Understanding the evolution and impact of green technologies: insights from the hydrogen-based technologies

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Understanding the Evolution and Impact of Green Technologies: Insights from the Hydrogen-based Technologies

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Introduction

Technology is characterized by continuous changes – related to progress along a technological trajectory – which has been conceived as a succession of technological paradigms (Dosi, 1982). Tracing a technological trajectory allows mapping the steps behind the possible directions of technology development (Martinelli, 2012; Verspagen, 2007) as these steps are often influenced by path-dependent nature (Vergne, 2013; L. Wang et al., 2020) or by technological lock-ins (Dolfsma & Leydesdorff, 2009). The shape of a technological trajectory is sculpted by knowledge flow dynamics (Hung et al., 2022) that characterize the technical change (Acemoglu et al., 2012; Taalbi, 2020) and, through them, it is possible to obtain a dynamic comprehension of the direction of technical changes (Meyer, 2002; Peri, 2005). Stated differently, studying technological trajectories allows gaining a deeper comprehension of technical change by focusing on the evolutionary steps behind the establishment of a given paradigm (Dosi, 1982). In particular, assessing the knowledge flows that shape a given technological trajectory makes it possible to understand previous directions and forecast potential future technological advancements (Biondi & Galli, 1992; Hung et al., 2022; Toole, 2001; Verspagen, 2007). Still, it is worth mentioning that not all technology sectors have similar development paths as well as the related technologies.

Therefore, on the one hand, it is important to understand how technological change in a given domain manifests itself, alongside the knowledge flows that shape such technical change by relying on a dynamic approach (Hummon & Doreian, 1989; Verspagen, 2007). On the other hand, to explain the development paths of a technology domain, it is worth studying also the technological impact that its technologies could exert since not all technologies influence technological change in the same way. In other words, the role one technology plays in shaping future technological developments can vary greatly compared to another. This raises the question of what determines how much a specific technology contributes to the creation of new technologies (Grodal et al., 2023), i.e., what affects its technological impact (Veugelers & Wang, 2019). For instance, academic research has identified several factors that influence technological impact, including the depth of a firm's knowledge base, integration capabilities, and technological breadth (Coccia, 2009; Ning & Guo, 2022a; Singh, 2008; Veugelers & Wang, 2019). Still, scholars have suggested that a more nuanced understanding of technological impact requires examining its various dimensions. One approach considers whether the influence of technological change remains within the organizational boundaries of the inventing organizations or extends beyond them (De Noni et al., 2017; Harpaz & Meshoulam, 1997). Indeed, when organizations adopt and further develop technologies they did not originally create, it fosters innovation, drives down costs, and strengthens collaboration (De Noni et al., 2017; Teece, 1986). Another perspective explores whether a technology's impact stays within the domain in which it first emerged or extends to other fields (Abernathy & Utterback, 1978; Phene et al., 2006; Pironti et al., 2010; Sood & Tellis, 2005). As a result, the study of technological change, also with a focus on technological impact, should consider such distinct approaches.

When studying technical change and technological impact, green technologies have been especially of interest. Notably, these technologies constitute one of the most complex domains, i.e., the green domain, that presents heterogeneous aspects, for which it is relevant to understand the development and generation of knowledge flows of green energy technologies, being highly complex and resource-intensive tasks. Moreover, the number of countries setting ambitious greenhouse gas reduction targets is growing, along with interest in low-carbon hydrogen as a solution for hard-to-abate emissions. These emissions stem from sectors like aviation, shipping, heavy industry, and long-distance transport, where electrification faces high costs or technical challenges. As nations, including the EU, aim for net zero emissions by 2050, hydrogen, as a green technology, is emerging as a viable alternative due to its versatility, compatibility with current energy systems, and potential to replace carbon-intensive fuels. Despite significant hurdles, such as infrastructure demands and entrenched practices, the urgency to develop hydrogen-based solutions is rising.(International Energy Agency, 2019)

In addition, green domain is in constant evolution due to their intrinsic innovativeness (Aldieri & Vinci, 2018; Guo et al., 2020; Karimi Takalo et al., 2021; Tan et al., 2021), is inherently knowledge-intensive, and based on knowledge owned by several different organizations (Nemet, 2012a, 2012b). Moreover, technologies in the green domain are considered more complex in comparison to non-green ones (Barbieri et al., 2020), being the result of the integration of green and non-green prior technologies and with potential impact outside the green domain (Fusillo, 2023). It is therefore important to assess the technological impact not only in general terms (overall technological impact) but also specifically within and beyond organizational boundaries, as well as within and beyond the initial green domain (Barbieri et al., 2020, 2023). Finally, the global energy crisis, climate change, and pollution have brought worldwide attention to the urgence for new approaches to creating a sustainable future (Guo et al., 2020). Consequently, efforts in policy and innovation have been focused on investigating the emergence of green technologies (Griffiths et al., 2021; Tan et al., 2021), considered a key driver of technological progress in the near future, with the potential to positively impact the environment, economy, and society overall driving an ongoing surge of technological advancement (Guo et al., 2020; Longden et al., 2022). This thesis follows this rationale. In detail, this thesis focuses on an emerging set of technologies related to the green domain, as the Hydrogen-Based Technologies (HBTs), for which there is an increasing need to understand their trajectories and impact given their emergence as relevant solutions for the green energy transition and their inner complexity (Barbieri et al., 2020). Indeed, hydrogen has being considered as a key energy source attracting significant attention, and HBTs are anticipated to play a crucial role in the global shift toward zero emissions (Chen et al., 2011). Because of its unique properties and abundance (hydrogen makes up about 75% of all matter), hydrogen is seen as an ideal energy carrier (Vezirocjlu & Barbir, 1992) that can help drive the global shift toward cleaner energy. HBTs are considered green technologies, albeit non-green technologies contribute to their development, with the potential to positively influence economic growth (D'Angelo et al., 2022) and contribute to sustainability goals, especially when combined with other technologies (Cappa et al., 2022). Understanding the past, present, and future development of HBTs is both timely and critical, considering the socio-economic and technical environments in which they are evolving.

However, there is a lack of a wide overview of the HBTs from the perspective of technical change and technological impact. In particular, HBTs have been studied to the invention as level of analysis and have been examined their temporal trends (Ampah et al., 2023), geographical origins (Moreno-Brieva et al., 2023), and technical characteristics (Fusillo, 2023; Gerloff, 2021; Moreno-Brieva et al., 2023; Tan et al., 2021), while neglecting their evolutionary dynamics especially considering their entire chain. Therefore, analyzing these technologies from a holistic viewpoint permit to identify whether such technology represents a pivotal solution within the plethora of solutions that constitute a technological trajectory, and whether the associated technological trajectory includes or even originates from non-green energy technologies and their interactions. As a result, extant understanding of the development paths of green energy technologies remains scant both in a holistic overview and in a dynamic approach. Moreover, there is a lack in the analysis of the technological impact that these technologies exert. In particular, no previous studies have considered the different contributes within the technological impact. With this in mind, the present research addresses these gaps in three main phases that led to three distinct chapters.

First, given the absence of a comprehensive overview of the hydrogen technology chain, in the first chapter, "Mapping hydrogen-based technologies progress through patent analysis," I have provided a wide overview of HBTs by mapping their development trends. To do so, I have collected patent families (PFs) related to HB production technologies (317.089 PFs from 1930 to 2020) and PFs regarding HB storage technologies (62.496 PFs from 1930 to 2020) granted by multiple patent authorities, hence identifying a more comprehensive set on data than previous studies (Chanchetti et al., 2016; Chen et al., 2011; European Patent Office & The International Renewable Energy Agency, 2022; Ursúa et al., 2011). These data were analysed using patent analysis techniques. For instance, I have counted PFs per year to examine the yearly technology development in terms of patented inventions (Acs et al., 2002; Popp, 2002; Singh, 2008). Then, I have compared the patenting activity related to HBTs across countries so as to outline the most active countries in the development of HBTs. In addition, I have built on patent applicant data to analyze the development of HBTs at the organizational level. Relatedly, I have delineated the most active organizations in terms of number of PFs (Deyle & Grupp, 2005; Nawaz, 1986) related to hydrogen production and storage technologies. Finally, I have performed the aforementioned analyses on highly-cited patent families, by considering the normalized number of forward citations (Bornmann et al., 2013) as a proxy for the technological impact of an invention (e.g., Gambardella et al., 2008; Trajtenberg, 1990). I have then compared the analysis across the sample of highly-cited PFs and the remaining PFs.

Second, to explore the technological trajectories of green technologies from a dynamic perspective, the second chapter, "Unveiling the Trajectories of Green Energy Technologies: The Case of Electrolysis," examines the technological pathways within the electrolysis domain (as a subset of hydrogen-based technologies). Using Main Path Analysis, I have identified key trajectories of electrolysis technologies and validated the findings by situating them within the broader context of their Technology Life Cycle. Electrolysis technologies represent particularly suitable research setting within the broad range of HBTs (Dincer, 2012; Martinez-Burgos et al., 2021; Ursúa et al., 2011) and for the purposes of this chapter since examining their evolution also allows delving into the interaction between green and non-green energy technologies as a source of technologies in the green domain. On the one hand, the electrolysis of water is a core process for the production of green hydrogen, that is hydrogen extracted by the electrolysis of water using renewable electricity (Dincer, 2012); on the other hand, these technologies result from the recombination of green and non-green technical solutions from a range of fields (e.g. chemistry, material science, electronics). This setting also allows advancing extant research that has examined electrolysis technologies in terms of technical/functional aspects, neglecting their evolution from the perspective of technical change (Bhandari et al., 2014; European Patent Office & The International Renewable Energy Agency, 2022; Gerloff, 2021; Netherlands Enterprise Agency, 2020; Utgikar & Thiesen, 2006). From a methodological perspective, I have relied on a sample of 43,832 electrolysis-related Patent Families from 1987 to 2021 and made available by the IRENA and the European Patent Office (EPO)[1] that I have distinguished between green and non-green. I have then collected and used citation data to perform a Main Path Analysis to delineate the major trajectories of development of electrolysis technologies and analyze results of Main Path Analysis by looking at the Technology Life Cycle

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[1] The dataset was compiled by querying the EPO's Espacenet database – queries (based on patent classification codes and keywords) are provided in the supplementary material of the corresponding report (European Patent Office & The International Renewable Energy Agency, 2022). For each PFs, the dataset includes a range of metadata (e.g. EPO Family ID, earliest priority dates, International Patent Classification codes, assignees, inventors) as well as variables identifying the specific electrolysis process phase(s) of each patented technology. The latter was provided by an EPO expert examiner in the electrolyzer/hydrogen field together with IRENA experts tasked to identify and classify PFs through the content analysis of PF documents. Five groups of technologies relevant for the electrolysis were identified: cell operation conditions and structure, electrocatalyst materials, separators (diaphragms, membranes), stackability of electrolysers (stacks), and photo electrolysis. See https://intelligence.help.questel.com/en/support/solutions/articles/77000436699-coverage-of-the-fampat-database

model (Taylor & Taylor, 2012) to identify milestones in this development. Results pointed out that fundamental contributions to the development path of electrolysis technologies are represented by both green and non-green technologies, albeit green technologies are more prominent. Moreover, three phases of development in electrolysis Technological Life Cycle are identified, namely i) the application phase, where major developments concern membranes and hydrogen separation, as well as electrochemical systems; ii) the paradigm phase, which included inventions about hydrogen production through water electrolysis; iii) the generation phase, where pivotal technologies about the process of electrocatalysis emerge, hence signalling efforts in the direction of cost reduction and performance enhancement.

Third, redirecting the attention to technological impact, to provide new insights into the technological impact of electrolysis technologies, the third chapter, "Assessing the impact of the green technologies: analysis of the electrolysis setting," explores factors affecting the overall technological impact of electrolysis technologies, the extent to which electrolysis technologies lead to new green technologies (impact within the green domain), and the extent to which the impact in terms of new green technologies remains within the organizational boundaries of the inventing organization or extends beyond those boundaries. To do so, according to previous studies, I have adopted patent data used in the second chapter of this thesis to identify developed technologies and related impact, also in the specific green domain (Ardito, Messeni Petruzzelli, & Albino, 2016; Fusillo, 2023; Haščič & Migotto, 2015; Petruzzelli et al., 2011). In particular, patent citations offer indication about the knowledge sources on which the development of the technology may have relied (backward citations), and the impact of the technology on subsequent technological developments (forward citations) (Aristodemou & Tietze, 2018; Trajtenberg, 1990a; Waltman, 2016). Then, as antecedents of technological impact, in its different manifestations, I have considered three factors. The first relates to the extent to which a technology is based on green technologies as the prior art by counting the number of green backward citations (*Green Prior Art).* The second, instead, refers to the extent to which a technology is based on non-green technologies as the prior art by counting the number of non-green backward citations (*Non-Green Prior Art).* The third classifies a technology as either green or non-green through a dummy variable taking the value of one if a PF can be classified as green (*Green Technology)*, according to the WIPO Green Inventory, zero otherwise (Rivera León et al., 2018). The two former independent variables assess the knowledge search and recombination process used to develop a technology, while the latter captures the nature as green or non-green of the technology.

Results of econometric analysis indicate that the higher the adoption of green technologies as the prior art, the greater the technological impact in all of its forms, hence suggesting that following green technological trajectories pays off. Conversely, a higher adoption of non-green technologies leads to detrimental effects in terms of technological impact, suggesting that green prior art is more relevant than non-green ones. Still, this result cannot imply that non-green prior art should be neglected totally. The green nature of the technology is relevant for developing new green technologies, but its impact on the overall technological impact is not fully supported.

Figure 1 shows the overall structure of the thesis.

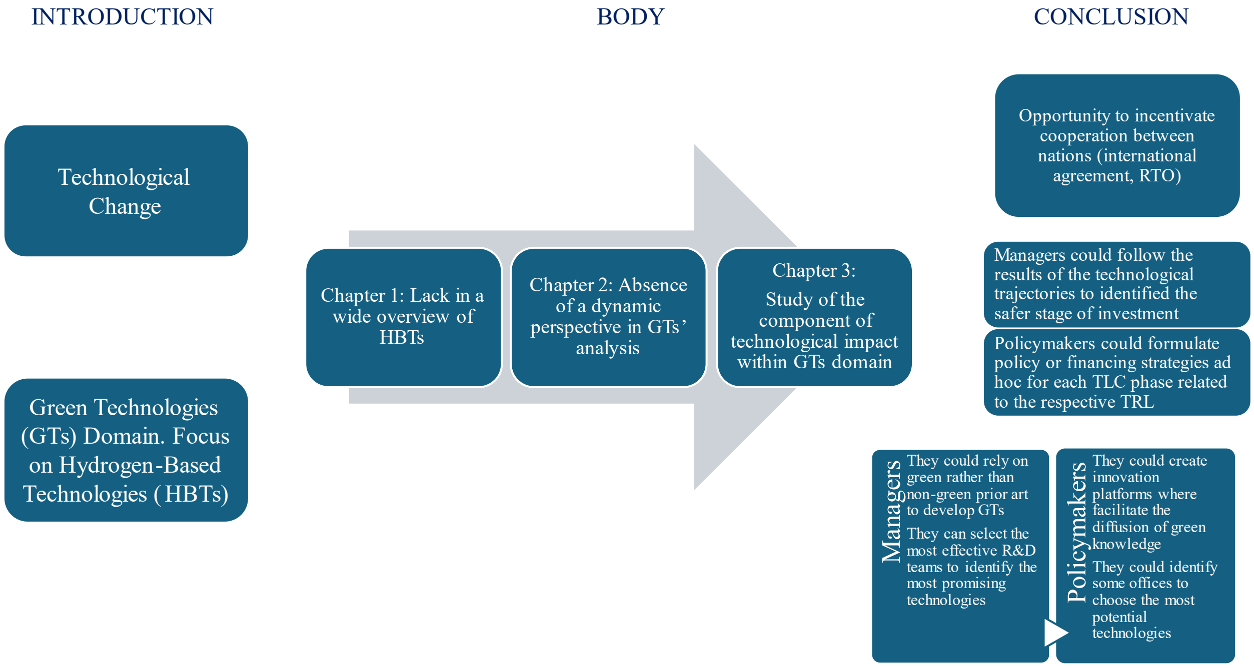

Figure 1. Thesis Structure

Mapping the Development of Hydrogen-Based Technologies (HBTs) through Patent Analysis

1 Introduction

Energy production has become an extremely topical issue. Geopolitical tensions, conflicts, and pollution have contributed to increasing pressure on governments, nations, and regions to develop and adopt production methods of green energy (George et al., 2016). Green energy is conceived as energy that is generated using natural sources such as biomass, solar power, wind power, hydropower, and geothermal energy (Tan et al., 2021). The increasing rate of technological development has also pushed policymakers and managers to engage in proactive planning for the development and adoption of green energy technologies (Guo et al., 2020; Tan et al., 2021). Within this context, hydrogen is one of the energy sources that is gaining considerable attention. Hydrogen-Based Technologies (henceforth, HBTs) are expected to play a decisive role in supporting the transition to a zero-emission world (Chen et al., 2011). As documented by the World Energy Council (2021), some countries have set long-term strategies for HBTs to replace established energy systems. These strategies have also contributed to shaping those of other countries. For instance, Japan's early commitment towards hydrogen has catalyzed interest in the Asian-Pacific region, with South Korea and Australia publishing their strategies shortly afterward. Germany was an early mover in Europe and contributed to pushing the EU hydrogen strategy during its presidency while in Latin America, Chile has moved with many neighbouring countries in the process of developing strategies for HBTs (World Energy Council, EPRI, & Pwc, 2021). About 95% of the hydrogen used on Earth (mostly for industrial purposes) is, however, obtained from methane reforming or from coal gasification, i.e., through production processes that generate a significant amount of carbon dioxide emissions (Hanley et al., 2018). As reported by the International Energy Agency (2019), low-carbon hydrogen may become cost-competitive only by 2030, while, at the same time, the development of infrastructures for hydrogen production, transport, and storage poses significant challenges to the uptake of this energy source in end-use sectors. While interest in hydrogen continues to be strongly linked with climate change ambition, there has been a noticeable broadening of the policy objectives to which hydrogen can contribute (International Energy Agency, 2019). These challenges, alongside the worldwide interest in hydrogen as an energy carrier, have led scholars to investigate and examine major development trends of HBTs (e.g., Hanley et al., 2018; Martinez-Burgos et al., 2021; Sazali, 2020). Assessing the technological advancement of HBTs can help to delineate the context in which these technologies progress as well as the stages of their life cycle. This, in turn, can provide valuable insights about the current state of technological evolution and their potential future development and applications. Extant research have examined HBTs by focusing on specific technological solutions such as fuel cells (Baumann et al., 2021; Chen et al., 2011; Garland et al., 2012), certain countries (Wu and Leu, 2014) and on sectors that have been subjected of particular political and media attention such as the automotive industry or 'hard-to-abate' sectors (Kushnir et al., 2020; Ranaei et al., 2016). At the same time, these efforts have analyzed HBTs over relatively short periods of observation (e.g., Sinigaglia et al., 2019, that have analyzed the period 1998-2018). While these studies have contributed to shedding light on some areas of HBTs, a comprehensive understanding of the technological development of the hydrogen chain has been neglected. Given the emergent nature of HBTs and the rapid and uncertain dynamics that feature in their development (e.g., Cozzens et al., 2010; Kapoor and Klueter, 2020; Rotolo et al., 2015; Small et al., 2014), I argue that a more holistic approach to examine HBTs is needed. To address this gap, this study examines HBTs along the hydrogen chain, including hydrogen production and storage technologies. In doing so, I aim to increase the understanding of the life cycle of these technologies and to delineate those organizational actors and countries that have been involved in their development – especially in the development of HBTs that have had a major impact on subsequent technological advancements. To do so, I examine all Patent Families (PFs) related to HBTs from 1930 to 2020. These include 317,089 PFs related to hydrogen production technologies and 62,496 PFs to hydrogen storage technologies. Results reveal that the patenting activity related to HBTs has been constantly growing, in both the cases of production (CAGR% 1,7%) and storage (CAGR% +2%) technologies. Applicants based in Japan, in the United States (US), and in Europe have been the primary contributors. However, it is worth noting that the patenting activity of applicants from other countries is also characterized by considerable growth in the most recent years. Firms – in the chemical sector, in particular – have contributed to the largest proportion of PFs suggesting a high level of expectations about the economic potential of HBTs. Two main implications emerge from this study. Firstly, there seems to be an urgent need to support the emergence of a dominant design (Abernathy & Utterback, 1978; Srinivasan et al., 2005) so as to facilitate the diffusion of HBTs. The growing patenting activity related to these technologies suggests considerable private and public interest as well as a lack of a dominant design. Secondly, when considering those countries most involved in the development of HBTs as measured by the number of patents, it is worth noting that major efforts have originated from developed countries (in particular, the US and Japan) and, especially in the most recent years, from developing countries too (i.e., BRIC and others). As a result, I argue that a possible solution to deepen the knowledge related to HBTs is to develop cross-country cooperation through international agreements that could minimize the risk of conflicting interests of various countries. Global policymakers could therefore leverage the knowledge base of leading nations (US and Japan) to facilitate technology transfers among countries by applying international agreements (such as the Kyoto Protocol or Paris Agreement) or by activating Research and Technology Offices (RTO) to support domestic firms in their learning of HBTs.

