-block* 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 considered but they start and keep 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). With no surprise, in line with the establishment of the ICT paradigm, electric/electronics and energy related technologies are common to the uprising 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 average trend. The definitions of all CPC labels in the figures can be found in Table A2 in the Appendix.

Secondly, we analyse the alternative HHI indexes specifications and test the counterfactual scenarios, to understand whether the digital dimension is part of the constellations of technologies driving the changes



(a) Absolute number of co-occurrences across sub-classes.



(b) Share of co-occurrences across sub-classes.

Figure 3: Identification of macro constellations of technologies.

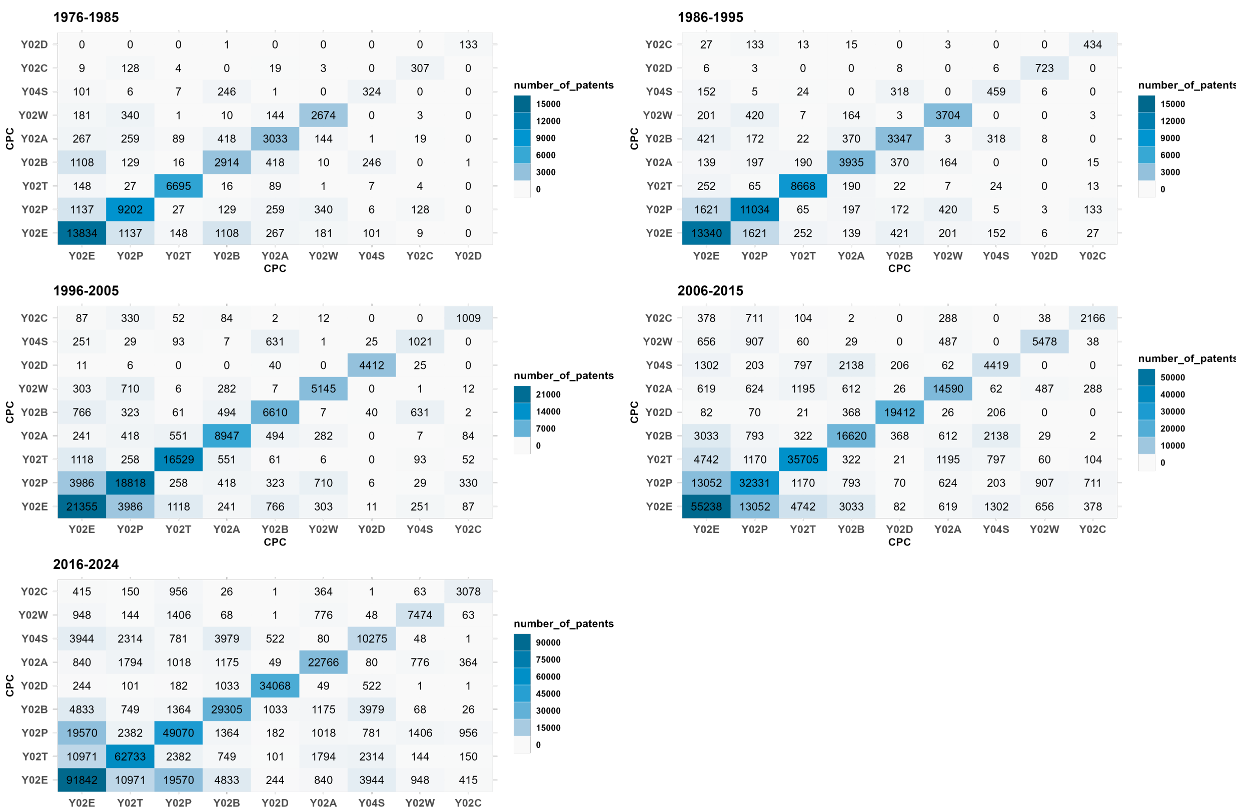
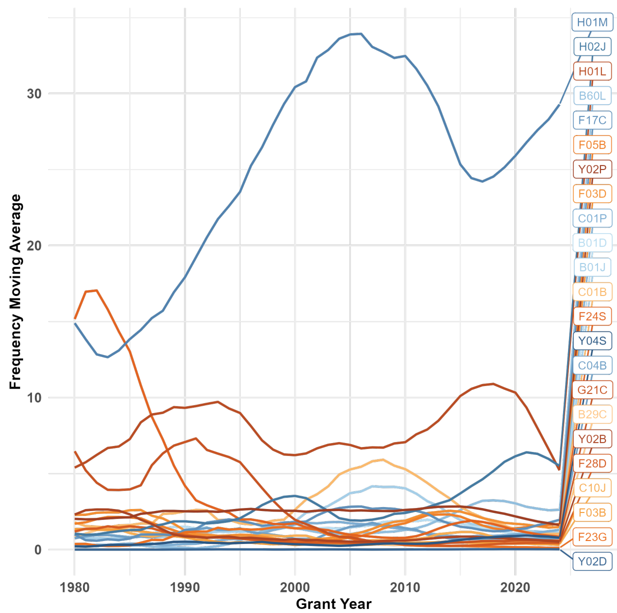


