Constellations of technologies in a green universe: technological patterns of the twin transition

63rd ERSA Congress

Regional Science Dialogues for Peace and Sustainable Development

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Extended abstract

The climate change is one of the main emergencies our society is facing and the urgent need for a radical transition is challenging the economy. The conversion of the production system is crucial to achieve these targets and climate change mitigation and adaptation technologies are at the core of the ecological transition.

The technological progress of the last decade is also characterized by the digitalization of processes and products. Other than being parallel, the ecological and the digital transition are overlapping in what has been defined a *twin* transition. The technologies of the twin transition are both digital technologies helping at the decarbonization of the economy (e.g. devices monitoring emissions) both new vintages of climate change mitigation and adaptation technologies with digital technical traits (e.g. emissions' capturing technologies, Muench et al. (2022)).

The twin transition could possibly represent a new energy and technological revolution. Since the use of coal with the British Industrial Revolution starting in the mid 18th century, the main phases of the capitalistic system found on technological revolutions characterized

by the exploitation of *core inputs*, as steel, coal, oil and natural gases (Freeman and Louçã (2001)). Each phase has implied a continuous increase in the need for energy sources and the development of energy conversion and diffusion mechanisms has lead to several energy revolutions (Kander et al. (2014)). The use of coal has been intensified with electrification, heavy industry and chemicals since the 1890s; oil has been the core input for the development of the automotive, aircraft and synthetic material industries, for the expansion of the mass production and mass consumption since the post Second World War (Freeman and Louçã (2001)). Since the 1970s with the information and communication technologies (ICT) revolution, on the one hand energy consumption has increased by the large use of ICTs, on the other hand the use of energy required by ICTs has been much lower with respect to the previous technological revolutions thanks to the development of energy saving devices (e.g. smart grids, Kander et al. (2014)). Indeed, *twin* technologies can already be identified in the ICT technological revolution (Perez (1983), p.373).
On the one hand, the exploitation of fossil fuels and the related technological innovations in each phase of capitalism has spurred the development and growth, albeit asymmetrically, of countries (among others Abramovitz (1986); Fagerberg (1987); Dosi et al. (1990); Dosi, Riccio, and Virgillito (2021)). On the other hand, the advancement of the capitalistic system towards targets of persistent growth has lead to the degree of climate change emergency we are dealing with today. In fact, the *degrowth* perspective argues that even if aimed at zero CO2 emissions, the *green growth* based on technological progress is still not sustainable as long as it aims at a process of growth (Giorgos et al. (2012); D'Alessandro et al. (2020)). Interestingly enough, developing countries are the regions expected to suffer the consequences of climate change the most (among others Mendelsohn et al. (2006); Palagi et al. (2022)).

The recursive extraction and combustion of fossil fuels through history have been and still are the main causes for the high level of GHG emissions and global carbon dioxide (CO2) emissions today (IPPC (2023)).[1] Electricity and heat, transport and manufacturing and constructions are the top three sectors for the level of GHG emissions[2] and they are the most targeted by the transition (other than buildings, agriculture, land use and waste).

[1]Coal accounts for 46.21% of CO2 global emissions in 2022, oil for 34.74%, gas for 14.77%. Data Source: Global Carbon Budget (2023) – with major processing by Our World in Data

[2]Electricity and heat are responsible for 32.17% transport for 17.16% and manufacturing and constructions 12.65% of global GHG emissions in 2019. Data Source: Climate Watch (2023) – with major processing by Our World in Data

The conversion of production activities in these sectors are inducing several implications on the labour market as well. According to the ILO framework (IRENA and ILO (2022)), the *green paradigm* is supposed to be labour-friendly, since it entails mainly product innovations assumed to foster employment both in the up and the downstream sectors. However, such framework does not consider the possible labour-saving nature of green technologies, which are also productivity-enhancing process innovations (Vivarelli et al. (1996); Vivarelli (2022); Dosi, Piva, et al. (2021)) and *twin* technologies with digital traits, both usually labour-saving (Rughi et al. (2023)). The green paradigm framework builds on the task based approach which does not consider the nature of technologies and the features of the innovation in general, thus it is insufficient to address the complexity of the process (Calvino and Virgillito (2018)). An in-depth analysis of the employment implications of the twin transition is not a matter of this paper, but delving into the features of technologies is crucial for the understanding of the possible dynamics of this technological paradigm.

We build on the evolutionary framework that analyses past technological revolutions looking at the co-existing paradigms of co-evolving clusters of technologies in different sectors (Freeman and Louçã (2001); Freeman (2019); Nuvolari (2019)). The analysis focuses on the core clusters of technologies of the twin transition and the evolution of their technological patterns over time, identifying the co-occurrences with clusters of different technological domains, the most relevant knowledge they build on, the pervasiveness and diffusion across sectors.

The evolutionary framework has provided for several definitions of technological clusters and paradigms and for the unfolding of past technological revolutions (Schumpeter (1939);Dosi (1982); Perez (1983); Nelson (1985);Freeman and Perez (1988); Dahmén (1988); Bresnahan and Trajtenberg (1995); Freeman and Louçã (2001); Silverberg (2007)).