This study is structured as follows. Section 2 outlines the hydrogen chain and the difference between HBTs related to hydrogen production and storage and provides background on the use of patent data to examine technological trends. Section 3 presents the data collection process and the empirical approach. Section 4 describes the main results of this analysis while Section 5 concludes the study by discussing emerging findings, implications, limitations, and future research directions.

2 Background

I build on the extant literature to provide an overview of HBTs with a focus on the differences between the production and storage of hydrogen. I first focus on the socio-economic and technical background related to HBTs; I then introduce the use of patent data as a proxy to examine technological evolution, specifically in the case of green energy technologies such as HBTs.

2.1 Socio-economic and technical background of HBTs

Ongoing severe socio-economic problems due to energy supply have pushed global attention towards the role of hydrogen as an energy source. Due to its unique characteristics and abundance (hydrogen represents about 75% of all matter), hydrogen is conceived as an ideal energy carrier (Vezirocjlu & Barbir, 1992) that can facilitate the energy transition. HBTs are also considered as green technologies able to exert a positive effect on economic growth (D'Angelo et al., 2022) and support the achievement of sustainability goals when combined with other technologies (Cappa et al., 2022). It is therefore timely and critical to understand the past, current, and future developments of HBTs considering the socio-economic and technical context in which they emerge. Countries have engaged in major efforts to support the development of HBTs: "At the beginning of 2021, over thirty countries have released hydrogen roadmaps, the industry has announced more than two hundred hydrogen projects and ambitious investment plans, and governments worldwide have committed more than USD seventy billion in public funding" (Hydrogen Council & McKinsey&Company, 2021, p. iv). These actions are especially aimed at reducing the environmental impact of 'hard-to-abate' sectors and diversifying the energy supply to generate an alternative to more traditional energy sources (Hydrogen Europe, 2021). Technology improvements, economies of scale, and reduction of energy costs are deemed to support hydrogen's adoption by 2030, further making hydrogen an essential element for the energy transition (World Energy Council, EPRI, & PwC, 2021). Taking advantage of these improvements, members of the Hydrogen Council have planned a six-fold increase in their total hydrogen investments through 2025 and a sixteen-fold increase through 2030 (Hydrogen Council & McKinsey&Company, 2021). These initiatives have contributed to the development of the so-called 'hydrogen economy' (Kreith et al., 2014), where hydrogen is expected to be the main energy carrier along with electricity. This would bring the current worldwide demand for hydrogen (70 million tonnes/year) to grow considerably (International Energy Agency, 2019). As reported by several studies, countries worldwide have set different energy policies and initiatives, which have contributed to support the emergence of the hydrogen economy. For instance, Godoe and Nygaard (2006) have conducted a study on the technological state of the art of Norway between 1990 and 2002. Their research described a successful project, among the four comparatively large fuel cell development projects, undertaken by Norway from the middle of the 1980s to the end of the 1990s. Specifically, this study describes a particular model of fuel cells combined with heat and power production for hydrogen suggesting that even Norway's government has been actively exploring and investing in specific HBTs, as part of their efforts to develop sustainable and efficient energy solutions. Li and Lin (2016) argued that financial support provided by the Chinese government for R&D activities related to HBTs could be an effective way to encourage firms to develop innovative solutions. Both studies highlight the importance of government support and incentives in driving technological advancements in the field of HBTs. By providing financial resources and creating a conducive environment for R&D, governments can play a significant role in promoting innovation and fostering the growth of HBTs in their respective countries. Despite the emerging consensus on the use of hydrogen as an energy source alternative to fossil fuels (Sazali, 2020) and the national and supranational efforts toward the hydrogen economy (Hydrogen Europe & Revolve, 2022), a key technical challenge is that hydrogen is not exploitable in nature but must be produced by separating water molecules or extracting hydrogen atoms from other compounds. A variety of technologies exist to produce hydrogen. These include electrolysis, which is the most studied and relevant for what concerns the green energy transition (Franch & Drane, 1930; Schmidt et al., 2017; Ursúa et al., 2011; Zoulias et al., 2004), and steam reforming (Kreith et al., 2014). However, most of the hydrogen production technologies are not yet mature (Martinez-Burgos et al., 2021). Scholars have questioned the technological progress made so far when compared to the potential of those technologies. For example, Kushnir et al. (2020) argued that hydrogen has the potential to make the Swedish steel industry fossil-free, but the main bottleneck is represented by the technical limits of the current hydrogen production technologies (Dincer, 2012). Moreover, it must be acknowledged that hydrogen cannot be immediately used because a production site is hardly ever close to a utilization site, or the quantity of hydrogen produced is greater than the demand. On the one hand, hydrogen is a chemical energy carrier, composed of molecules and not only electrons that can be stored and transported stably or can be combined with other elements (i.e., carbon and nitrogen) to make hydrogen-based fuels easier to handle (International Energy Agency, 2019). For example, hydrogen can be stored in high-pressure tanks in gaseous form (large-scale storage, very low density) and in liquid form (air and space transportation), or in the form of metal hydrides absorbing or reacting with metals or chemical compounds (Kreith et al., 2014; Robles et al., 2018). Considering large-scale storage facilities instead, hydrogen can be stored underground in ex-mines, caverns, and/or aquifers (Kreith et al., 2014). On the other hand, making such storage options feasible and reliable present major challenges (Hirscher, 2010). It is very difficult to store hydrogen due to its low volumetric energy density (it is the lightest of all elements). Hydrogen is easily dispersible into the atmosphere when attempted to be stored in the gaseous form. Also, storing hydrogen as a gas requires the use of high-pressure tanks (350-700 bar or 5000-10,000 psi), while the very low boiling point of liquid hydrogen (−252.8°C) requires hydrogen to be kept cryogenically stored at low temperatures. Considering the socio-economic context and the technical challenges above described, I argue that it is critical to investigate the technological evolution of two interrelated phases of hydrogen production and storage to provide insights for managers and policymakers on the potential developments of HBTs.

2.1 Technological evolution and patent analysis

Much attention has been devoted to understanding the evolution of technology from a different range of theoretical and methodological perspectives. Technological evolution has been conceived as a complex process the evolution of which is shaped by several factors along the technological (Suarez, 2004), economic (Klepper, 1996), cognitive (Kaplan & Tripsas, 2004), and social dimensions (Dokko et al., 2012). The environment in which the technology evolves, the variety of knowledge recombination processes, and path dependence add to this complexity (for a review see Grodal et al., 2023). The concept of emerging technology has received particular attention (Adner & Levinthal, 2002; Cozzens et al., 2005; Rotolo et al., 2015; Small et al., 2014). An emerging technology has been defined as a technology that is radically novel when compared to established technologies in the domains in which it emerges and capable of exerting a considerable socio-economic impact in these domains; such a technology grows rapidly and has achieved a certain level of coherence since a community of practice has established and acquired a certain level of independence from their parent communities; the impact of an emerging technology remains, however, uncertain and ambiguous since probabilities cannot be defined for the outcomes of the emergence process neither potential outcomes are known (Rotolo et al., 2015). Tracing the rapid evolution of an emerging technology is crucial to understand the evolution of technology. In this vein, a widely adopted methodological approach to analyze technological development path is patent analysis (Haščič & Migotto, 2015; Organisation for Economic Co-operation and Development., 2009). Patents can be used as indicators since are available for a rather long period and provide detailed technological information. Indicators and studies based on patent data are extremely heterogeneous and can be applied in terms of the publication format (reports, academic research) or considering the level of aggregation of the data compiled (national, regional, company level) or based on the approach taken (compilation of indicators, performance of econometric estimates). For instance, different indicators are available to measure the internationalization of science and technology (e.g., domestic ownership of inventions made abroad or foreign ownership of domestic inventions) (Frietsch & Schmoch, 2010; Jaffe & Trajtenberg, 1999) or, through citations, it is possible to investigate connections between technologies(McJeon et al., 2011), between science and technology(Fusillo, 2023), or between firms, industries, countries or regions(Ardito, 2018; K. Li & Lin, 2016; Y. Park & Yoon, 2017) . Thus, patents can be used as a proxy for technological development (Evangelista et al., 2020; Lee & Lee, 2013; M. Li & Xu, 2023). Patents protect inventions ensuring economic and technological advantage. In addition, the process adopted to validate them is very scrupulous, hence making patent data reliable. Relatedly, patent documents contain precious information that can be used to trace development paths such as the reference date, the country of attribution, and their diffusion among countries (patent families) (Jaffe & Trajtenberg, 1999; Trajtenberg, 1990a). Drawing on the information contained in patent documents, it is possible to trace the technological life cycle of a specific technology (Hsu et al., 2015) and to compare the extent to which a certain technology domain has evolved over time and within different nations (Albino et al., 2014). These types of analysis have been conducted with regard to various sectors such as augmented reality (Evangelista et al., 2020), microgravity (Ardito et al., 2020), and Internet of Things (Ardito et al., 2018) or in the definition of emerging technologies. Indeed, patent analysis has enabled to obtain the definition of the main attributes that describe them (namely radical novelty, relatively fast growth, coherence, prominent impact, and uncertainty and ambiguity). (Rotolo et al., 2015). HBTs can be conceived as emerging technologies (Sazali, 2020) since they are characterized by recombination of knowledge that brings novelty (Sinigaglia et al., 2019), fast growth (Ampah et al., 2022), and a prominent impact (Cader et al., 2021; Tseng et al., 2005), even though they are characterized by uncertainty (Dehghanimadvar et al., 2020; Rizzi et al., 2014). However, several studies have been conducted to better understand HBTs using patent analysis. For instance, Olivo and colleagues have applied patent analysis to confront the patenting activity trend of the People's Republic of China (PRC), Japan, the Republic of Korea, the European Union, and the US - but restricted to the biohydrogen field - revealing that the PRC is the biggest contributor worldwide in terms of hydrogen production methods by academic institutions, while Japan is a relevant patent contributor by private firms (Olivo et al., 2011). Sinigaglia and colleagues, instead, have identified Japan and the US as the most active countries in patenting activity concerning the hydrogen economy. For what concerns the firms, Toyota Motor and Honda Motor are the leading firms in all the research considered (Sinigaglia et al., 2019). Nevertheless, the first study is related to a restricted sample of HBTs while the second is referred to a relative short period (between 1998–2018), omitting previous steps in the analysis of HBTs. Therefore, in line with several studies examining the emergence of new technology by using patent data and patent analysis (i.e., Ampah et al., 2022; Ardito et al., 2020; Evangelista et al., 2020; Lai et al., 2011; Leu et al., 2012;), I also rely on involve these methods to study the technological emergence of HBTs and their development.

3 Methodology

3.1 Patent data collection

In this analysis, I relied on Patent families which consider a set of patents filed in various countries covering the same invention (Tahmooresnejad & Beaudry, 2019). A PF refers to “a collection of patent documents that are considered to cover a single invention […] Members of a simple patent family will all have the same priorities”.[2] To delineate PFs related to HBTs, I defined a list of keywords by reviewing previous studies examining these technologies (Edwards et al., 2007; Kreith et al., 2014; Martinez-Burgos et al., 2021; Waltman, 2016). I combined the keywords suggested in these studies and developed two keyword-based searches to delineate hydrogen production and storage technologies (Table 1). I used these queries to retrieve PFs into the Orbit FAMPAT database, by selecting as patent authorities for search purposes the World Intellectual Property Organization (WIPO), the United States Patent and Trademark Office (USPTO), the European Patent Office (EPO), and the Japan Patent Office (JPO). Indeed, the EPO, the JPO, and the USPTO are commonly referred to as the Trilaterals, being the major patent offices (Drahos, 2009; Martínez, 2011) since they are recognized as the most reliable and accurate Patent Offices due to their processes and standard. However, it may present a ‘home advantage’ (Criscuolo, 2006). Therefore,

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[2] https://www.epo.org/searching-for-patents/helpful-resources/first-time-here/patent-families/docdb.html (accessed on 5 May 2023).

I took into consideration also the WIPO. The search was performed on 14 March 2022 and restricted to the granted PFs from 1930 to 2020. The reasons for choosing a relatively long observation period are twofold. On the one hand, I aim to examine the evolution of HBTs since their roots, and by studying the patenting activity trend I have noticed that before 1930 there were few patents. On the other hand, I aim to expand previous research efforts mostly limited to relatively short observation periods (e.g., Dehghanimadvar et al., 2020; Rizzi et al., 2014; Sazali, 2020). It is worth noting that I excluded the years starting from 2021 to minimize the impact of grant time lag on this analysis. The search returned 379,585 PFs related to HBTs: 317,089 PFs refer to hydrogen production technologies and 62,496 PFs refer to hydrogen storage technologies.

HBTs	Keyword-based search
Production	hydrogen AND (energy OR production OR generation OR power OR manufactur* OR obtain* OR reform*)
Storage	hydrogen AND (storag* OR reservoir* OR adsorb* OR accumulation OR stock OR vessel OR tank)

Table 1. Keyword-based searches to delineate PFs related to hydrogen production and storage.

Source. Authors' elaboration.

3.2 Patent analysis

I conduct a range of explorative analyses. I first count of PFs per year to examine the yearly technology development in terms of patented inventions (Acs et al., 2002; Popp, 2002; Singh, 2008). This analysis considers both priority dates – i.e., the closest date to the invention process – and grant dates – i.e., when the intellectual property protection for an invention is granted to the corresponding applicant. Second, I compare the patenting activity related to HBTs across countries so as to outline the most active countries in the development of HBTs. To do so, I rely on the earliest priority country since this represents the country where the first application is filed. I consider the following countries and groups: BRIC (i.e. Brazil, Russia, India, and China), Europe, Japan, US, and Other (i.e. the remaining countries). Third, I build on patent applicant data to analyze the development of HBTs at the organizational level. I delineate the most active organizations in terms of number of PFs (Deyle & Grupp, 2005; Nawaz, 1986). In doing so, I identify those organizations that have contributed the most to the development of HBTs related to production and storage. I also examine the emerging geographical dynamics of HBTs based on the countries of these organizations. Finally, I conduct all the analyses described above on highly-cited PFs in the hydrogen production and storage areas. To do so, I consider the number of forward citations as a proxy for the technological impact of an invention (e.g., Gambardella et al., 2008;

Trajtenberg, 1990) and normalise these. More precisely, I define highly-cited PFs as those within the top 1% of the normalized forward citation count – I divided the number of citations a patent received by the average number of citations PFs in the same year and within the same IPCs received (see Bornmann et al., 2013). I then compare and contrast the analysis across the sample of highly-cited PFs and the remaining PFs.

4 Results

4.1 Temporal trend

The patenting activity related to HBTs has considerably grown from 1930 to 2020 both considering the production and storage fields although the magnitude of the patenting activity is considerably higher in the former than in the latter (Figure 1). While priority dates-related trends anticipate grant trend and could give guidance on the attention regarding technological efforts in hydrogen production technology, I also observe a decline in the number of patents according to their priority dates since this analysis focussed on granted patents only. However, the peak is in proximity to the year 2005. When considering the political scenario, it is worth noting that, in 2005, the US supported a national hydrogen policy through the enactment of the Energy Policy Act, demonstrating that the attention towards hydrogen strategy was maximum in the first decade of 2000 (International Energy Agency, 2019). In 1970, around 1990, and in 2000, it is possible to observe steady growth in the curves shown in Figure 1 for both production and storage cases. This aligns with the analysis by the International Energy Agency (IEA) (2019) which refers to “waves of enthusiasm” related to HBTs. The first wave occurred in the 1970s as a possible response to oil shocks and the feared scarcity of oil resources. The second wave sought to respond to growing concerns about climate change in the early 1990s in conjunction with the launch of major research programs on the production and use of hydrogen, especially in the US and in Japan. The third wave began in the early 2000s with the reappearance of concerns about the so-called “Peak oil” with the intensification of policies to stop climate change, for which HBTs appeared as a privileged solution in the transport sector. It is precisely during this phase that the European Union attempted to change the momentum related to HBTs inspired by the intensification of Japanese and US efforts. More recently, I can observe the fourth of these waves. After 2005, Japan and the US approved substantial support plans for the development of hydrogen production technologies and set ambitious goals to be achieved between 2010 and 2030.