Figure 4: Co occurrence matrix across sub-classes by decade

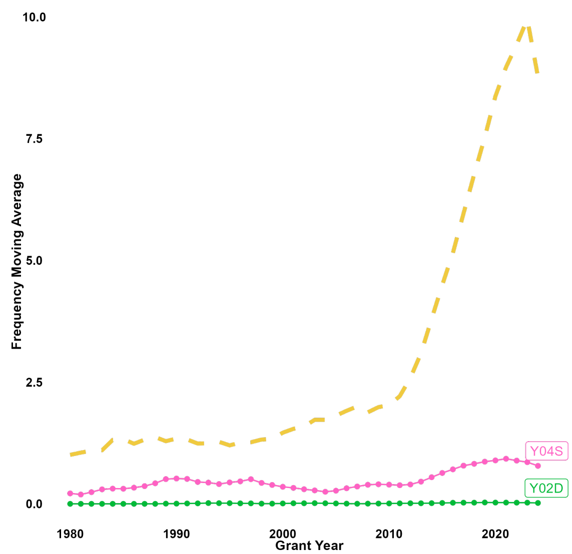
in the nature of each dominant block. The proposed analysis allows to detect to what extent the digital dimension enters the technological nature of the key technologies of the green transition and to identify the nature of the alleged twin transition as a technological trajectory (either widespread or localized, see Section 3). We show the analysis for each dominant block separately.

5.2.1 Energy

Figure 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 as circuits arrangements for energy supply (H02J) and propulsion of electrically propelled vehicles (B60L) is evident. Despite the co-occurrence in mitigation technologies against climate change in production or processing of goods (Y02P) has decreased its co-occurrence (in red), the trend is stable. Even if Y04S and Y02D have grown in co-occurrence over time (in blue in the top panel), we can see from Figure 5b that the co-occurrence is below average and it is negligible for Y02D. The co-occurrence of Y04S is small but positive and increasing since the first years.

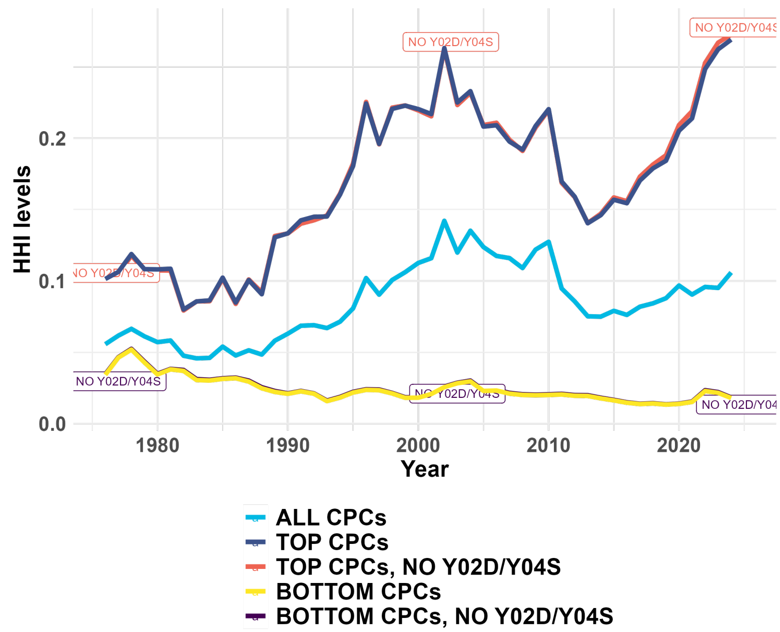


(a) CPCs Co-occurring above the mean for at least one period, Y02D and Y04S.

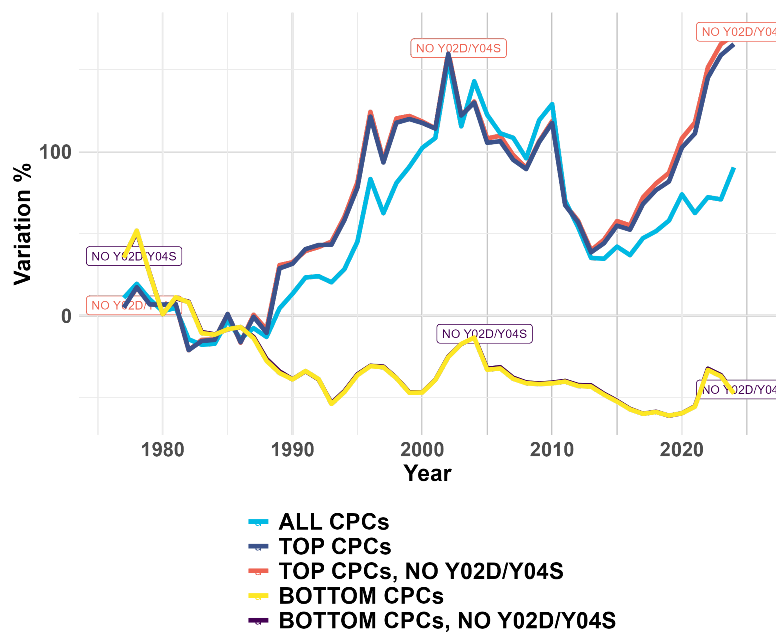


(b) Co-occurrence of the twin CPCs. Mean in yellow.