For instance, Freeman and Louçã (2001) define technological clusters as constellations of technologies, that include not only new artefacts but also new industries, new infrastructures, services and organizational innovations. Their diffusion occurs over Kondratieff waves, five long term fluctuations of the economic cycle (Kondratieff and Stolper (1935)). The main constellation of technologies of the first wave (1780s-1848) has been the water-powered mechanization of industry, of the second wave (1848-1895) the steam-powered mechanization of industry and transport, of the third (1895-1940) the electrification of industry, transport and the home, of the fourth the motorization of transport, civil economy and war (1941-1973), and of the fifth (since 1973), the computerization of entire economy (Freeman and Louçã (2001), p.141). Building on the work of Perez (1983), according to the authors each Kondratieff wave is characterized by the *wide availability of cheap core inputs* (for instance, oil, gas and synthetic materials for the fourth Kondratieff wave) on which several combinations of factors and *constellations of technologies* develop (innovations in cracking, automobiles, diesel engines, tractors, tanks, aircraft, consumer durable, new transport infrastructures as motor highways in the US); both in *leading sectors* (oil and the automobile sector) and *induced branches* (as supplied components, washing machines, repair, petrochemical and synthetic material industry); *organizational innovations* (as Fordism, the moving assembly line approach, the standardization of components, subdivision of work tasks, production planning and control, mass production and mass consumption) and *other subsystems* as the *social* one (mass culture) co-evolve with the technological subsystem leading to a structural transformation. Each technological revolution is determined itself by *socio-institutional changes* from the need for a structural transformation and leads to a new structural change of the current setting itself, wave after wave.

Taking a different perspective, technological revolutions may not strictly follow waves but may constitute development blocks, surging from autocatalytic connections and interactions across different clusters of technologies (Nuvolari (2019); Staccioli and Virgillito (2021)). Dahmén (1988) defines a development block as the balance between technological, technical, economic and related factors complementarities and structural tensions, for instance the lack of organization limiting the efficient production of a new artefact in early stages of the innovation process. Development blocks spur from transformations, an example is the *"closing of old sources of raw material and energy"*(Dahmén (1988), p.4).

Can we detect some similarities of the twin transition with these characterizations of the previous technological revolutions? We may presume that the twin transition builds on the exploitation of *cheap and widely available core inputs* (renewable energy sources as hydrogen, solar and wind power, minerals) on which several *constellations of technologies* have been developed (to name a few solar panels, wind turbines, hydrogen technologies, batteries for electric vehicles); in *leading sectors* (energy and transport) and in *induced branches* (as the production of components, services, infrastructures for public mobility) and co-evolving *organizational innovations* (circular economy), *social innovations* (in consumption and living), and *institutional changes* can be identified. This technological revolution in particular surges by institutional changes and specifically by a policy push to reduce CO2 emissions. At the same time, the surge of different constellations of technologies together with complementary organization, social and institutional innovations seem to respond to the transformation *to close with old sources of energy* (Dahmén (1988)) and shaping a new development block more than constituting a new long wave. This paper has the aim to delve into such patterns to understand the inner nature of this new technological phase, to identify possible outcomes of the transition and to better frame and guide the policy interventions needed (Nuvolari (2019); Taalbi (2021)).

To this purpose, Pearson and Foxon (2012) analyse the low carbon transition under a comparative perspective with the First Industrial Revolution with respect to the required scale of changes in technologies and institutions and to the consequent benefits for the economy that characterize both the ecological transition and past revolutions. Mathews (2013) claims renewable energy technologies to constitute a second phase of the fifth Kondratieff wave, overlapping with the ICT paradigm. Kander et al. (2014) analyse the three energy revolutions under an historical perspective and with respect to the co-occurring technological revolutions to discuss the energy transition by the deployment of renewable energy sources as a new energy revolution. Taalbi (2021) identifies and describes the evolution of three development blocks in Sweden between 1908 and 2016. He discusses the emergence and the evolution of renewable energy sources technologies, highlighting the crucial role played by public institutions and policy interventions. More contributions look at the knowledge on which green innovation builds. For instance Mazzei et al. (2023) find that firms in the automotive industry which are more innovative in brown technologies are also the most innovative firms in the electrification and hydrogen solutions in vehicles; Barbieri et al. (2020) analyse the different sources of knowledge recombined in the green technologies and they compare them with non-green ones in terms of complexity and novelty; similarly Quatraro and Scandura (2019) look at the impact non-green technologies have on the development of green ones, which emerge as a recombination of different sources of knowledge, and on how the involvement of academic inventors affect green inventions.

This paper embraces an historical perspective to analyse the evolution of technological patterns, adopting the definition of constellations of technologies (Staccioli and Virgillito (2021)). By looking at which other technological domains twin technologies relate, we analyse also the knowledge recombination effect and its evolution over time.

We try to answer the following research questions: which are the main constellations of technologies characterizing the twin transition? Which are the main clusters of technologies in terms of co-occurrences of other technical fields? Which are and how do the identified co-existent technological paradigms and past trajectories evolve? Can we detect a sort of long waves or development block characterization? In which sectors do these technologies penetrate? The answers to these questions allow us to comprehend and to further analyse the potential paths the twin transition may undertake. For instance, we believe this analysis to be crucial for the understanding of the labour market implications of the twin transition. We use patent data from 1976 to 2021 from the US Patent Office classified as climate change mitigation and adaptation technologies and twin technologies (ICT for improving the electrical power generation, transmission, distribution, management or usage and ICT aiming at the reduction of their own energy use). A selection of key words has been identified for a more comprehensive selection on twin technologies. We asses the existence and a classification of green and twin -green with digital traits- technologies; the pervasiveness by the identification of their sectoral penetration; the advancement by weighting for the "greeness" of the technologies by looking at the CO2 emissions by sector using input-output tables of the OECD's Inter-Country Input-Output (ICIO) dataset (Meng et al. (2018); Yamano and Guilhoto (2020)).

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