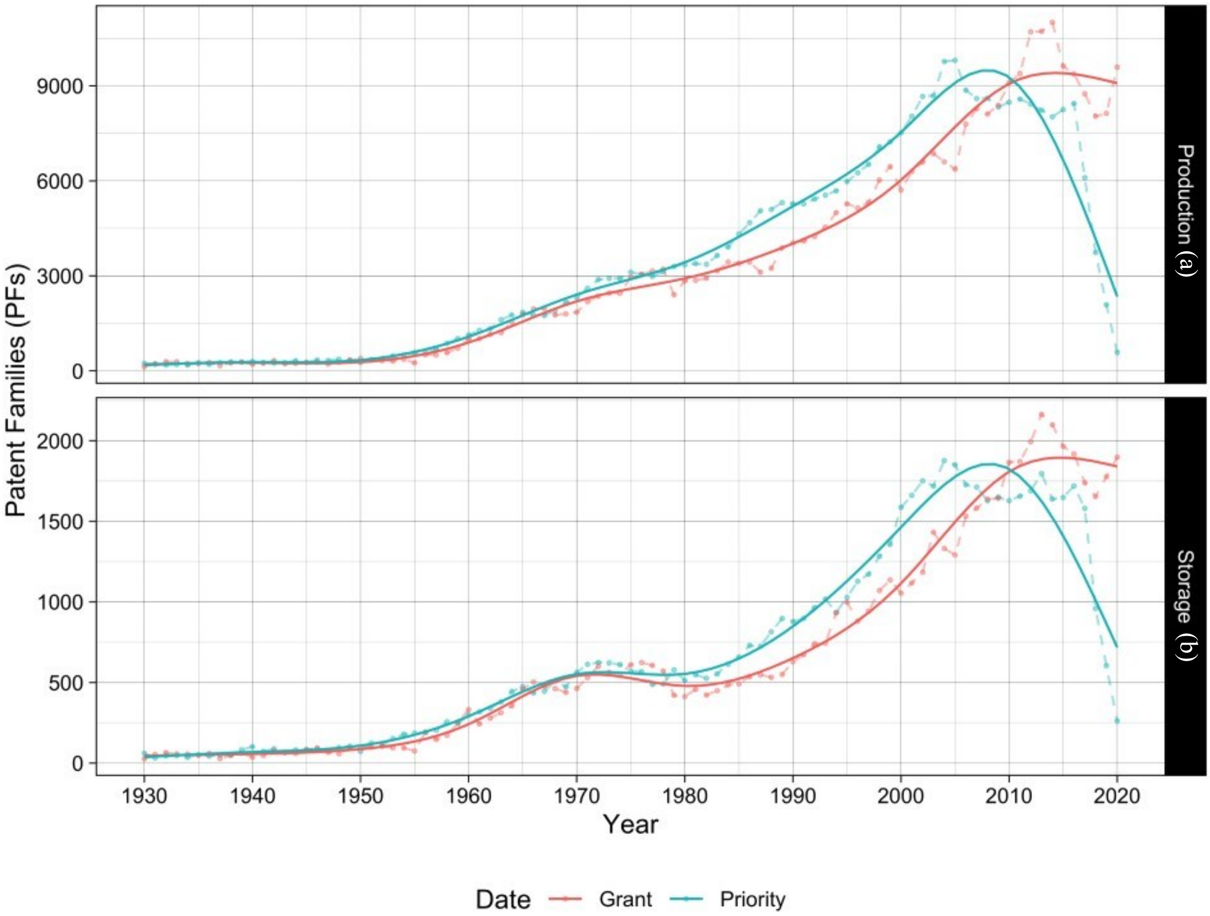

Figure 1. Longitudinal analysis of the number of PFs related to hydrogen production (a) and storage (b) technologies (1930-2020).
Source: Authors' elaboration.

4.2 Geographical distribution

The most active countries in terms of the number of PFs across production and storage HBTs are depicted in Figure 2. There is evidence that Japan has been the most active country in hydrogen production technologies with the highest share of 34.4% PFs (Figure 2a). This result is also supported by the analysis of the current applicants. Among the top ten most frequent applicants, five out of ten are Japanese firms: Mitsubishi Corp., FUJIFILM Holdings Corp., Sumitomo Chemical Co., Shin-Etsu Chemical Co., and Hitachi Ltd. Albeit from the analysis of patenting activity is not possible to identify a unique driver for the Japanese intense patenting activity, a key factor could be the government support to enterprises focussed on hydrogen (World Energy Council, EPRI, & Pwc, 2021). Japan's strategy is indeed centred on cooperation: the Tokyo Metropolitan Government has collaborated with Tokyo Technical University to establish a research centre specializing in the development of integrated activities for the advancement of a hydrogen-based energy company (Harada et al., 2016). This research centre has served as the foundation for many recent developments in HBTs. In 2020, the world's largest green hydrogen production centre was inaugurated in the city of Namie, while an impressive research facility – the Fukushima Hydrogen Energy Research Field (FH2R) – was built by a consortium of firms. The centre will generate over 1,200 Nm3 of hydrogen every hour, powered by a surrounding twenty MW solar panel farm. The Japanese government intends to establish a comprehensive international hydrogen supply chain to reduce hydrogen costs and encourage the use of ammonia as a low-carbon transitional fuel in thermal power generation (Harada et al., 2016; Potter & Graham, 2019). The US has, in contrast, been particularly active the development of hydrogen storage technologies (Figure 2b). US patents originate about 38% PFs in this technological area. This could be attributed to the effort of the Hydrogen and Fuel Cell Technologies Office (HFTO) of the US government, which plans to develop more reliable and high-performing hydrogen storage systems for automotive applications. These developments can enable greater driving distances and lower costs (Chen et al., 2011; Karaca & Dincer, 2021; Rizzi et al., 2014; Velazquez Abad & Dodds, 2020). Europe is the second geographical area for what concerns the development of hydrogen production technologies and the third geographical area for what concerns the development of hydrogen storage technologies, thus confirming that the attention towards hydrogen that started in the 2000s has been amplified by the European Commission through the "hydrogen strategy for a climate-neutral Europe" (Hydrogen Europe & Revolve, 2022).

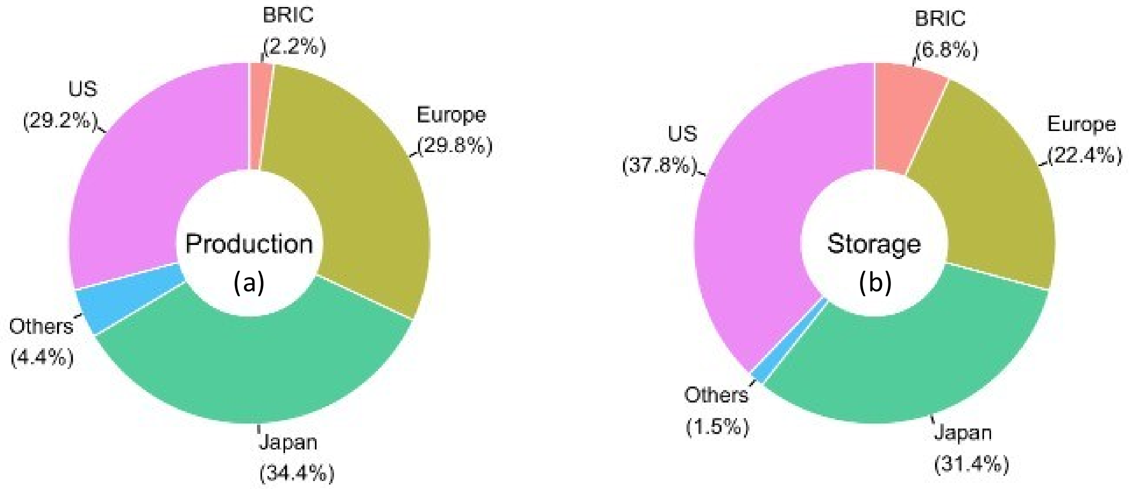

Figure 2. Proportions of PFs related to hydrogen production (a) and storage (b) by country (1930-2020).

Source: Authors' elaboration.

The analysis of the geographical distribution of PFs by year reveals Japan's growing interest in HBTs since 1960 (see Figure 3). Europe and the US were pioneers in the study of hydrogen technologies, encompassing both production and storage. When one considers the trend in HBT production (Figure 3a), it is worth noting that European patenting activity surpassed US efforts from 1965 until 2000. However, despite starting later than Europe and the US, Japan's patenting trend surpassed both European and the US between 1980 and 1990. Japan remains the leading country in terms of PFs. BRIC nations and other countries increased their patenting activity after 2000, reaching levels comparable to those of Europe and the US. Focusing on HBTs for storage (Figure 3b), the US had the highest patenting trend until Japan surpassed it around 1980. Overall, the trends (Figure 3) are similar for both production and storage cases. However, BRIC nations reached the European trend curves in 2015 for storage (Figure 3b).

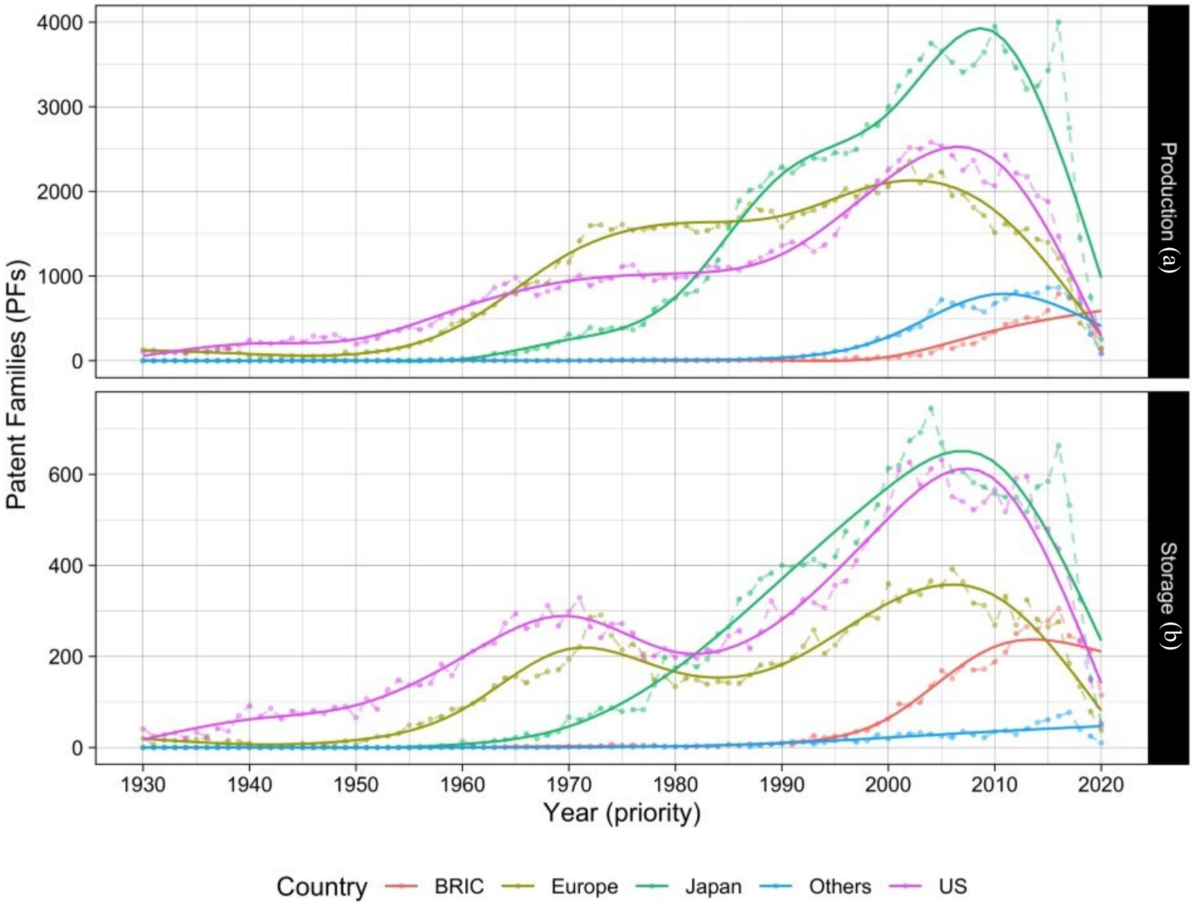

Figure 3. Longitudinal analysis of the number of PFs related to hydrogen production (a) and storage (b) by country (1930-2020).

Source: Authors' elaboration.

4.3 Analysis of the Top ten organizations

Figure 4 shows the top ten applicants holding the highest number of PFs related to production and storage HBTs.

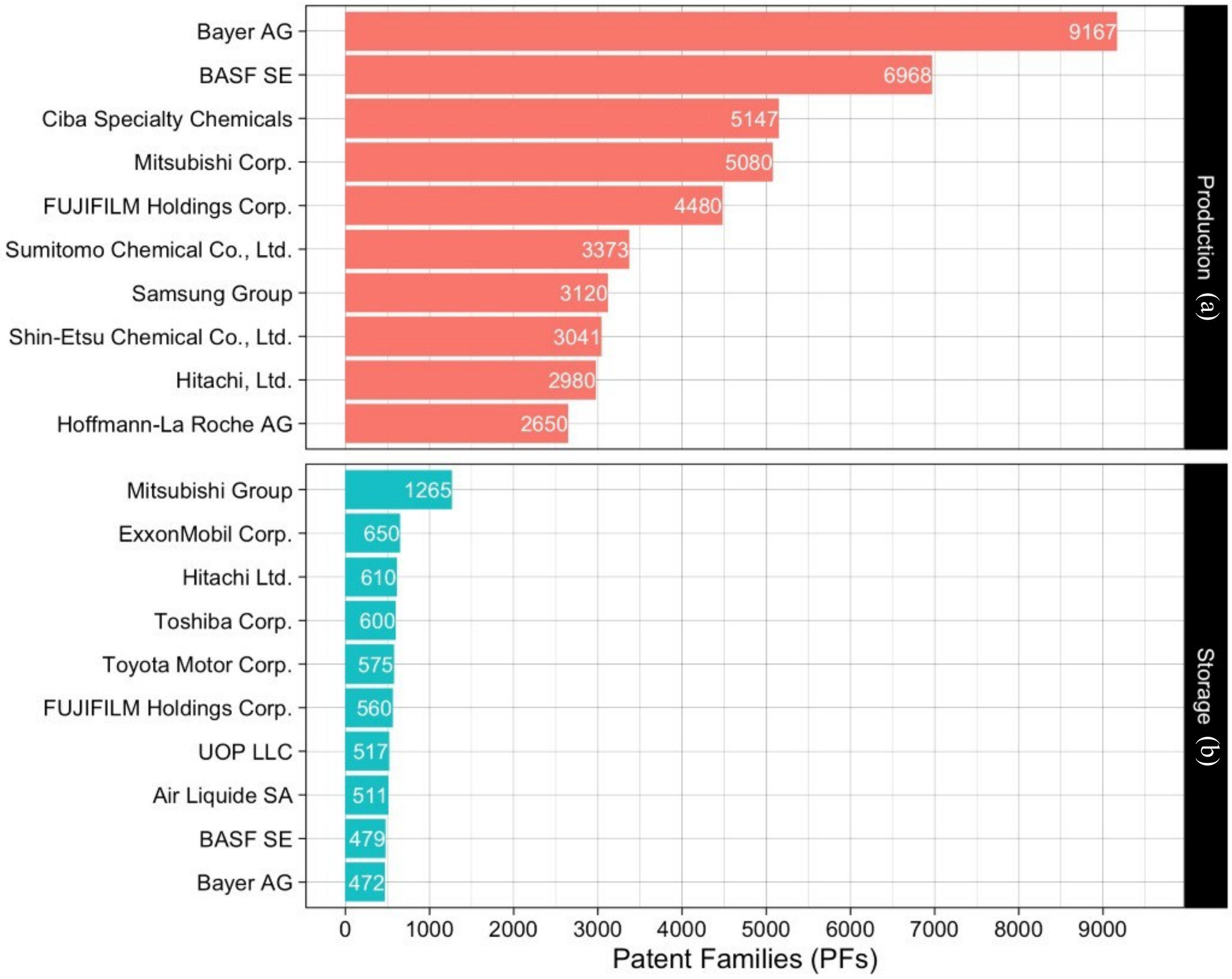

Figure 4. Top ten applicants by number of PFs related to hydrogen production (a) and storage (b) (1930-2020).

Source: Authors' elaboration.

In both the cases of production and storage HBTs, the most patent-intensive (top ten) applicants are firms (Figure 4a and 4b); that is, no universities, research centers, or governmental entities figure in this list. Of course, the related assumption that universities are ivory towers that produce academic output disconnected from technology is rhetoric and is not supported by evidence (Geuna and Nesta, 2003). For instance, studies available on university patenting in Europe show convincingly that university-invented patents were and are an important and increasing phenomenon. Additionally, in the field of green technologies, several universities have engaged in intense patenting activity (Albino et al., 2014; Ardito et al., 2016). However, in the analyzed domain, universities or research centers hold only 1% of PFs. Among the identified firms, four are European, five are Japanese, and one is South Korean. These firms are primarily from the chemical sector since hydrogen production necessitates a strong chemical foundation for designing production models. This finding is also supported by a recent report contending that the chemical industry is a critical sector in developing innovative solutions since they have the know-how required to tap into the opportunities of the emerging hydrogen economy and can create a competitive advantage (Deloitte, 2021). It is worth noting that US firms are not among the top ten firms reported in this analysis. This may indicate a less concentrated market without clear leader firms. Regarding HBTs related to storage (Figure 4b), this ranking includes two firms located in the US, three in Europe, and five in Japan. These results may indicate that, generally speaking, HBTs are economically promising and attractive to firms that can obtain first-mover competitive advantage.

4.4 Analyses of highly-cited Patents

In previous analyses, I identified significant information using PFs, but I did not assess whether these PFs had a notably higher or lower citation impact compared to others. Therefore, I conducted a second analysis, this time normalizing the sample (Kostoff & Martinez, 2005) by considering citations and International Patent Classification (IPC) (Bornmann et al., 2013). Indeed, to study highly impacting technologies, I focused on the top one percent of PFs in terms of normalized citations received, identifying the highly-cited patents.

4.4.1 Temporal trend

The analysis of the number of highly-cited PFs by year (Figure 5) outlines trends similar to those observed for the entire population of PFs (Figure 1). It is worth noting a rise in the steepness of the trend line when considering the years of the “enthusiasm waves” which have been previously discussed (in correspondence of 1970, 1990, 2000, and 2010, (International Energy Agency, 2019). Moreover, the trend line of the priority date anticipates the grant trend line according to the time lag required to grant a patent. Approaching 2020, the earliest priority number curve decreases, since patents need some years from the request to be granted.