Figure 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).



(a) Alternative specification of HHI considering CPCs above and below the mean



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

Figure 6: HHI and counterfactual scenarios for Y02E.

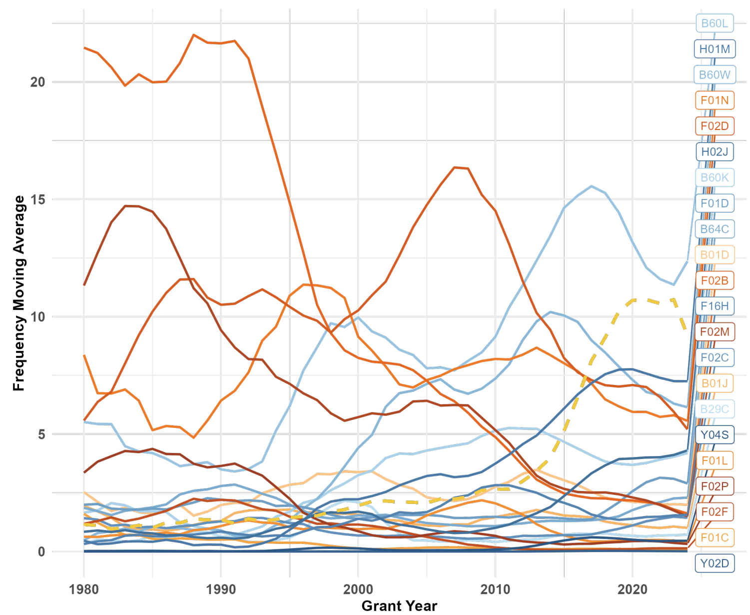
Figure 6a shows the alternative HHIs for the development block Y02E. It shows the Y02E block to be highly complex even considering only the top CPCs (in blue), since it reaches 0.3 points, with 1 of maximum concentration. Excluding Y02D and Y04S doesn't change the pattern (in red). The overall HHI (light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

Figure 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 (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, that is the opposite behaviour of the total HHI with all CPCs (light blue) and the top CPCs (blue). This outcome suggests the top CPCs drive the concentration dynamics. By removing the digital CPCs (red), the variation doesn't change, highlighting the fact that despite they marginally increase in co-occurrence over time (especially Y04S in Y02E, see Figure 5), they are not key in driving the concentration patterns. This is true also even when excluding the digital dimension from the HHI with the bottom CPCs (purple). 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 low complexity, because the dominant block is prevalently populated by a bunch of technological fields.

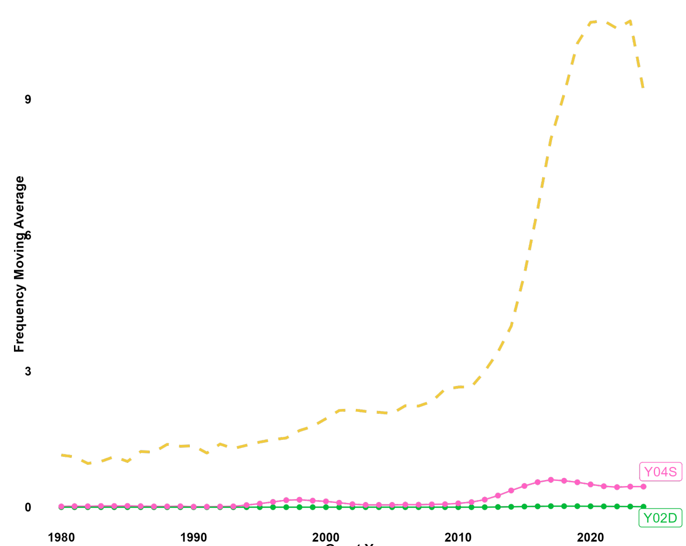
5.2.2 Transportation

The second dominant block of the green technological domain is mitigation technologies in transportation. From Figure 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 Figure 7b) despite they are both increasing in co-occurrence over time (in blue in Figure 7a, the top panel of Figure 7).

Figure 8a provides for the comparison of the different HHI specifications for Y02T. The HHI computed with the top CPCs (blue) mirrors the trend of the HHI with all CPCs (light blue) and despite 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. In the last years, concentration increases, highlighting the top CPCs to gain more shares, while looking at the HHI with only bottom CPCs (yellow) the concentration decreases. Removing the digital shares does not change concentration levels, neither from the top HHI (red) nor from the bottom HHI (purple). Looking at Figure 8b we see that the variation of the HHI with all CPCs and top CPCs 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) and without (purple) digital CPCs, have different upswing phases. The variation for the HHI index with bottom CPCs behaves exactly the opposite with respect to the all CPCs and top CPCs HHI, confirming the counterfactual result for which top CPCs drive the changes in concentration. This outcome holds also when digital CPCs are excluded (red), highlighting the role of the top CPCs and not of the Y02D and Y04S.