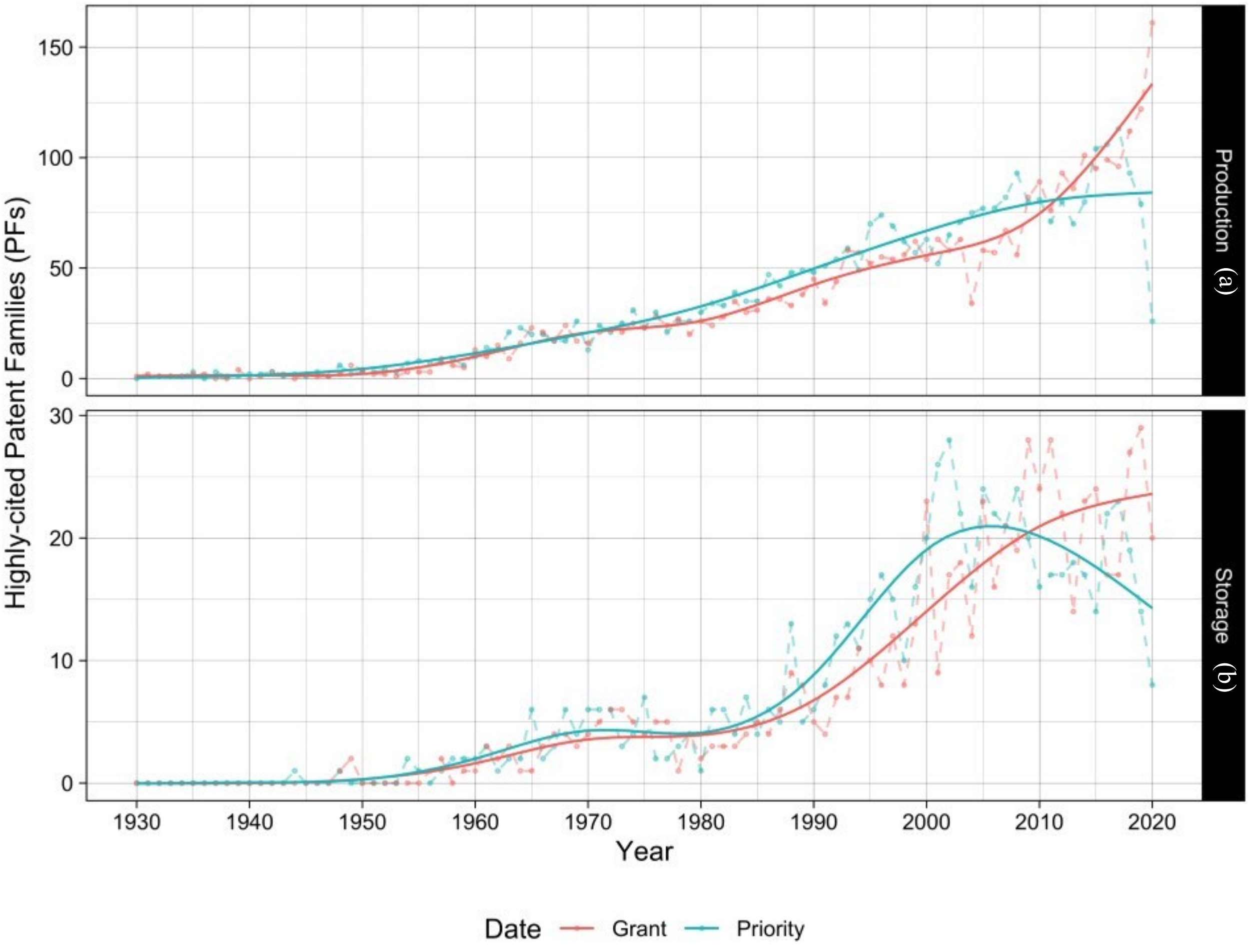

Figure 5. Longitudinal analysis of the number of highly-cited PFs related to hydrogen production (a) and storage (b) by country (1930-2020).

Source: Authors' elaboration.

4.4.2 Geographical distribution

The geographical distribution of highly-cited PFs (Figure 6) is different from what is observed for the whole population of PFs (Figure 2). The leading country is the US both for PFs related to production and storage HBTs. This result may suggest that, while the highest number of patent families are located in Japan, the US holds the most impactful patents (Waltman, 2016). Europe is positioned in the second place in terms of number of highly-cited PFs.

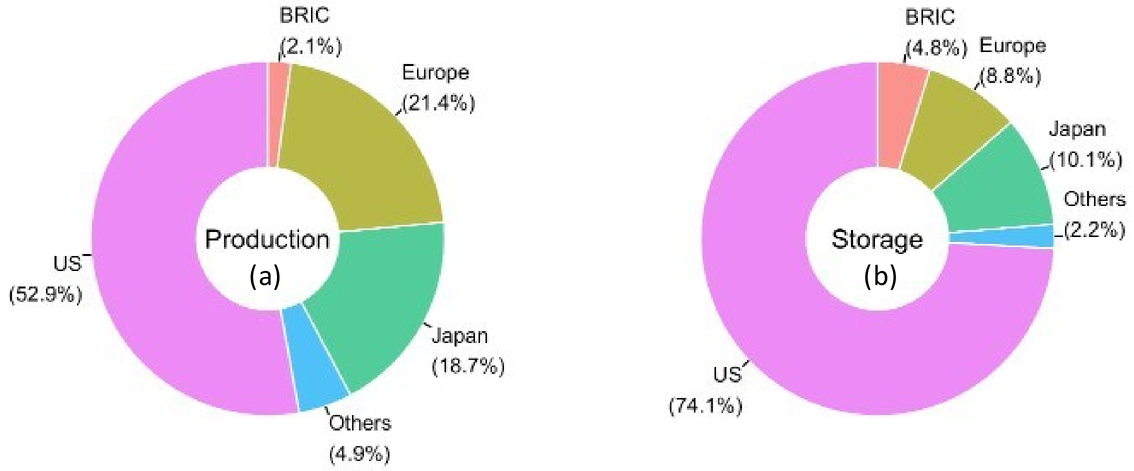

Figure 6. Proportions of highly-cited PFs related to hydrogen production (a) and storage (b) by country (1930-2020).

Source: Authors' elaboration.

To shed light on the dynamics that led to this upheaval compared to the analyses on the initial samples, I also studied the patenting trends at the country level (Figure 7). The US remains the leader in terms of highly-cited PFs. The maximum number of highly-cited PFs is in correspondence of 2009 (Figure 7a), four years after the Energy Policy Act where the US supported hydrogen policy through enactment. Europe instead shows the maximum number in the year 2019 according to the recent policy by the European Commission which is also stimulating enterprises' patenting activities. Finally, in the HBTs of storage after the supremacy of the US, in the years after 2015, BRIC have intensified patenting activity (Figure 7b). This result seems to align with the effort made specifically by China which has had strong activity in the development of storage technologies (Chanchetti et al., 2016).

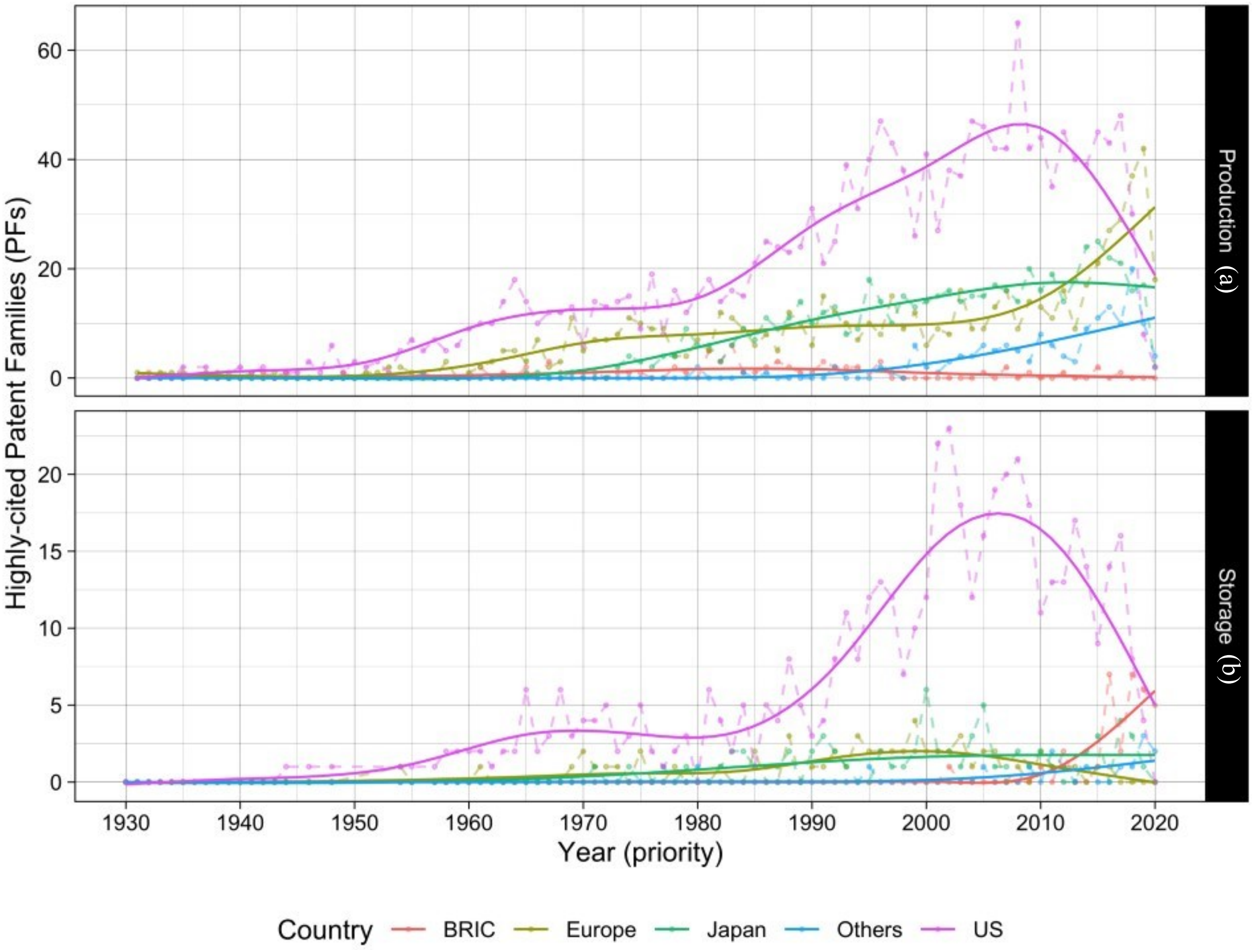

Figure 7. Longitudinal analysis of the number of highly-cited PFs related to hydrogen production (a) and storage (b) by country (1930-2020).

Source: Authors' elaboration.

4.4.3 Analysis of the top organizations

Figure 8 shows the organizations that hold the highest number of highly cited PFs in production (a) and storage (b) hydrogen technologies. The top firms in Figure 8a are composed of four firms from Europe, seven from Japan, and three from the US; considering Figure 8b, six firms are from the US, five are European, and five are Japanese. Considering the organizations with the highest number of highly-cited PFs within a specific country, the most patent-intensive organizations are European and Japanese. This analysis considers only the number of PFs related to the organizations rather than just the absolute number of PFs related to that area. This may suggest that Europe and Japan have extremely effective organizations conducting highly impactful R&D as compared to the US, where the development of highly cited PFs is lower. The firms considered are in the chemical sector or in the energetic sector, otherwise are related to the activities linked to semiconductors.

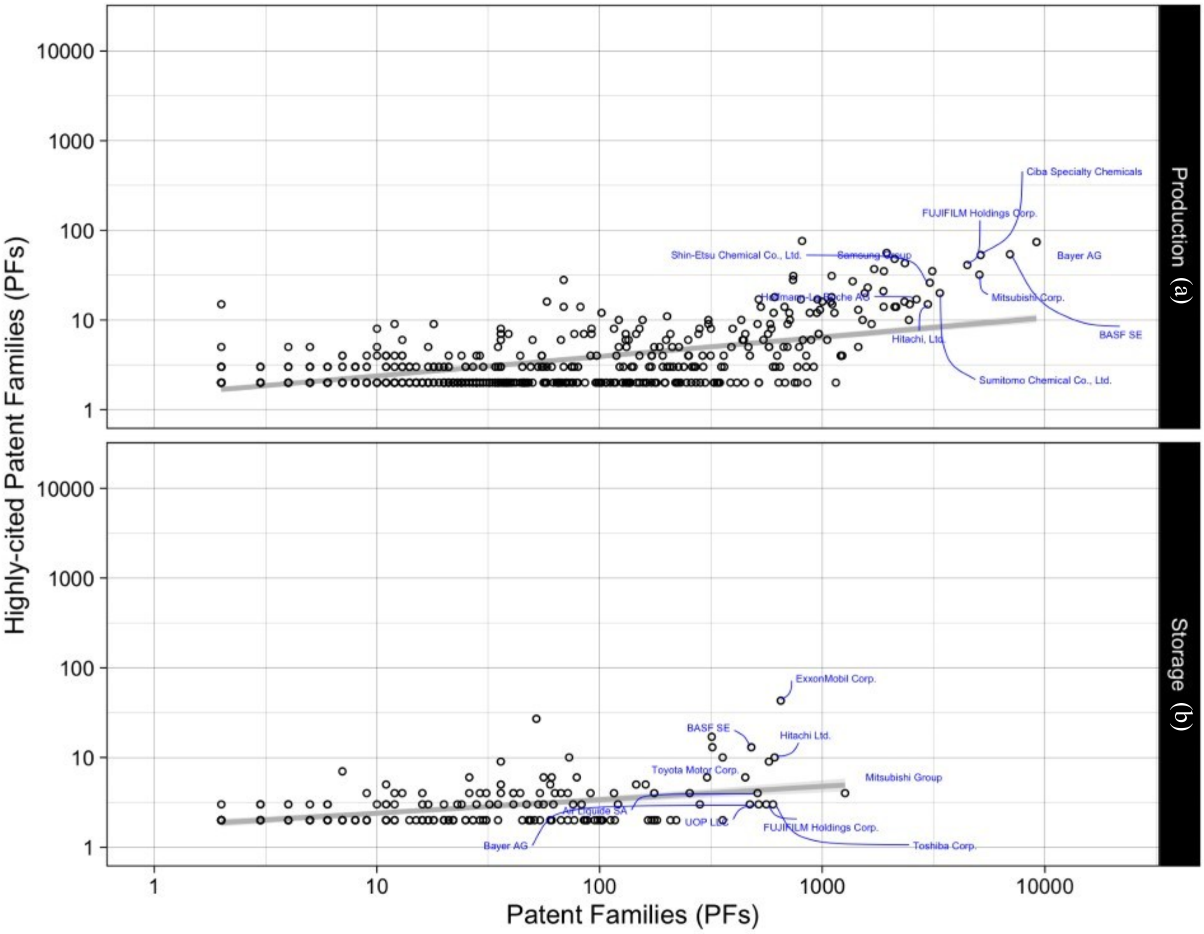

Figure 8. Top firms in terms of the number of PFs and of highly-cited PFs related to hydrogen production (a) and storage (b) (1930-2020). The names of the organizations are reported for the top 10 in terms of the number of PFs and the top 10 in terms of H-C PFs.
Source: Authors' elaboration.

5 Discussions and implications

This study aimed at tracing the technological developments of HBTs by investigating trends of the related patenting activity. This analysis provided an overview of the technological landscape of HBTs in terms of magnitude and geographical distribution of the global inventive efforts on these technologies while at the same time contextualizing these trends within national policies, historical events, and corporate initiatives. In doing so, this study advances on previous research efforts [(Chanchetti et al., 2016; Chen et al., 2011; European Patent Office & The International Renewable Energy Agency, 2022; Ursúa et al., 2011)] by expanding the analysis on the production and storage HBTs, which I observed over a relatively long period. I created a database of HBT-related patented inventions filed at major patent offices from 1930 to 2020 and distinguished those between hydrogen production and storage technologies. The patent analysis provided a number of findings. First, the analysis of the trends of the patenting activity suggested a significant influence of the geopolitical circumstances on growing number of granted patents. This is primarily associated with government strategies and energy programs that have contributed to establish frameworks and initiatives to promote the development of HBTs. Such a pattern is exemplified by the leadership of the US and Japan, the nations with the highest government contributions in the hydrogen field [(European Patent Office & The International Renewable Energy Agency, 2022; International Energy Agency, 2019)]. However, previous studies have shown that private firms own the majority of patents, underscoring how economic motivations drive the economic process (Teece, 1986). Second, I found evidence that, while HBTs have attracted global enterprise attention, a dominant model for both production and storage has yet to emerge. Third, this study shed light on the most active countries in the patenting of HBTs: Japan accounts for the largest proportion of patents, while the US holds the largest proportion of highly-cited patents. Europe is also notable both in terms of patent quantity and impact, yet BRIC countries still lag behind in terms of the intensity of the patenting activity. It is however worth noting that BRIC countries have made considerable progress in HBTs more recently and particularly in the field of storage.

Two implications emerge from this study. Firstly, from a technological perspective, the growing HBT-related patenting activity (Figure 1) and highly-cited PFs (Figure 5), suggest the absence of a dominant design (Abernathy & Utterback, 1978; Srinivasan et al., 2005), albeit underlines the economic potential of these technologies. Therefore, there seems to be space to create policy instruments that can support the emergence of a dominant design so as to facilitate the development and diffusion of HBTs (Tushman & Murmann, 1998). Secondly, the US and Japan hold the majority of PFs related to HBTs, while European firms hold the highest number of highly-cited PFs. However, considering the subdivision of knowledge in HBTs, the dominant position of a few countries in terms of HBTs development could generate a supremacy of knowledge (Pachauri et al., 2012) and, consequently, concrete difficulties for other nations in achieving widespread access to advanced energy technologies (Pachauri & Spreng, 2004). Therefore, given the significance of HBTs in shaping a new energy-economic design, there is a potential risk of encountering energy justice issues (Healy & Barry, 2017; Heffron & McCauley, 2017; Jenkins et al., 2016; Sovacool & Dworkin, 2015) and of leaving out other nations from the possibility to contribute to the establishment of a dominant design for HBTs. To address these issues, a potential solution would be facilitating cooperation between nations by setting new international agreements by following and improving previous efforts such as the Kyoto Protocol or the Paris Agreement. Furthermore, by utilizing Research and Technology Offices (RTO) (Albors-Garrigos et al., 2010) within government entities, it becomes possible to capture innovations from other countries and harmonize knowledge sources. Figure 3 and Figure 6 demonstrate that in the last years, BRIC and other countries have intensified their patenting activity while the US leads in the share of highly-cited PFs, indicating its significant impact on patenting activity. Figure 7 illustrates Europe's recent progress in catching up with the United States in terms of highly-cited PFs for HBTs related to production, while the BRIC nations have surpassed the United States in HBTs of storage. Therefore, there is attention towards HBTs worldwide. As a result, global policymakers could leverage the knowledge base of leading nations (US, Japan) to facilitate technology transfers among countries by applying international agreements or guidelines and by activating RTOs to deepen the knowledge of the HBTs. In this way, it could be also possible to facilitate the instauration of a dominant design related to HBTs.

6 Limitations and future research directions

This study presents a number of limitations that may represent avenues for future research. First, I built on patent analysis techniques without deepening into the specifics of HBTs, e.g., examining green HBTs. Therefore, it would be interesting to identify all IPCs related to Green HBTs and analyze them through patent analysis to compare the results obtained with a sample completely green. In addition, different approaches of analysis could be applied to identify, for instance, the technological trajectories of HBTs. Second, I have analyzed only the storage and production phases without considering the commercialization of solutions that used HBTs, as did in previous studies (Ardito, Ernst, et al., 2020). Thus, to further advance the understanding of HBTs, other studies could deepen this last phase to identify all the bottlenecks and the promising perspectives (De Rassenfosse, 2018). Third, I have highlighted the importance of enterprises in diffusing HBTs. Accordingly, future research should focus on identifying alternative approaches for capturing collaborative dynamics among firms to incentivize firms' cooperation in developing technological innovations to face environmental circumstances. In conclusion, I believe that showing the history of the patents related to HBTs as made in this study, has offered to the literature another point of view in the ongoing debate on the hydrogen economy and hope that it may stimulate further studies to generate a dominant paradigm.

Unveiling the Trajectories of Green Energy Technologies: The Case of Electrolysis

1 Introduction

Extensive research has gone into examining technical change as a driving force of economic growth (David, 1975; Griliches, 2007; Mowery & Rosenberg, 1991; Soete & Freeman, 1997). Technical change has been considered as the first appearance in local production of any novel process or product (Evenson & Westphal, 1995). However, further studies have revised the concept of technical change as the result of a process of recombination and evolution of existing technologies (Dosi, 1982; Kaplan & Tripsas, 2004). Within this process, relationships between technologies shape knowledge flows into cyclical divergence-convergence patterns that represent cumulative efforts to overcome emerging problems in specific domains (Barberá-Tomás & Consoli, 2012; Epicoco, 2013; Fontana et al., 2009; Martinelli, 2012). These patterns can be traced by identifying the determinants and the directionality of technical change – i.e., technological trajectories moving from one technological paradigm to another (Dosi, 1982). Assessing trajectories could enable us to understand the intrinsic peculiarities of a specific technological domain (Epicoco, 2013). Notwithstanding, these trajectories could be influenced by constraints – such as path dependencies (Antonelli, 1997; Fouquet, 2016; Martin & Sunley, 2010; Vergne, 2013) – that tend to strengthen the technological status quo (Vergne & Durand, 2011) and, consequently, their inner knowledge flows (Hung et al., 2022).

The examination of technological trajectories and related knowledge flows has been extensively employed to comprehend and measure technical change (Alcácer et al., 2006; Hung et al., 2022; Jaffe & Trajtenberg, 1999; Meyer, 2002; Peri, 2005). Yet, such an approach has been limitedly applied to examine green energy technologies, with a few exceptions (Choi & Woo, 2022; Mueller et al., 2015), and the interplay between green and non-green energy technologies. Research has produced extensive evidence of how green energy technologies present a higher degree of novelty in comparison to non-green energy technologies (Barbieri et al., 2020; Gallagher et al., 2012) as well as has revealed that these are the result of the integration of heterogeneous technologies and knowledge sources (Nemet, 2012b, 2012a; Petruzzelli et al., 2011). These research efforts have considered the invention as level of analysis and examined the temporal trends (Ampah et al., 2023), geographical origins (Moreno-Brieva et al., 2023), and technical characteristics (Fusillo, 2023; Gerloff, 2021; Moreno-Brieva et al., 2023; Tan et al., 2021) of green energy technologies, while neglecting the evolutionary dynamics that have led to a given green technology, whether such technology represents a pivotal solution within the plethora of solutions that constitute a technological trajectory, and whether the associated technological trajectory includes or even originates from non-green energy technologies. As a result, the understanding of the development paths of green energy technologies remains scant. However, the set of green technologies are extremely large and heterogeneous, consequently, to analyze them it is useful to consider a representative subset.

Therefore, this study aims to address this gap by examining the case of electrolysis technologies, – i.e., technologies aimed at producing hydrogen using electricity (McPherson et al., 2018; Ursúa et al., 2011) – and seek to unveil the extent to which different (green and non-green) technical solutions contribute to shaping the evolution of these technologies. This setting is particularly suitable for this study since “hydrogen is one such promising environmentally friendly renewable energy” [36 p.13794] and considerable expectations lie on the role of electrolysis technologies in supporting the greening of the energy sector and the emergence of the green hydrogen economy (Calise, 2022; Dincer, 2012), yet the development trajectory of these technologies involves the recombination, over time, of green and non-green technical solutions from a range of domains (e.g. chemistry, material science, electronics).

This analysis builds on a sample of 43,832 Patent Families (henceforth, PFs) related to electrolysis technologies and the corresponding 77,009 citing and cited PF pairs (from 1987 to 2021). Data on PFs were gathered from the data sample published by IRENA and the European Patent Office (International Renewable Energy Agency, 2020), while citation data were collected through the Orbit Intelligence database. I then distinguished electrolysis-related inventions between green and non-green, applied the Main Path Analysis (MPA) on the corresponding citations network to identify the main trajectories of technological development (Verspagen, 2007) and adopt the Technology Life Cycle (TLC) model – proposed by Taylor & Taylor (Taylor & Taylor, 2012) – to identify milestones in the main development path (Bareiß et al., 2019). In doing so, I unveil key groups of inventions as emerging from the MPA in the different TLC phases – namely application, paradigm, and generation – and interplay between green and non-green technical solutions.

Findings reveal four groups of inventions that feature in the main development path of electrolysis technologies. In the application phase, the main development path includes inventions that provide key technical advancements related to membranes, separators, and electrochemical systems. In the subsequent phase, the paradigm phase, the main development path is consolidated by inventions representing technical solutions to optimize electrolyzer performance in the production of hydrogen through water electrolysis. Finally, in the generation phase, the main development path includes inventions about the process of electrocatalysis; this suggests development efforts in the direction of cost reduction and performance enhancement. This analysis also outlines that the main development path of electrolysis technologies involved both green and non-green technical solutions, with green solutions more prominent in the early phases, while non-green solutions in most recent periods.

This work contributes to the extant literature on green energy technologies in three main ways. First, this study provides evidence that green energy technologies generate fundamental knowledge flows for subsequent developments (the majority of the inventions in the main path of electrolysis technologies can be classified as green inventions), hence extending previous research on the impact and pervasiveness of green energy technologies (Barbieri et al., 2020; Fusillo, 2023; Wietschel & Seydel, 2007). Second, this study demonstrates that the development trajectory of a technology that is expected to provide a key contribution to the green and sustainable transition relies on the interplay between green and non-green energy technologies. This also expands recent efforts on the understanding of the sources of green energy technologies by examining this issue longitudinally and embedded within the field (green and non-green) in which a group of green energy technologies emerges (Barbieri et al., 2023). Finally, I highlight the key solutions among the plethora of electrolysis technologies (European Patent Office & The International Renewable Energy Agency, 2022; Schmidt et al., 2017; Ursúa et al., 2011) that are at the forefront of the green energy transition.

The remainder of the study is as follows. Section 2 outlines the theoretical background of the study by introducing concept of technological trajectory and its use to understand the evolutionary dynamics of green energy technologies. Section 3 describes the empirical approach, while Section 4 presents the results. Section 5 discusses the contribution and implications of the study, as well as its limitations and future research directions.

2 Theoretical background

2.1 Green versus non-green energy technologies

Global energy crisis, climate threats, pollution have pushed worldwide attention toward new paradigms aimed at generating a sustainable future. Policy and innovation efforts have been directed toward the development of the so-named green energy technologies, which are deemed to be as a major source of technological change for the next future (Fusillo, 2023; Griffiths et al., 2021), contributing to the well-being of the environment, economy, and society as a whole (Guo et al., 2020; Longden et al., 2022). Consequently, these technologies are expected to fulfil various technical and environmental requirements (Florida, 1996; Oltra & Jean, 2005), which are further exacerbated by stringent regulatory demands (Carrillo-Hermosilla et al., 2010). This often requires that green energy technologies result from the integration of diverse and heterogeneous technologies and knowledge sources (Petruzzelli et al., 2011), making them more sophisticated and pervasive compared to non-green energy technologies (Ardito, Messeni Petruzzelli, & Albino, 2016; Barbieri et al., 2020).

Extant research has outlined several features that distinguish green energy technologies from non-green energy technologies. First, green energy technologies often exhibit higher levels of novelty since they introduce innovative approaches to address environmental challenges and promote sustainability (Schiederig et al., 2012). Second, green energy technologies are inherently knowledge-intensive and based on a wider knowledge base (Nemet, 2012a, 2012b). This, in turn, makes these technologies more complex and creates higher entry barriers for new players in the industry (Bointner, 2014; Lee & Lee, 2013). These barriers often relate to higher investments in R&D as well as in a more complex search and recombination of knowledge (Di Ciccio et al., 2015; Smith, 2000). Third, green energy technologies tend to have a more significant and pervasive impact on subsequent inventions and technological developments (Barbieri et al., 2020). The impact of these technologies extends beyond the specific technology itself, thus shaping and inspiring advancements in various related fields (Ardito, Messeni Petruzzelli, & Albino, 2016). This further highlights the potential of green energy technologies in driving broader changes and improvements in different industries (McPherson et al., 2018; Mihailova, 2023), hence creating further knowledge flows both within and beyond green domains. Finally, green energy technologies are subject to specific technological, infrastructural, institutional, and behavioural lock-ins (Barbieri et al., 2023; Eitan & Hekkert, 2023) that can make it difficult for them to evolve and adapt to changing circumstances.

These characteristics of green energy technologies make the comprehension of their trajectories, and knowledge flows thereof, a complex and resource-intensive endeavour. Despite being challenging, this endeavour is crucial to gain deeper insights into green energy technologies and offer an interpretation focused on their evolution. Existing studies have attempted to shed new light on the trajectories of green energy technologies, yet many of these studies have not fully considered their complexity and rapidly evolving nature, except for a few examples (Arts et al., 2013; Oltra & Saint Jean, 2009; Rizzi et al., 2014; Verspagen, 2007). For instance, some studies analyze the development trends of green energy technologies through patent analysis, yet without considering the impact of the interconnections among them and thus, their knowledge flows, relying on the static patent count (Albino et al., 2014; Bointner, 2014). Other studies focus on the characteristics of prior knowledge that shape green energy technologies (Guo et al., 2020; Tan et al., 2021) or on the influence of green energy technologies on subsequent solutions (green and non-green) (Ardito, Messeni Petruzzelli, & Albino, 2016; Barbieri et al., 2020). However, these are invention-level studies that tend to neglect knowledge flow dynamics that shape the evolution of green energy technologies and the related technological trajectories over time , namely, these studies do not delve deeply into the different role of green and non-green technologies on the development of green technologies. In the same spirit of (Barbieri et al., 2023)) that examined the extent to which the development of green energy technologies is also dependent of the advancement in non-green technological domains, I instead focus on a dynamic approach that aims at unveiling technological trajectories through their knowledge flows. This, in turn, contributes to advancing the literature on green energy technologies by providing a more comprehensive understanding of the development and evolutionary dynamics of green energy technologies. At the same time, through this study tries to identify the role of green and non-green technologies within the main path of development of the electrolysis technologies.

2.2 Technological change: Trajectories and knowledge flows

Technology is characterized by continuous changes – related to progress along a technological trajectory – which has been conceived as a succession of technological paradigms (Dosi, 1982). Tracing a technological trajectory allows mapping the steps behind the possible directions of technology development (Martinelli, 2012; Verspagen, 2007) as these steps are often influenced by path-dependent nature (Vergne, 2013; L. Wang et al., 2020) or by technological lock-ins (Dolfsma & Leydesdorff, 2009). The shape of a technological trajectory is sculpted by knowledge flow dynamics (Hung et al., 2022) that characterize the technical change (Acemoglu et al., 2012; Taalbi, 2020) and, through them, it is possible to obtain a dynamic comprehension of the direction of technical changes (Meyer, 2002; Peri, 2005) Stated differently, studying technological trajectories allows gaining a deeper comprehension of technology by focusing on the evolutionary steps behind the establishment of a given paradigm (Dosi, 1982). In particular, assessing the knowledge flows shaping a given technological trajectory makes it possible to understand previous directions and forecast potential future technological advancements (Biondi & Galli, 1992; Hung et al., 2022; Toole, 2001; Verspagen, 2007).

The concept of technological trajectories has been applied in several fields, such as IoT, 3D printing, printers, semiconductors and electric vehicles (Feng & Magee, 2020; Filippin, 2021; Hung et al., 2022; Kim et al., 2017; L. Wang et al., 2020), to offer a dynamic comprehension of the development paths of respective technologies. Eventually, it has emerged that not all technology sectors have similar development paths. Green energy technologies may be explanatory in this sense since, as discussed earlier, they present an inherent complexity, require the combination of heterogeneous knowledge domains, and affect the development of technologies in green and non-green sectors (Barbieri et al., 2020, 2023; Heng & Zou, 2010), hence requiring specific attention. However, a focus on these technologies from the perspective of technological trajectories is scant. Therefore, considering the increasing attention toward green energy technologies (Calise, 2022; Guo et al., 2020; Tan et al., 2021), their idiosyncratic characteristics (Barbieri et al., 2020, 2023; Fusillo, 2023; Heng & Zou, 2010), and the lack in the previous literature on dynamic analysis of their evolution, I apply the theoretical lens of technological trajectories in the context of green energy technologies (Xu et al., 2016; Xu & Ni, 2017). In this way, by focusing on the interactions between different technologies through their knowledge flows (Hung et al., 2022) and, consequently, on the dynamics of innovation I can offer a new perspective related to green energy technologies.

2.3 Technology Life Cycle (TLC) Model

To contextualize the evolutionary perspective, I have combined the study of technological trajectories (Dosi, 1982) with the notion of the Technology Life Cycle (Kaplan & Tripsas, 2004; Suarez, 2004; Tushman & Murmann, 1998). Historically, of the notion of Technology Life Cycle was blurred, often confused with Product Life Cycle or Industry Life Cycle. To address this issue, and hence explain how separate paradigms emerge over time to achieve a given application, Taylor and Taylor (2012) reviewed the multiple concepts associated with life cycles (e.g. industry and product life cycles), and then generated an integrated model of the technology life cycle. The model comprises three main phases. The first phase is the application phase and "is described by the purpose for which it is used." (Taylor & Taylor, 2012, p. 547). The second phase is the paradigm phase, which "represents a particular technological approach that is used to achieve a target application."(Sood & Tellis, 2005, p. 153). Third, the generation phase refers to solutions that represent "a particular form or variation of the technological solution but shares the underlying scientific principles of all other generations within the same paradigm" (Taylor & Taylor, 2012, p. 548). I will rely on this module to interpret the results obtained when assessing the technological trajectories of green energy technologies so as to identify the pivotal technologies in each phase.

3 Data and Methodology

3.1 Research Setting

This study focuses on the case of electrolysis technologies. Considerable expectations have emerged about the role that hydrogen-based technologies can play in boosting the green energy transition (Griffiths et al., 2021; Hydrogen Europe & Revolve, 2022; International Energy Agency, 2019; Martinez-Burgos et al., 2021; Martino et al., 2024; Sazali, 2020). Hydrogen has been considered an attractive energy carrier since it is abundant in nature and its use does not directly result in CO_2 emissions. However, hydrogen is not exploitable in nature, but it must be produced by separating water molecules or extracting hydrogen atoms from other compounds. Electrolysis technologies have therefore attracted considerable interest from public and private organisations.

The process of electrolysis involves an electrolyzer that separates water molecules in hydrogen and oxygen using electricity. An electrolyzer, also known as an electrolytic cell or electrolytic reactor, is a device or apparatus that performs the process of electrolysis using an electric current to generate a non-spontaneous chemical reaction, typically breaking down a compound into its constituent elements or producing new compounds (Ursúa et al., 2011; Zoulias et al., 2004). The basic components of an electrolyzer are the electrodes (conductive materials often made of metals like platinum, graphite, or other materials with high electrical conductivity) and the electrolyte. One electrode is the anode (positively charged), while the other is the cathode (negatively charged); the electrolyte is the substance that facilitates the flow of electric current between the electrodes and can be a liquid- or a solid-state electrolyte. The electrolyzer is connected to an external direct current power supply, such as a battery or a power converter, which provides the electric current necessary for the electrolysis process. By applying electric current, the chemical reactions occur at the electrodes, leading to the desired products or transformations in the electrolyte. For instance, in water electrolysis, water (H_2O) is split into hydrogen gas (H_2) at the cathode and oxygen gas (O_2) at the anode.

Electrolysis technologies represent particularly suitable research setting for the purposes of this study since examining their evolution enables us to delve into the understanding of the interaction between green and non-green energy technologies. On the one hand, the electrolysis of water is a core process for the production of green hydrogen, that is hydrogen extracted by the electrolysis of water using renewable electricity (Dincer, 2012); on the other hand, these technologies result from the recombination of green and non-green technical solutions from a range of fields (e.g. chemistry, material science, electronics). This setting also permit to advance extant research that has examined electrolysis technologies in terms of technical/functional aspects, and environmental and socio-economic (Bhandari et al., 2014; European Patent Office & The

International Renewable Energy Agency, 2022; Gerloff, 2021; Netherlands Enterprise Agency, 2020; Utgikar & Thiesen, 2006) by increasing the understanding of the origins and directionality of a groups technologies that is expected to be pivotal to the green transition.

3.2 Data collection

Patent data and citations have been extensively used as a tool to identify technological developments and related knowledge flows (Alcácer et al., 2006; Jaffe, 1986; Meyer, 2002; Peri, 2005; Sinigaglia et al., 2022; Trajtenberg, 1990b), especially to study green energy technologies (Albino et al., 2014; Mueller et al., 2015; Nemet, 2012a). A patent document makes publicly available information about the type of technology that is protected (description of the invention and/or technological classification codes) when the technology was developed (filing year), the knowledge sources on which the development of the technology may have relied (backward citations), and the impact of the technology on subsequent technological developments (forward citations).