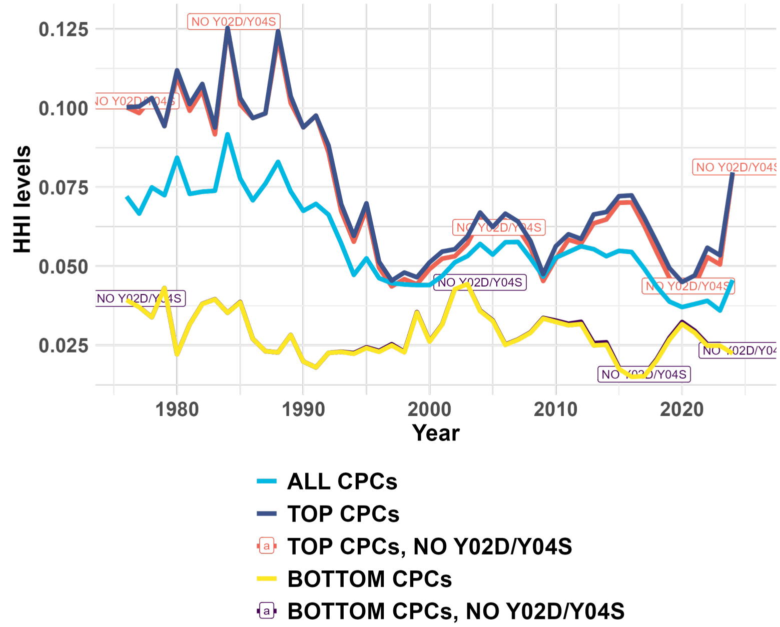


(a) CPCs Co-occurring above the mean for at least one period, Y02D and Y04S.

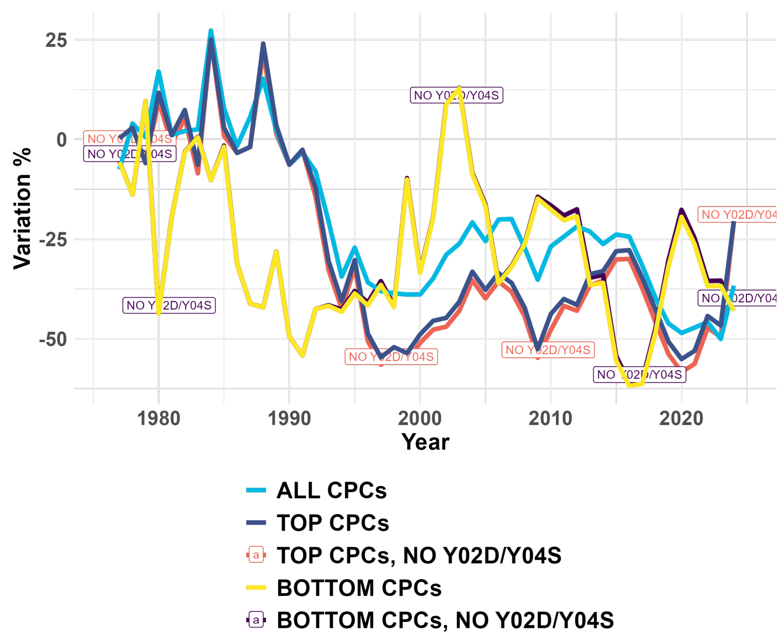


(b) Co-occurrence of the twin CPCs. Mean in yellow.

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



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



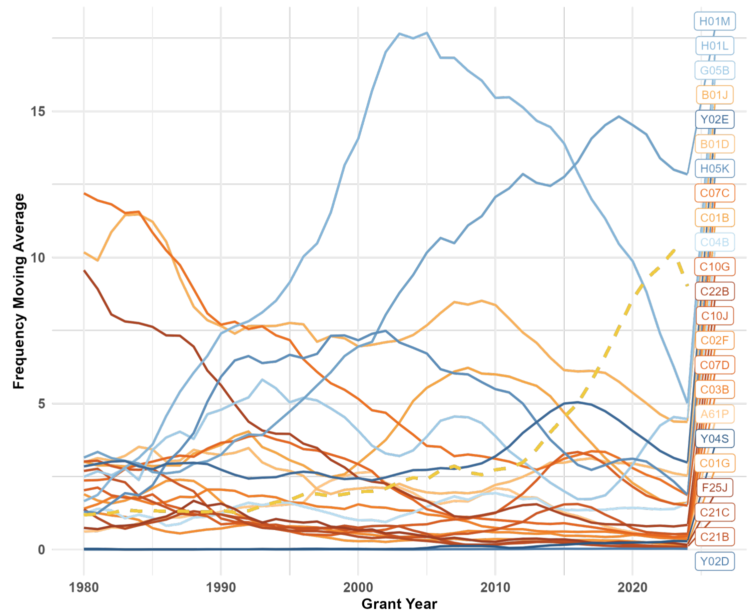
(b) Baseline variation of the HHI with all co-occurrent CPCs and counterfactual specifications.