In this study, I considered patent data related to electrolysis technologies at the level of the simple Patent Family (PF). By focusing on simple PFs I avoid issues such as double counting of an invention being protected in different jurisdictions. I started from the sample of PFs related to electrolysis technologies as made available by the IRENA and the European Patent Office (EPO), recently adopted for a joint report on innovation trends in electrolyzers for hydrogen production (European Patent Office & The International Renewable Energy Agency, 2022). This sample includes 43,832 PFs from 1987 to 2021.[3] I then integrated the sample with citation data. More precisely, I gathered all citation between pairs of PFs by querying the Orbit Intelligence FAMPat database[4] (Orbit, hereafter). This process resulted in 77,009 citing-cited pairs that I used to build a citation network to map knowledge flows and study the technological trajectories of electrolysis technologies by using the MPA as described below.

3.3 Citation network and Main Path Analysis (MPA)

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[3] The dataset was compiled by querying the EPO's Espacenet database – queries (based on patent classification codes and keywords) are provided in the supplementary material of the corresponding report (European Patent Office & The International Renewable Energy Agency, 2022). For each PFs, the dataset includes a range of metadata (e.g. EPO Family ID, earliest priority dates, International Patent Classification codes, assignees, inventors) as well as variables identifying the specific electrolysis process phase(s) of each patented technology. The latter was provided by an EPO expert examiner in the electrolyzer/hydrogen field together with IRENA experts tasked to identify and classify PFs through the content analysis of PF documents. Five groups of technologies relevant for the electrolysis were identified: cell operation conditions and structure, electrocatalyst materials, separators (diaphragms, membranes), stackability of electrolysers (stacks), and photo electrolysis.

[4] See https://intelligence.help.questel.com/en/support/solutions/articles/77000436699-coverage-of-the-fampat-database

I employed MPA to examine the citation network associated with electrolysis patented-inventions and to obtain a dynamic comprehension of the evolutionary trajectories related to green energy technologies. Indeed, MPA allows to understand the pivotal technologies which shape the technological evolution of a given innovation (Filippin, 2021). This methodology was first developed by Hummon and Doreain (1989) – who applied MPA to examine the citation network of scholarly articles related to DNA theory so as to identify key advancements in the area – and subsequently applied to patent citation data by Verspagen (2007) to operationalise the concept of technological trajectories (Dosi, 1982). MPA considers the overall structure of the citation network to identify primary streams or main paths in this network. On the core assumption that patent citations are a proxy of knowledge flows (Alcácer et al., 2006; Liu et al., 2019), these main paths constitute the main developments and most relevant solutions of a given technological domain. Such an approach has been subsequently extensively applied to examine technological dynamics (e.g. Filippin, 2021).[5]

I acknowledge two major limitations may be associated with MPA (Filippin, 2021; Liu et al., 2019). First, the focus on a single main path may overlook trends in other segments of the network that are fundamental to the development of the examined technology. I attempt to minimize this risk by triangulating the results with previous academic work and reports describing the history of electrolysis (European Patent Office & The International Renewable Energy Agency, 2022; International Renewable Energy Agency, 2020; Schmidt et al., 2017; Ursúa et al., 2011; Zoulias et al., 2004). The second limitation is the assumption that citations are proxies of knowledge flows (Alcácer et al., 2006). To overcome this limitation, I have corroborated the results of the MPA by interpreting them within a TCL model.

I applied MPA on the citation network of electrolysis-related PFs[6](Kolaczyk, 2014). MPA starts with a citation network, where the relationship between a pair of nodes is depicted as a directed link pointing from the cited node to the citing node (Verspagen, 2007). It is possible to describe the citation network using an adjacency matrix C, in which the element c_{ij} is equal to 1 if node j cites node i, and zero otherwise. In this matrix C, rows represent citing PFs, while columns represent cited PFs. It is worth noting that I focus on the citation networks involving only electrolysis-related PFs. Within the citation network, I can identify different types of nodes: source nodes (or start points) are defined as those PFs that cite other PFs but receive no citations $(\forall j : c_{ij} = 0)$; sink nodes (or endpoints) represent PFs that are cited but make no citations to other PFs $(\forall j : c_{ji} = 0)$; intermediary nodes are PFs that cite and receive citations $(\exists j : c_{ij} \neq 0 \wedge \exists j : c_{ji} \neq 0)$; and

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[5] A recent survey of the literature adopting to map technological trajectories can be found in (Filippin, 2021).

[6] We developed a script in R language and used the igraph package (Kolaczyk and Csárdi, 2014).

isolate nodes represent PFs are not cited neither receive citations (this nodes are excluded from the analysis). A path between a source node and a sink node is defined as a search path.

Two main approaches exist to assess the importance of a link c_{ij}: the Search Path Link Count (SPLC) and the Search Path Node Pair (SPNP(Hummon & Doreian, 1989; Verspagen, 2007)). In the case of the SPLC, a link c_{ij} is weighted by the number of search paths that include c_{ij}; while in the case of the SPNP, the weight of the link is calculated as the product of n_i and m_j, where n_i is the count of PFs in C that can reach i and the i itself, while m_j is defined as the number of PFs in C that can reach j and j itself. Once the SPLC or SPNP values for each link are calculated, one or more main paths can be identified. In this study, I present the results obtained with the SPLC algorithm – the results are qualitatively similar to those obtained with the SPLC algorithm. I then identified the main path by taking the max of the sum of SPLC by applying the global search approach (Liu & Lu, 2012). It is worth noting that the C matrix on which I perform MPA, includes 42,236 PFs (about 96% of the original sample of PFs). The reaming PFs were excluded since they were not included in the largest weakly connected component of the citation network accounting for all PFs in the original sample. The PFs in the matrix were filed from 2003 to 2020, while the reaming PFs were filed before 2003 (177 PFs) or after 2020 (1,419 PFs). Drawing on the results from MPA, in the next section, I present the key technological advancements that have shaped the development of electrolysis technology and positioned these in the phases of the TLC model.

4 Results

In this section, I first delineate the set of core inventions relevant to the evolutionary trajectory of electrolysis technologies by outlining the main paths I identified through MPA. I then examine the sequence of these main technological advancements by using the TLC model (Taylor & Taylor, 2012). I conclude the analysis by investigating the interplay between green and non-green inventions within the main evolutionary path of electrolysis technologies.

4.1 Mapping technological trajectories

The citation network corresponding to the electrolysis-related PFs includes 77,009 citation links that connect 30,692 nodes– 11,024 are sink nodes, while 7,374 are source nodes. This network is depicted in Figure 1. MPA returned six main paths that differ: each main path involves 14 PFs and share all intermediary PFs. The network of main paths is depicted in Figure 2.

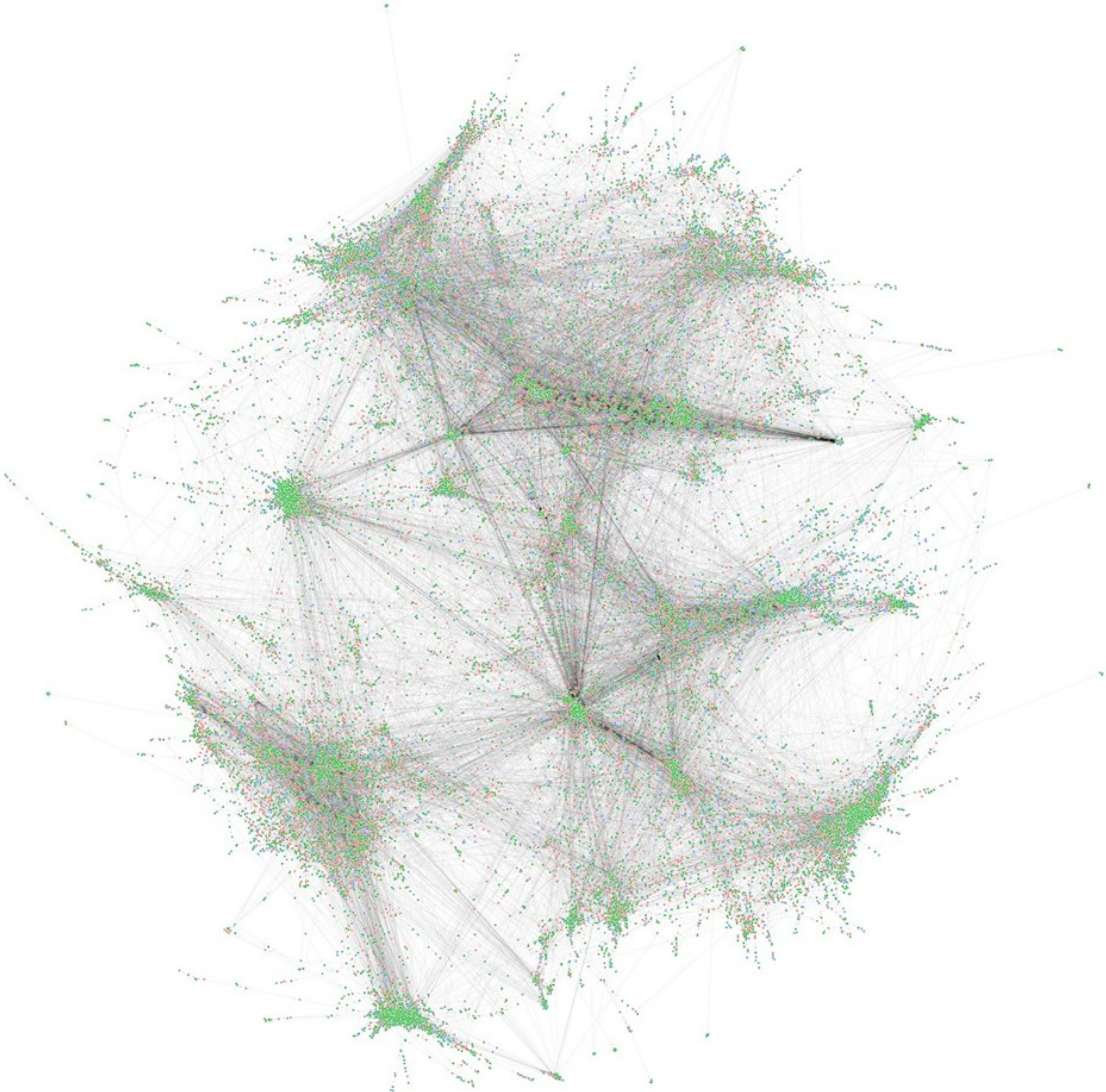

Figure 1. Citation network of electrolysis-related PFs (source, intermediary, and sink PFs are represented as blue, red, and green nodes, respectively).

Source: Authors' elaboration

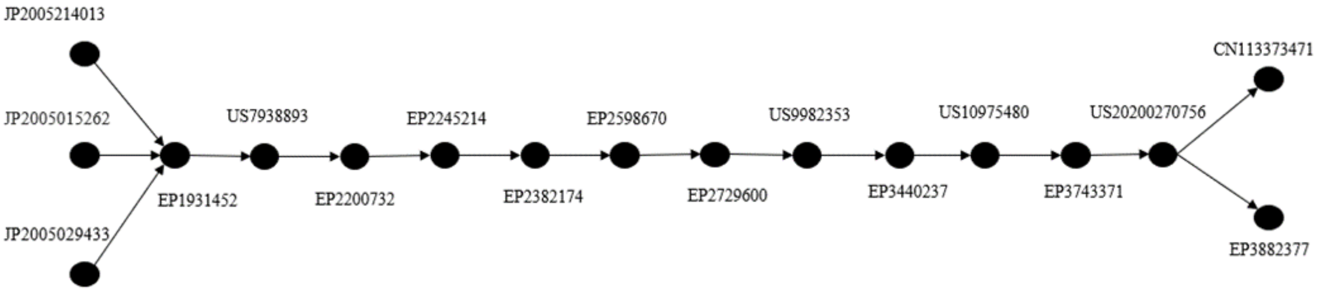

Figure 2. Electrolysis technology: Network of main paths (2003-2020).

Source: Authors' elaboration.

I analysed each PF constituting the network of main paths to identify its function. I triangulated this analysis by examining available technical literature on electrolysis (Bareiß et al., 2019; European Patent Office & The International Renewable Energy Agency, 2022; Ursúa et al., 2011; Zoulias et al., 2004). Four groups of inventions were identified. These relate to membranes and separation of hydrogen, electrochemical systems, hydrogen production through water electrolysis, and electrocatalysis. Table 1 outlines these inventions with corresponding PFs. On the one hand, inventions related to membranes and separation of hydrogen [JP2005214013, JP2005015262, JP2005029433, EP1931452, US7938893, EP2200732] include innovative solutions applied to improve membranes and the separators involved in dividing the water molecules. These technologies attempted to reduce the membrane thickness, enabling an increase in efficiency combined with a reduction in electricity consumption. On the other hand, inventions related to electrochemical systems [EP2245214, EP2382174, EP2598670, EP2729600] aimed at separating various types of gases. By applying electric current, a chemical reaction occurs at the electrodes, hence leading to the desired products or transformations in the electrolyte, namely, splitting water (H2O) into hydrogen gas (H2) at the cathode and oxygen gas (O2) at the anode (Dincer, 2012; Edwards et al., 2007; Yu et al., 2021). PFs related to hydrogen production through water electrolysis protected inventions that attempted to address a number of challenges in this process. For instance, it is important to raise the current densities within the electrolyzer (i.e., using an alkaline design with base metal catalysts that can provide even higher current densities) [US9982353] to improve the efficiency or to involve the Proton Exchange Membrane (PEM) electrolyzers (i.e., employing base metal catalysts and an anion-conducting polymeric membrane comprising a polymer of styrene, vinyl benzyl-Rs and possibly vinyl benzyl-Rx) [EP3440237]. The more recent set of inventions have focussed on electrocatalysis [US10975480, EP3743371, US20200270756, EP3882377, CN113373471] and have aimed to replace relatively expensive materials (Eftekhari, 2017) with cheaper ones such as non-noble materials.

Function	***PFs****	**Title**
Membranes and separation of hydrogen	JP2005214013	Power Generation System Using Methane-Containing Gas as Supply Gas
	JP2005015262	Hydrogen Production System
	JP2005029433	Hydrogen Production Equipment and Stop-Start Method of the Equipment
	EP1931452	Functionalized Inorganic Membranes for Gas Separation
	US7938893	Membrane reactor for H2S, CO2 and H2 separation
	EP2200732	Production of Carbonate-Containing Compositions from Material Comprising Metal Silicates
Electrochemical systems	EP2245214	Electrochemical System and Method for CO2 Utilization
	EP2382174	Conversion of Carbon Dioxide to Organic Products
	EP2598670	Electrochemical Production of Synthesis Gas from Carbon Dioxide
	EP2729600	Carbon Dioxide Capture and Conversion to Organic Products
Production of hydrogen through water electrolysis	US9982353	Water electrolyzers
	EP3440237	Water electrolyzers
Electrocatalysis	US10975480	Electrocatalytic process for carbon dioxide conversion
	EP3743371	System and Method for Carbon Dioxide Reactor Control
	US20200270756	Electrode Catalyst Layer for Carbon Dioxide
	EP3882377	Electrode Catalyst Layer for Carbon Dioxide
	CN113373471	Preparation method and application of indium-based catalyst for preparing low-carbon alcohol through electrocatalytic reduction of CO2

Table 1. Electrolysis technologies and related PFs.

* Standardized Publication Numbers;

Source: Authors' elaboration.

I could recognize that technologies related to membranes and separation of hydrogen, as well as to electrochemical systems, are deemed to solve key problems of the electrolysis process, i.e., the separation of hydrogen and oxygen and electrochemical power production – these are also the earliest technologies appearing in the main paths. Technologies related to the production of hydrogen through water electrolysis, instead, can be considered at the 'heart' of the main paths and are part of the different paths. These technologies present configurations of the key systems required for the electrolysis process – i.e., systems of electrodes, membranes, and separators that enable the water electrolysis – and deepened between 2012 and 2014. Finally, technologies related to electrocatalysis represent advancements in technologies to produce hydrogen through water electrolysis and are the most recently developed.

Such an evolutionary path can be examined from the perspective of the TLC phases proposed by Taylor & Taylor (2012). In this analysis, technologies related to separation and electrochemical power production are explanatory of the purpose of the electrolysis' utilization. Therefore, by assessing the TLC model of Taylor, I can collocate these technologies in the application phase. Subsequently, I can categorize technologies for producing hydrogen through water electrolysis as part of the paradigm phase. Indeed, the target applications are the production of hydrogen, and the technological approach is the water electrolysis, according to the definition of the paradigm phase. Finally, the generation phase includes solutions related to electrocatalysis aimed at varying the electrolysis process not from an architectural perspective but from a modular perspective (i.e., using components of diverse materials that do not affect the overall electrolysis process) (Henderson & Clark, 1990). Figure 3 depicts the set of inventions in the main paths along with the phases of the TLC model. I describe each phase below.

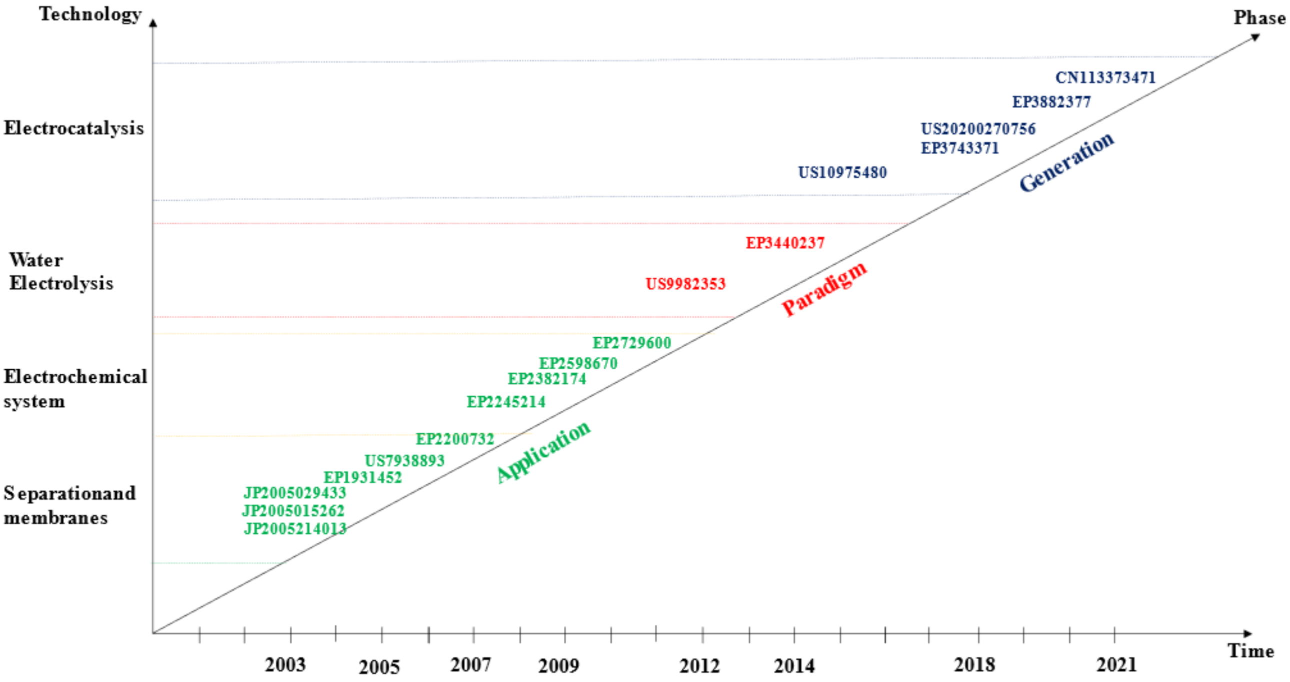

Figure 3. The evolution of the electrolysis technology according to the results of the MPA within the phases of the TLC model (only those years referring to PFs are reported).