Figure 8: HHI and counterfactual scenarios for Y02T.

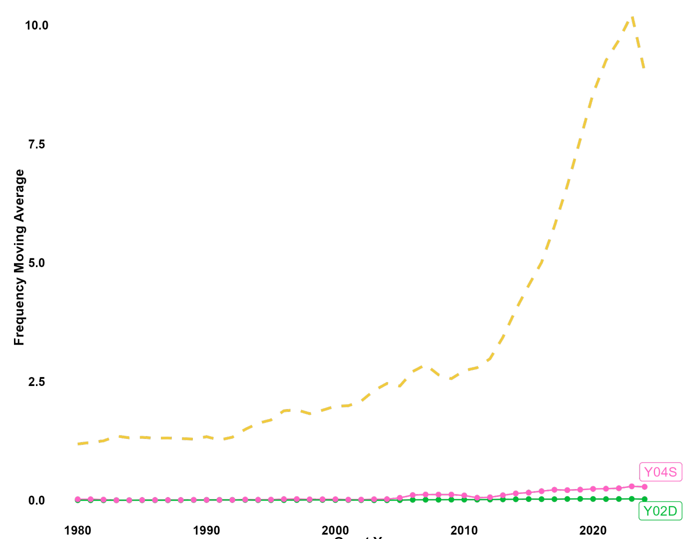
On the whole, the "supposed" twin technologies seem to play a negligible role in the evolution of green technologies aimed to mitigation against climate change in transportation.

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. Figure 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 until reaching the maximum in 2005 and then decreases 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), the "supposed" twin transition co-occurrence is around zero and it starts quite late in time (close to zero and always below the yellow -average- line in the bottom panel Figure 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, as e.g. B01J, B01D, C22B).

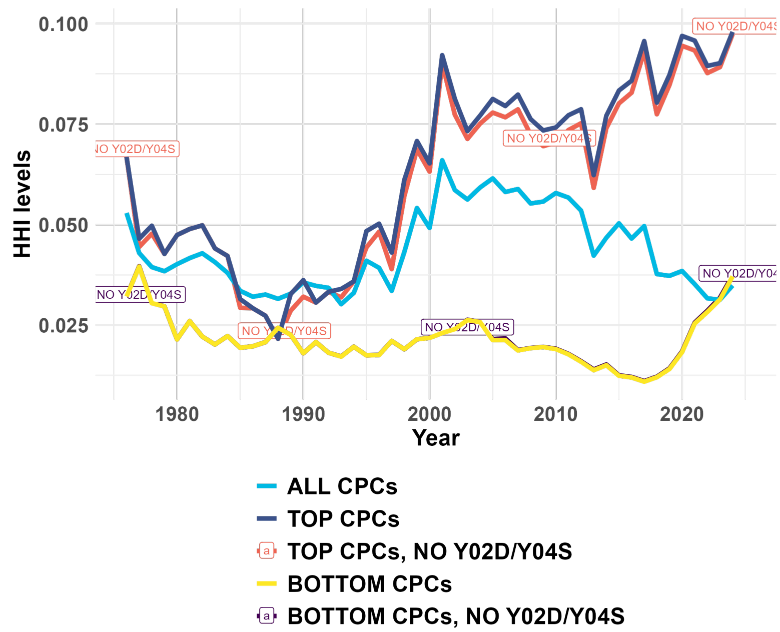


(a) CPCs Co-occurring above the mean for at least one period, Y02D and Y04S.

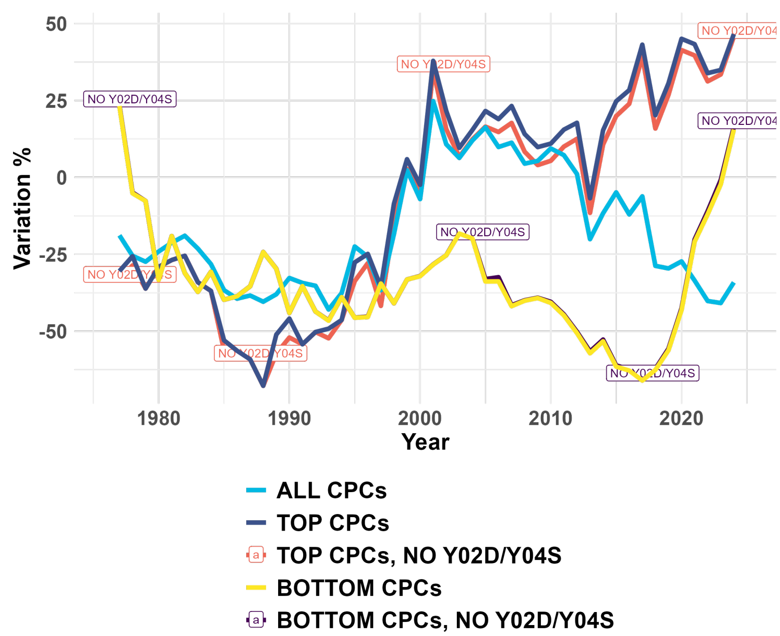


(b) Co-occurrence of the twin CPCs. Mean in yellow.

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



(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 10: HHI and counterfactual scenarios for Y02P.

Figure 10a shows the different specifications of the HHI. The Y02P block is also very complex, the HHI reaches a maximum of 0.1 with respect to maximum concentration of 1. When computing the HHI with the top CPCs (blue) and including Y02D and Y04S, concentration is higher and has an opposite behaviour with respect to the baseline HHI computed with all CPCs (light blue). The HHI increases since 2010, while the baseline HHI decreases. This pattern is confirmed by looking at the variation in Figure 10b, highlighting the top CPCs are gaining shares, the variation is mainly positive after 2015. At the same time, both in the HHI and the variation excluding the digital dimension (red), the concentration decreases more than for the other dominant blocks Y02E and Y02T (see 6a and 8a). The counterfactual scenario is confirmed also for this dominant block, since the HHI specification excluding the top CPCs, i.e,. the HHI with the bottom CPCs (yellow), have different upswing phases with respect to the baseline HHI including all CPCs (light blue). The counterfactual is robust to the exclusion of the digital CPCs (purple). The variation is positive and steep in the last years. Also the variation of the HHI with top CPCs (blue), it has different upswing phases than the baseline 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 and, among the bottom CPCs, there are other CPCs increasing co-occurrence and driving the final upswing phase. Despite there is an increase in concentration both in the bottom and the top CPCs specification, the fact that bottom CPCs are more may drive the concentration when computed with all CPCs down (according to Ukav (2017), the smaller the share of each technological domain, the lesser it counts and if there is a large number of technological domains with equal volumes, the HHI approximates 0). Also looking at Figure 9, we can see that despite several CPCs in 2024 have still a higher share than in 1976, they are decreasing over time and more CPCs that were above average are declining, being mainly H01M the only CPC keeping its top position.

Regardless 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 doesn't change the scenarios, highlighting they are not driving concentration dynamics. This is true also 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 production and processing of goods, as in transportation and in energy. The counterfactual scenarios suggest the "supposed" twin transition not to be timely and intense and thus not reflected into the start of a pervasive 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 and static level (see Figure 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 Figures 5, 7, 9).[4]

All in all, there is a lack and 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 below average, since it relates to ICTs having an impact on other areas as systems integrating technologies for power network operations. This is especially true for the technologies related to the energy sector (Y02E) and more obvious in the last decade. This may be the outcome of the evolution of the energy-saving heuristics embedded in the ICT 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 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.

On the whole, the twin transition cannot surely be considered as a "widespread technological trajectory". If any, it can be (partially) detected as a "localised niche" within the green technologies related to the energy sector.

Interestingly enough, patenting activity is higher in Y02D than in Y04S, but Y04S co-occurs more with the green dominant blocks.[5] Therefore, even from this perspective, we may derive that the ICT paradigm is not developing in the twin suggested direction since it is patenting more in ICTs as green products rather than ICTs that may help other sectors to become sustainable.

This interpretation is supported also when looking at top-applicants behind twin transition patents and comparing them with top-applicants in green patents. 13.66% of applicants patent in green technologies and in twin applications as well.[6] Figure 11 shows the share of patents for each dominant block Y02E, Y02T, Y02P and twin applications Y02D and Y04S for the top 20 firms by patenting activity. The firms are ordered by numbers of patents. We detect that there is an overlap only for ICTs having an impact on other areas, systems integrating technologies for power network operations (Y04S), while only ICTs firms patent in ICTs aimed to reduce their own energy use (Y02D). For instance, the top applicant is Toyota[7] 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

[4] If we consider a wider selection of digital technical traits extending the analysis of co-occurrences to the DIGITAL CPCs (see the Appendix), we can notice that only G05B-control or regulating systems in general- is co-occurring above average and increasingly within the production and processing of goods block (Y02P, in blue in Figure 9a). The co-occurrence of G05B may be motivated by the fact that the block of Y02P is constituted by technologies aimed to reduce GHG emissions in manufacturing, thus it may relate more to the nature of process innovation becoming more digital over time regardless of the green and "twin" characterization.

[5] We remind the reader of the fact that Y02D technologies are ICTs aimed to reduce their own energy use, thus they are green products of the ICT sector, while Y04S technologies are ICTs having an impact on other technological areas, mainly process innovations that can be adopted by other sectors to be energy efficient.