Source: Authors' elaboration.

Application phase (2003-2011). Electrolyzers have been known for over two centuries and, while the fundamental technology has remained the same, different trends have characterized their development, as also confirmed in a report by IRENA (2020). In the first phase of the electrolysis's history (1800-1950), the electrolyzers operated at atmospheric pressure, using concentrated corrosive basic solutions (e.g., potassium hydroxide [KOH]), and asbestos was used as gas separators (called diaphragms). Asbestos can pose large health hazards, therefore was replaced by membranes in the second generation of electrolyzers (International Renewable Energy Agency, 2020). The second generation was defined by polymer chemistry breakthrough findings that were the basis for Proton Exchange Membranes (PEM) electrolyzers. PEM cells could be easily fed with pure water, contrariwise to alkaline systems that involve caustic solutions, and this provided a considerable reduction of system complexity, footprint, higher efficiencies, and power densities. In this scenario, the diaphragms of asbestos were replaced by the membranes. In line with this historic account, it is possible to note that the early patents in the main path relate to gas separation technologies [EP1931452, US7938893, EP2200732] and to electrochemical systems to convert and utilize these gases containing hydrogen [EP2245214, EP2382174, EP2598670, EP2729600]. A representative example of this set of technologies is depicted in Figure 4 which displays two drawings from the PF [EP1931452]. Specifically, Figure 4a relates to porous membranes for the separation of carbon dioxide from a fluid stream (at a temperature higher than about 200°C), while Figure 4b describes a low-voltage and low-energy electrochemical system. This method removes protons and generates a base solution containing hydroxide, carbonate, and bicarbonate ions. It utilizes carbon dioxide within a cathode compartment divided into a first and second cathode electrolyte compartment, allowing liquid flow but restricting gaseous communication between them. On this basis, the PFs describing technologies related to separators and electrochemical solutions can be considered part of the application phase since describe the purpose for which the electrolysis is applied (Taylor & Taylor, 2012, p. 547). Moreover, from a temporal perspective, it is possible to verify that there exists a path dependency between the inventions related to the separation method and membranes and technologies about water electrolysis. Considering the evolution of these technologies, the purpose of separators – using diaphragms first and membranes afterward – is to reduce membrane thickness, thereby increasing efficiency and consequently reducing electricity consumption (Peters et al., 2017). At the same time, the objective of optimizing electrochemical systems is to create an efficient process for energy conversion. Thus, the combination of gas separation technologies and electrochemical systems lays the groundwork for the establishment of the paradigm of the next phase, namely the development of water electrolysis.

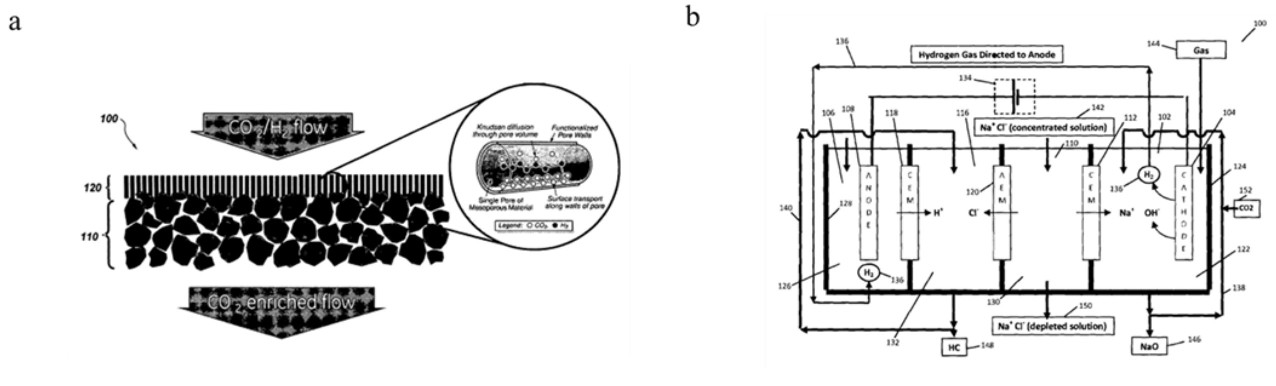

Figure 4. (a) Porous membranes for separation of carbon dioxide; (b) Low-voltage, low-energy electrochemical system.

Source: PF EP1931452.

Paradigm phase (2012-2014). After the application phase, I can identify the inventions related to modern electrolyzers (2012-2014) [US9982353, EP3440237]. Specifically, the inventions identified are focalized on methods for raising the current densities within the electrolyzers (i.e., using an alkaline design with base metal catalysts that can provide a high current density at temperatures of 80°C). In particular, these PFs deal with water electrolyzers that employ base metal catalysts and an anion-conducting polymeric membrane. For instance, Figure 5a illustrates a fuel cell hardware assembly, which includes a membrane electrode assembly interposed between rigid flow field plates (typically formed of graphite or a graphite composite material). Membrane electrode assembly consists of a polymer electrolyte (ion exchange), and of a membrane interposed between two electrodes (namely, anode and cathode typically formed of porous electrically conductive sheet material, such as carbon fiber paper, and have planar major surfaces). Electrodes have a thin layer of catalyst material disposed on their surfaces at the interface with the membrane to render them electrochemically active. Figure 5b shows the current measured when a copolymer of styrene and vinyl-benzyl-tetramethyl imidazolium (a positively charged ligand containing an imidazole group). The experiment conducted and reported in Figure 5b showed 1 A/cm2 at 60°C and a cell voltage of 1.9 V. The target application is the optimization of electrolyzers, and to obtain this goal several technologies are applied generating a technology different from the previous ones.

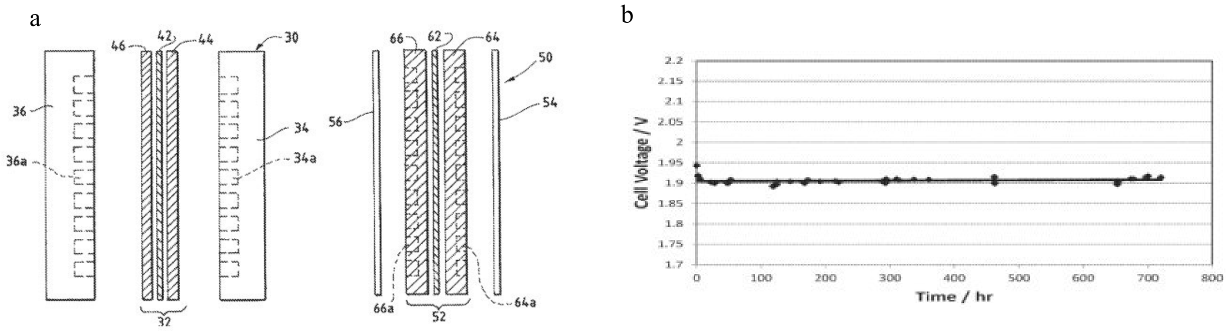

Figure 5. (a) Fuel cell hardware assembly; (b) Current measured when a copolymer of styrene and vinyl-benzyl-tetramethyl imidazolium was tested.
Source: PF EP3440237.

Generation phase (2014-2020). After the inventions concerning the electrolyzers, it is possible to identify the technologies related to electrocatalysis, which is the key to reducing the cost of electrolysis and increasing its performance (Eftekhari, 2017). The goal related to electrocatalysis is the identification of solutions to replace the expensive materials needed by using cheaper ones such as non-noble materials (European Patent Office & The International Renewable Energy Agency, 2022). This focus is made on the most recent group of inventions identified by MPA [US10975480, EP3743371, US20200270756, EP3882377, CN113373471]. For instance, PF [US20200270756] presents an electrode catalyst layer for an electrolysis cell with a controlled porous structure (Figure 6a), and an electrolysis cell and a carbon dioxide electrolysis apparatus comprising that layer (Figure 6b). The catalyst layer has a controlled porous structure that can realize a high partial current density. The catalyst layer contains pores of 5 to 200 μm diameters, and the pores have a volume per weight of the catalyst layer in the range of 3.0 to 10 mL/g in total. I reported the PF

[US20200270756] as representative of the generation phase since it deals with technologies of optimization of the technological paradigm. In addition, considering the timeline, these patents are the latest ones in the MPA, following, as expected, the issuance of the patents that describe the paradigm.

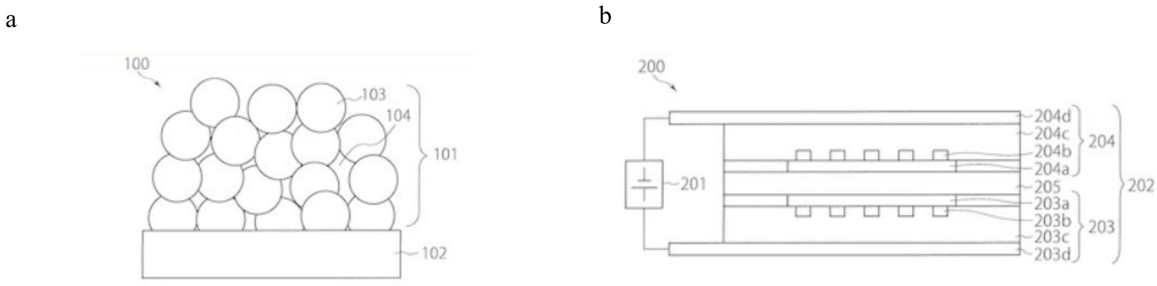

Figure 6. (a) Schematic sectional view of an electrode catalyst layer for an electrolysis cell with a controlled porous structure; (b) Schematic sectional view showing an electrolysis cell and a carbon dioxide electrolysis apparatus.
Source: PF US20200270756.

4.2 The interplay between green and non-green energy technologies

Developments in an environmentally-friendly technological domain are likely to require both green and non-green energy technologies (Barbieri et al., 2023). I delve into this issue by distinguishing the inventions in the main development trajectory of electrolysis between green and non-green inventions. To do so, I codified an invention as green if the corresponding PF is classified in at least one of the International Patent Classification (IPC) code of in the World Intellectual Property Organization's (WIPO) IPC Green Inventory (Frietsch et al., 2016; Guo et al., 2020; Karimi Takalo et al., 2021).[7] As depicted in Figure 7, this analysis revealed that the majority of the inventions (64.7% or 11/17 inventions) in the network of the main paths are green. It is worth noting that the application and paradigm phases of the TLC model are mainly composed of green inventions, while the generation phase is mainly composed of non-green inventions. In the application and paradigm phases, major technical developments aimed for optimization of performance initially related to separators and membranes, and subsequently to the electrochemical system and current densities. This ensured higher performance and, therefore, environmental improvements. In the generation phase, the prevalence of non-green energy technologies may lie in the fact that the shift to electrocatalysis requires enabling technologies that depart from the green domain: except for PF

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[7] https://www.wipo.int/classifications/ipc/green-inventory/home

[EP3882377], which applies the principles of electrocatalysis to electrode catalyst layer for carbon dioxide electrolysis cell – hence, ensuring optimization of the performance related to electrolysis – the remaining technologies refer to the general principles of electrocatalysis that are needed for electrolysis but not only for electrolysis. For instance, PFs [CN113373471] deal with the preparation method and application of indium-based catalyst for preparing low-carbon alcohol through electrocatalytic reduction of CO_2 and PF [EP3743371] describe the system and method for carbon dioxide reactor control. In summary, the application and paradigm phases are particularly influenced by the presence of green energy technologies, while the generation phase is relatively less green. The reasons behind these results could be related to the purpose of the technologies in the generation phase which are more general purpose and oriented to chemistry and electricity and not strictly to the concept of "green" (electrocatalysis could be implied for several aims). In addition, these technologies are even more recent, hence they could still become an input to feed future green energy technologies. The presence of green energy technologies within the main paths is extremely high in comparison to the probability of finding these technologies in the respective time periods (as reported in Table 2). This evidence could be interpreted as proof of the impact of green energy technologies in the development of a paradigm. In particular, while non-green energy technologies are necessary within the technological trajectory, green energy technologies eventually play a pivotal role.

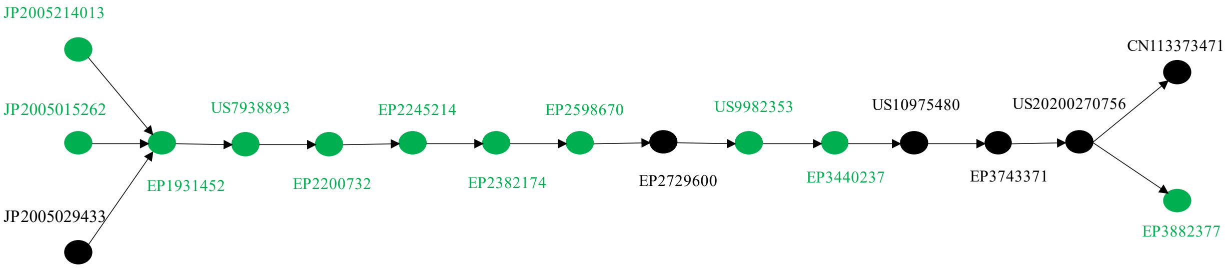

Figure 7. Green inventions within the network of main paths (2003-2020).

Source: Authors' elaboration

Phase (period)	***PFs***	***Green PFs***	***Probability of green PFs***	***PFs in the network of main paths***	***Green PFs in the network of main paths***	***Probability of green PFs in the network of main paths***
Application (2003-2011)	14,884	8,859	59.5%	10	8	80.0%
Paradigm (2012-2014)	6,445	3,157	49.9%	2	2	100.0%
Generation (2015-2020)	20,907	7,712	36.9%	5	1	20.0%
Total	42,236	19,728	46.7%	17	11	64.7%

Table 2. Electrolysis PFs and composition of technologies.

Source: Authors' elaboration.

Note: I considered the period covered by the PFs in the C matrix to present the table.

5. Discussion, implications, and limitations

In this study, I propose an analysis of the technological trajectories of electrolysis technologies to dig into the evolutionary dynamics that may characterize green energy technologies (Xu et al., 2016; Xu & Ni, 2017). Drawing on the technological trajectories as a theoretical lens, this study identified and elaborated on the knowledge flows underlying electrolysis technologies to trace key solutions and their development stages. To do so, I relied on a sample of 43,832 PFs, and related citation data, to build a citation network that I analyzed through MPA. This enabled to identify four key sets of solutions in the different phases of the TLC model proposed by Taylor & Taylor (2012) – (i) solutions about membranes and hydrogen separation and (ii) electrochemical systems (application phase), (iii) inventions about hydrogen production through water electrolysis (paradigm phase), (iv) inventions about electrocatalysis (generation phase). The results show that, in the application phase of the TLC model, the technical solutions that feature in the main development path of electrolysis technologies aim to reduce membrane thickness, thereby increasing efficiency and consequently reducing electricity consumption (Peters et al., 2017). At the same time, inventions related to electrochemical systems aimed at creating an efficient process for energy conversion are present. The combination of gas separation technologies and electrochemical systems lays the groundwork for the establishment of the paradigm phase, namely the development of water electrolysis. In this phase, major inventive effort targeted the optimization of electrolyzers. Finally, in the generation phase, main technical solutions deal with technologies of optimization of the technological paradigm, specifically describing the innovations required to a cheaper electrocatalysis (Eftekhari, 2017).

These findings offer some relevant implications for both theory and practice. From the theoretical perspective, this study advances the understanding of green energy technologies (Barbieri et al., 2020, 2023) by offering a view on their technological trajectories and evolutionary paths. Indeed, on the one hand, extant research has demonstrated that green energy technologies present a higher degree of novelty in comparison to non-green energy technologies (Barbieri et al., 2020; Gallagher et al., 2012) since they are the result of the integration of heterogeneous technologies and knowledge sources (Nemet, 2012b, 2012a; Petruzzelli et al., 2011). On the other hand, this initial evidence is based on invention-level studies that do not consider the evolutionary dynamics that have led to a given (green) technology and do not follow their technological trajectories. Results depicted in Figure 7 demonstrate that green energy technologies are more present in the evolutionary path in comparison to non-green energy technologies when considering technological trajectories over time despite what the odds suggest (as reported in Table 2). Therefore, it could be reasonable to sustain that green energy technologies are more impactful and pervasive in subsequent technological developments as reported by Barbieri and colleagues (2020) and present a pivotal role for the instauration of a dominant paradigm. Specifically, I delve into the development paths of a set of technologies that have been widely examined from a technical perspective but less from the perspective of their evolution, neglecting more dynamic approaches over more conventional invention-level statistics (e.g. Medeiros Araújo de Moura et al., 2024).