[6] 6,855 firms over a total of 50,180 applicants patenting for green technologies.

[7] Toyota is the first applicant with 2.6% of overall patents, that corresponds to 12,648 patents over 481,685. By

in twin applications that concentrates in the Y04S twin category appears as a complementary activity by giant conglomerates as General Electrics in the energy sector and the automotive industry as Toyota, Honda and Mitsubishi; and electrical components manufacturer (mainly batteries) as Siemens. Patenting in Y02D emerges as product innovation activity of ICT companies (see Section 2)[8] as Intel, Qualcomm, Samsung Electronics and IBM. At the same time, ICT companies are among the top applicants in mitigation and adaptation technologies against climate change together with cars manufacturers, but the patenting activity is mostly concentrated in green ICTs (Y02D, in green in Figure 11). The other technological category to which patents of ICT firms relate the most is production and processing of goods (Y02P, in purple), supposedly ICT process innovations for manufacturing processes. Overall, each company patents the most in the technological category prevalently related to its industry core activity (transport Y02T for players in the automotive sector in 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 its 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 for which there is not an interweaving between the green and the digital domains, since key innovators in the green technologies are not innovating in digital applications. We may derive that ICT companies innovating in green ICTs relates to the development of energy saving heuristics of the ICT paradigm and Y02D technologies are ICTs becoming more green, while we do not have evidence that green technologies are becoming more digital, shaping a twin path. Of course, green ICTs as product innovations of the ICT sector may be adopted as process innovations by other firms in other sectors to reduce emissions, given the co-occurrence with the Y02P category. This aspect of investigation is out of the scope of this paper and can be pursued as a possible future development of the current analysis.

matching firm data we loose some patents' observations, from 560,720 to 481,685 that corresponds to the 85.9% of the original patent selection. It emerges there is a large number of players patenting in green technologies, as we see from Toyota being the first applicant for the number of patents but that corresponds only to 2.6% of overall patenting activity.

[8]The core sectors of the main ICT applicants are: Semiconductor and Other Electronic Component Manufacturing (NAICS 3344, Intel); Communications Equipment Manufacturing (NAICS 3342, Qualcomm and Samsung Electronics), Computer Systems Design and Related Services (NAICS 5415, IBM)

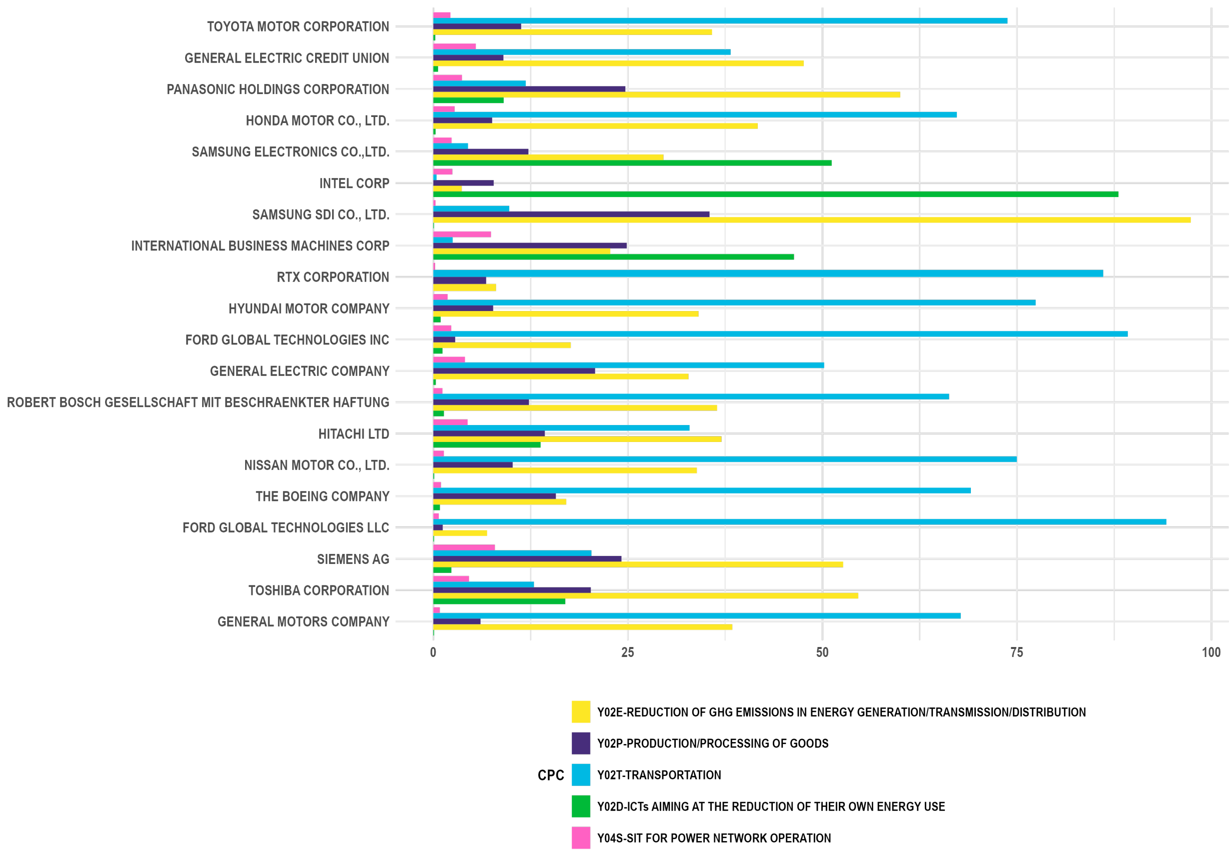


Figure 11: Share of patents by CPC of the top 20 patenting firms in the green and twin domain.

6 Conclusions

The green and the digital transitions are two of the main transformative processes of our economy. To challenge the climate change emergency, a strong policy push is forwarding the convergence of the two transitions into a unique one, where digital technologies are identified as key to reduce emissions. In this paper, we try to detect whether this strong policy push for a twin transition is reflected in the technological domain. Using patent data, we identify the dominant blocks of the green transition and look to what extent the digital dimension enters the green technological domain. In so doing, we are able to understand whether there is a convergence between the two technical fields and to what extent a new technological trajectory (either widespread or localised) can be detected. In addition, we look at the nature of the technologies of interest in terms of complexity and combination of different knowledge sources.
The main limitation of the paper concentrates on well known limitations of using patent data (Hall et al. (2001)). Moreover, alternative indexes could be used to compute concentrations, as the Entropy Index that overcomes the limitations of proportionality of weights to size of HHI (Ukav (2017)).

We find that technologies reducing GHG emissions in energy generation, distribution and transmission;

mitigation technologies in transportation and production or processing of goods are the main dominant blocks within the green technological domain. ICTs reducing their own energy use and ICTs having an impact on other technology areas are not relevantly part of the main constellations of technologies of the green technological domain. All technologies of interest emerge as complex, with different rates of knowledge recombination, as measured by the HHI.

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

On the whole and for the time being, the "twin transition" should be considered just a policy flagship with its correlated wishlist realized only and partially in some technological niches within the energy sector. Policy makers should be aware of this empirical evidence and - instead of evoking the twin transition as an ongoing process – they should promote those institutional changes that are crucial to increase the (at present very weak) match between green transformation and the digital technologies (Perez (1983); Perez (2016)), if relevant to face climate change challenges.

Implications of our study go beyond the relevance for the policy agenda, and challenge at a deeper scale the relationship between technology and society, and the more general premises of relying on "exogenous" technological solutions to solve human and productive based catastrophes, as the climate crisis. Given the assessed patterns, we do not identify any endogenous technological euphoria of existing players towards overall decarbonization. For example, we clearly see the lack of big oil companies as top players in the patenting activity of climate change mitigation technologies (see Figure 11); together, we do not see clear emerging shifts towards specific technologies, but rather diversified and heterogeneous efforts. Our evidence in fact depicts a story of a timid incremental path towards technologies meant to mitigate the climate crisis, revealing the lack of bets of private actors in market rewards. Absent market rewards, economics 101 defines the emergence of market failures: however, beyond market failures, it is clear that the current fragmented and simplistic policy directions are not able to secure enough critical innovative efforts towards a "technological singularity" able to solve the climate crisis. The politics behind technological generation has to come back at the centre of the stage and of the analysis, also to avoid the creation of expectations hardly verified in empirics.

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Appendix

As a robustness test, for all dominant blocks Y02E, Y02T and Y02P we check the behaviour 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 (OECD, 1994); (Wagner, 2006); (Breschi et al., 2003)). 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 behaviour of the HHI, and its temporal change, are completely unaffected when looking at the trend of such codes, while only the overall level of concentration is slightly reduced. This is the mechanistic 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, signalling; G09B, educational or demonstration appliances; appliances for teaching or communication with the blind, death 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 cryctographic 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.

CPC	Definition	Additional specifications	Green & "Supposed" 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 subclass covers information and communication technologies [ICT] whose purpose is to minimize the use of energy during the operation of the involved ICT equipment	"SUPPOSED" TWIN
Y02E	Reduction of GHG emissions related to energy generation, transmission or distribution		GREEN
Y02P	Climate change mitigation technologies in the production or processing of goods	This subclass 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
Y02T	Mitigation technologies related to transportation		GREEN
Y02W	Mitigation technologies related to wastewater treatment or waste management		
Y04S	Systems integrating technologies related to power network operation, ICT for improving the electrical power generation, transmission, distribution, management or usage (e.g. smart grids)		"SUPPOSED" TWIN

Table A1: Main CPCs at four digits of the patent selection and description. Source: Cooperative Patent Classification - Table

CPC sub-class	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; APPARATUS THEREFOR
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; ELEMENTS/COMPONENTS THEREFOR
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

Table A2: Definitions of the CPC in development sub-blocks