From the practical perspective, I shaped the boundaries of the evolution phases of the electrolysis technologies within the TLC model, hence informing practitioners and policymakers, especially in the energy domain, of which are the key electrolysis technologies that have set the technological trajectory in such domain and that are, hence, those on which it is probably safer to invest private and public money for the greening of the energy sector and run businesses. Of course, I do not intend to suggest discarding investments in novel technologies that depart the existing trajectory, but I seek to provide insights for balancing the risks between following a safer path that may lead to short-term economic and environmental advantages and following new paths that will constitute important improvements in the long run. Still, I acknowledge that every evolution phase has different economic potential and economic needs. Indeed, it is reasonable that early technical solutions in the main development path present a higher Technology Readiness Level (TRL) in comparison to the last which are more recent. Specifically, considering Figure 3, the more mature technologies are included in the application and paradigm phases from 2003 to 2014 while and the more recent ones (Generation, from 2014 to 2021). Relying on this assumption, it could be possible for policymakers to formulate policy or financing strategies ad hoc for each phase. For instance, the

European Union (EU) provides funding programs for research and innovation such as Horizon Europe, in which the TRL plays an essential role, and needs to be specified and demonstrated in project proposals. The Horizon Europe program has allocated around € 95.5 billion in funding for 2021-2027, and the TRL scale is used to help align applicant expectations with call topics, giving an idea of the current research maturity level to applicants, and determining project eligibility (Doussineau et al., 2018). Thereby, policymakers could deepen the TRL associated with the technological solutions of the MPA to obtain insight into their market potentiality and to adopt the appropriate financing measure (Carfora & Scandurra, 2024; Suzuki et al., 2023). Finally, the results obtained through MPA could help managers to formulate their strategies regarding the choice of innovation of a given technology. Indeed, this study could help R&D managers to choose what specific technological domain of electrolysis shell be deepened. For instance, results seem to suggest that electrocatalysis is the current technological topic. Therefore, to obtain a technological advantage, it could be useful to accelerate the knowledge related to this technology.

In summary, I have proposed insight into the economic promise of investing in electrolysis technologies, and, at the same time, I have identified the technological trajectories and the related phases with the technological questions solved. This endeavour could help managers and policymakers in the energy sector to identify the nature of the investment to reserve for each phase, by considering the maturity of their development. However, it must be considered that there are some limitations to this study. First, I have retrieved and used only patent data for the analysis but not all inventions are patented, or not yet. In addition, the patent analysis may be limited since patent documents offer only restricted information on electrolysis technologies. Therefore, as a further external validation other technical knowledge sources, such as scientific articles and journal articles, could be added. Second, in this work, I do not describe technically or in detail the technologies of electrolysis, but I have focused the attention on the technological trajectories, taking into consideration neither the economic aspects related to the production costs. Therefore, could be interesting to deepen these aspects in future research. Third, considering the methodological approach, it would be reasonable to perform a further robustness check by applying an analysis of the patents through text mining. For instance, using text mining it would be possible to identify the category of electrolysis most studied (PEM or AEM Anion Exchange Membrane or AEL Alkaline Electrolyser) related to electrolysis technologies. In this way, it would be possible to compare these results with the indications obtained from text mining. Therefore, broader discussions on social, environmental, and sustainability aspects are also important in the future. Resolving these limitations and improving the methods could be useful for further studies to better manage the complexity related to green energy technologies.

Assessing the impact of the green technologies: analysis of the electrolysis setting

1 Introduction

This study tries to answer to the question of what affects the extent to which one technology contributes to the development of new technologies (Grodal et al., 2023), i.e., what affects its technological impact (Veugelers & Wang, 2019). While the overall magnitude of technological impact is essential, a deeper investigation into its diverse manifestations is warranted. Two primary lines of reasoning emerge: the first examines whether a technology significantly influences its original domain or extends beyond it (Abernathy & Utterback, 1978; Phene et al., 2006; Pironti et al., 2010; Sood & Tellis, 2005). The second focuses on whether technological change remains within the organizational boundaries of the innovating firm or reaches beyond them (De Noni et al., 2017; Harpaz & Meshoulam, 1997). Thus, the study of technological impact requires assessing heterogeneous aspects, including types of technologies, pervasiveness, and multiple organizations involved in R&D.

With this in mind, one could recognize that the green domain, involving the development of green technologies, is a complex domain characterized by heterogeneous aspects, making it essential to assess technological impact both within and beyond the starting domain and organizational boundaries (Barbieri et al., 2020, 2023). Indeed, the green sector is continuously evolving due to its intrinsic innovativeness (Aldieri & Vinci, 2018; Guo et al., 2020; Karimi Takalo et al., 2021; Tan et al., 2021) and is inherently knowledge-intensive and relies on information held by various organizations, highlighting the collaborative nature of R&D in green technology (Nemet, 2012a, 2012b). Research indicates that numerous organizations participate in developing green technologies, with no clear leader emerging in the field (Ardito, Messeni Petruzzelli, & Albino, 2016; Guo et al., 2020; Heng & Zou, 2010). These characteristics make green technologies generally more complex than their non-green counterparts (Barbieri et al., 2020) and can have effects that extend beyond the green domain. Additionally, extant literature suggest that green technologies often emerge from the hybridization of green and non-green technologies, resulting in diverse outputs (Barbieri et al., 2020; Dechezleprêtre et al., 2017; Zeppini & van Den Bergh, 2011) and in more heterogeneous technologies in the output phase (Fusillo, 2023), confirming that green technologies can impact both green and non-green domains. Therefore, I try to answer to the following research questions: i) Do green technologies positively impact innovation and specifically promote the development of future green technologies, including by organizations that did not originally create them? ii) Do technologies built on green prior art positively impact overall innovation and specifically foster the development of future green technologies, including by organizations that were not the original inventors? iii) Do technologies based on non-green prior art have a positive overall impact, particularly on the development of future green technologies, and do they also benefit organizations that were not the original inventors in creating new green technologies?

To answer to these questions, I considered three main variables. First, I calculated the *Overall Technological Impact* (*OTI)* as the total number of forward citations received by the PF in the five years after its first application. Second, I calculated the *Green Technological Impact (GTI)* as the total number of green forward citations (classified as green) received by the PF in the five years after its first application. Third, I calculated the *GTI beyond organizational boundaries (GTI-BOB)* as the total number of green and non-self forward citations received by the PF in the five years after its first application. In sum, the first dependent variable looks at the overall impact of a technology, the second dependent variable looks at the impact in terms of development of new green technologies instead of new non-green technologies, and the third dependent variable looks at the impact in terms of development of new green technologies spanning organizational boundaries.

To conduct this study, I focus on electrolysis technologies as the research setting since these are considered highly promising for the green transition. Moreover, electrolysis technologies originate from the search and recombination of green (Shiva Kumar & Lim, 2022) and non-green Albino et al., 2014; Martinez-Burgos et al., 2021) energy technologies and can be considered as either green or non-green themselves. This emphasizes that it is possible and relevant to distinguish technologies and their prior art among green and non-green; likewise, their impact relates to the development of new green or non-green technologies. Finally, these technologies are studied by several organizations across the world (Martino et al., 2024; Schmidt et al., 2017; Ursúa et al., 2011) as a proof of their economic promising as well as their innovativeness. This dispersion across organizations is another reason for choosing electrolysis technologies as the research setting since by evaluating the development of technologies between organizations, it becomes easier to assess the technological impact across them. Relatedly, I collected a sample of 43,832 granted PFs in the electrolysis field, applied from 1987 to 2021 and made available by the IRENA and the European Patent Office (EPO)[8]. I found that a higher adoption of green technologies as prior art is consistently beneficial in terms of technological impact, suggesting that following green

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[8] The dataset was compiled by querying the EPO's Espacenet database – queries (based on patent classification codes and keywords) are provided in the supplementary material of the corresponding report (European Patent Office & The International Renewable Energy Agency, 2022). For each PFs, the dataset includes a range of metadata (e.g. EPO Family ID, earliest priority dates, International Patent Classification codes, assignees, inventors) as well as variables identifying the specific electrolysis process phase(s) of each patented technology. The latter was provided by an EPO expert examiner in the electrolyzer/hydrogen field together with IRENA experts tasked to identify and classify PFs through the content analysis of PF documents. Five groups of technologies relevant for the electrolysis were identified: cell operation conditions and structure, electrocatalyst materials, separators (diaphragms, membranes), stackability of electrolysers (stacks), and photo electrolysis. See https://intelligence.help.questel.com/en/support/solutions/articles/77000436699-coverage-of-the-fampat-database

technological trajectories is advantageous. Conversely, a higher adoption of non-green technologies has a detrimental effect on technological impact, indicating that green prior art is more relevant than non-green prior art. However, this does not imply that non-green prior art is generally harmful. While the green nature of the technology is important for developing new green technologies, its impact on overall technological advancement is not fully substantiated.

2 Theoretical background

2.1 Technological impact

Several scholars have dealt with the topic of technological change, as an important lever for growth (Abernathy & Utterback, 1978; Chesbrough, 2006), by explaining some of its key features such as the defining characteristics of an emerging technology (Rotolo et al., 2015), the process required to shift from a technological paradigm to (Dosi, 1982), the relationship between applied and basic research (Subtil Lacerda, 2019), or the constraints that influence the emergence of a technological trajectory (Dolfsma & Leydesdorff, 2009; Eitan & Hekkert, 2023; Martin & Sunley, 2010; Vergne, 2013). All of these studies have contributed to obtain a major knowledge on the technological change, yet almost all agree with the idea that technological change is characterized by cumulativeness of innovative success (Dosi & Nelson, 2010), whereby new technologies are often based on previous technologies, as new technological problems can be “solved with pieces – components – that already exist (or pieces that can be created from ones that already exist)” (Arthur 2007, p. 285). A notion in line with the idea that technological change “is often the result of an ordinate (rather than unusual or genius) creative process that is rooted in previous learning and uses of existing technologies” (Ardito, Messeni Petruzzelli, & Panniello, 2016, p. 918; Lettl et al., 2009). Of course, not all technologies contribute to technological change equally. State differently, the impact of one technology on the development of future technologies can differ significantly from that of another. This has led to the question of what affects the extent to which one technology contributes to the development of new technologies (Grodal et al., 2023), i.e., what affects its technological impact (Veugelers & Wang, 2019).

So far, academic research has provided several insights into the factor that affects technological impact such as depth of firms’ knowledge base, integration capabilities or the technological breadth (Coccia, 2009; Ning & Guo, 2022a; Singh, 2008; Veugelers & Wang, 2019). Still, research has also indicated that technological impact could be better investigated by digging into its diverse manifestations. In this vein, aside from its overall magnitude—which remains a crucial factor—a first line of reasoning examines whether a technology exerts significant influence within or outside the domain in which it first emerged (Abernathy & Utterback, 1978; Phene et al., 2006; Pironti et al., 2010; Sood & Tellis, 2005). Instead, a second line of reasoning focuses on whether technological change is confined within the organizational boundaries of the organizations that has developed the focal technology or extends beyond them (De Noni et al., 2017; Harpaz & Meshoulam, 1997). Indeed, on the one hand, it is necessary to identify the impact that a technology can generate within or beyond domain boundaries. For instance, Messeni, Rotolo and Albino (2015), by analyzing biotechnology sector, have studied the key drivers leading certain innovations to exert a stronger influence on the subsequent technological developments and the implications within or outside the starting sector. Notably, boosting the development of technologies across diverse domains enables cross-disciplinary innovation, foster technological convergence, and opens up new opportunities for solving complex global challenges, ensuring that technological advancements contribute meaningfully across multiple fields (Banerjee & Cole, 2010; Hazy & Tivnan, 2003; Shin & Jalajas, 2010; J. Wang et al., 2022). Also, in the biotechnology domain, the conservation of genetic resources has been obtained through established technologies previously adopted in the genomic domain (i.e., cryopreservation, artificial seed production, somatic embryogenesis, and other forms of in vitro cell or tissue culture) (FAO, 2010). This further confirms that technological advancements in one domain could imply positive effects also considering other domains through spillover effects (Guadagno et al., 2024). On the other hand, it is relevant to comprehend the influence that a given technology could exercise on organizations that are not the inventors of the focal technology. Indeed, when a technology developed by one organization is adopted and further developed by others, it drives innovation, reduces costs, and fosters collaboration (De Noni et al., 2017; Teece, 1986). This interconnected approach to technological development creates a dynamic environment where technological change benefits society at large. Accordingly, some scholars have been interested in this issue, for instance by explaining the relationship between the use of external innovation sources and innovation performance within organizations (Fındık & Beyhan, 2015; Guan et al., 2006; Svetina & Prodan, 2008).

Following the foregoing discussion, in this study, I aim to offer an analysis of the technological impact by integrating these two lines of reasoning.

2.2 Green technologies and their technological impact

As previously argued, assessing technological impact is not straightforward. In fact, understanding how one technology affects the development of new technologies across different domains and in other organizations can be valuable in evaluating its impact (Dokko et al., 2012; Phene et al., 2006;

Rosenkopf & Nerkar, 2001). In other words, the study of technological impact requires assessing heterogeneous aspects, including types of technologies, pervasiveness, and multiple organizations involved in R&D. From this viewpoint, one of the most complex domains that presents such heterogeneous aspects, for which it is relevant to assess technological impact within and beyond the starting domain, as well as within and beyond organizational boundaries, is that of green technology (Barbieri et al., 2020, 2023). Notably, the green domain is in constant evolution due to their intrinsic innovativeness (Aldieri & Vinci, 2018; Guo et al., 2020; Karimi Takalo et al., 2021; Tan et al., 2021) and the need to create a more sustainable world. Second, the green domain is inherently knowledge-intensive and based on knowledge owned by several different organizations (Nemet, 2012a, 2012b), hence involving diverse organizations in R&D showing that a wide range of organizations are involved in developing green technologies, with no single clear leader emerging in the field (e.g.,Ardito, Messeni Petruzzelli, & Albino, 2016; Guo et al., 2020; Heng & Zou, 2010). This suggests that a single technology can influence not only the R&D activities of the innovating organization but also those of other organizations. Third, technologies in the green domain are considered more complex in comparison to non-green ones (Barbieri et al., 2020), with potential impact outside the green domain. This is corroborated by the fact that green technologies lead changes and innovations in different industries (McPherson et al., 2018; Mihailova, 2023), hence having a more significant and pervasive impact (Ardito, Messeni Petruzzelli, & Albino, 2016; Barbieri et al., 2020). Moreover, empirical evidence suggests that green technologies are often generated from the hybridization of green and non-green technologies in new and creative ways (Barbieri et al., 2020; Dechezleprêtre et al., 2017; Zeppini & van Den Bergh, 2011). Thus, the results of the search and recombination of such diverse technologies lead to more heterogeneous technologies in the output phase (Fusillo, 2023), confirming that green technologies could have an impact on different domains, including green and non-green domains.

In sum, the foregoing discussion underlines that it is relevant to focus not only on what favours the impact of green technology on a broader scale, but also on what favours the impact of green technology beyond the innovating organization and on the green domain specifically. I embrace this perspective and seek to study antecedents of these different types of impacts of green technologies. In detail, I first consider whether the status of green technology permits the technology to have a greater overall impact than a non-green technology, and whether the green technology helps diverse organizations develop new technologies and new green technologies specifically (i.e., whether a green technology is more used by organizations different from the one that has developed it to generate new green technologies). Second, I look at the knowledge used to develop a technology (green or non-green prior knowledge), examining the technological impact by looking at the extent which one technology is based on previous green and non-green technologies, hence assessing whether technological change happens more easily when green technologies are used as prior art than non-green technologies. Such distinction is relevant because it could offer an estimation of the effectiveness of the search and recombination process involving green technologies in shaping technological change. Given that green technologies are based both on green and non-technologies (Barbieri et al., 2020; Fusillo, 2023), I would like to stress that being a green technology does not imply being based on green knowledge heavily, and vice versa, hence requiring a distinct examination.

Therefore, the research questions are articulated as follows: i) Do green technologies have a positive impact overall and on the development of subsequent green technologies specifically? Do these have a positive impact on the development subsequent green technologies by organizations that are not the inventing organizations? ii) Do technologies based on green prior art have a positive impact overall and on subsequent green technologies specifically? Do these technologies have a positive impact on the development of subsequent green technologies by organizations that are not the inventing organizations? iii) Do technologies based on non-green prior art have a positive overall impact and on subsequent green technologies specifically? Do these technologies have a positive impact on the development of subsequent green technologies by organizations that are not the inventing organizations?

3 Methodology

3.1 Research setting

This study considers electrolysis technologies as the research setting for several reasons. First, electrolysis technologies refer to a set of methods capable of splitting water molecules into hydrogen and oxygen. The only byproduct of this process is oxygen, which does not contribute to pollution (Shiva Kumar & Lim, 2022; Ursúa et al., 2011; Zoulias et al., 2004). As a result, these technologies are considered highly promising for facilitating the green transition. Given their importance, electrolysis technologies are classified within the green domain, making an evaluation of their impact both academically and practically significant (Bareiß et al., 2019).

Second, it must be acknowledged that electrolysis technologies originate from the search and recombination of green and non-green energy technologies and can be considered as either green or non-green themselves. For instance, technologies that generate green hydrogen through water electrolysis (Moreno-Brieva et al., 2023) can be considered as pertaining to the green domain specifically (Shiva Kumar & Lim, 2022). Conversely, part of electrolysis technologies are obtained from domains such as chemistry, electronics and engineering (Albino et al., 2014; Martinez-Burgos et al., 2021), hence serving as sustaining/complementary solutions still recognized as electrolysis technologies, but not classified as green specifically. This emphasizes that it is possible and relevant to distinguish technologies and their prior art among green and non-green; likewise, their impact relates to the development of new green or non-green technologies.

Third, electrolysis technologies are studied by several organizations (both institutional and private) across the world (Martino et al., 2024; Schmidt et al., 2017; Ursúa et al., 2011) as a proof of their economic promising as well as their innovativeness. This dispersion across organizations is another reason for choosing electrolysis technologies as the research setting since by evaluating the development of technologies between organizations, it becomes easier to assess the technological impact across them.

3.2 Sample data

According to previous studies, I adopted patent data to identify developed technologies and related impact, also in the specific green domain (Ardito, Messeni Petruzzelli, & Albino, 2016; Fusillo, 2023; Haščič & Migotto, 2015; Petruzzelli et al., 2011). In particular, patent citations offer indication about the knowledge sources on which the development of the technology may have relied (backward citations) and the impact of the technology on subsequent technological developments (forward citations) (Aristodemou & Tietze, 2018; Trajtenberg, 1990a; Waltman, 2016). I focused on the simple Patent Family (PF) as the unit of analysis instead of the single patent to avoid issues as double counting of an invention being protected in different jurisdictions (Criscuolo, 2006; Martínez, 2011). PFs about electrolysis technologies were made available by the IRENA and the European Patent Office (EPO),[9] which represents the sample. It includes 43,832 granted PFs applied from 1987 to 2021 (European Patent Office & The International Renewable Energy Agency, 2022). Subsequently, I retrieved additional information, especially about backward and forward citations, through the Orbit Intelligence FAMPat database (Orbit, hereafter). To do so, I first matched PF number of electrolysis technologies provided by IRENA and EPO in Orbit. Then, through Orbit, I identified and collected information about backward and forward citations of focal PFs. I identified 329.943 pairs PFs focal-backward citations and 267.143 PFs focal-forward

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[9] The dataset was compiled by querying the EPO's Espacenet database – queries (based on patent classification codes and keywords) are provided in the supplementary material of the corresponding report (European Patent Office & The International Renewable Energy Agency, 2022). For each PFs, the dataset includes a range of metadata (e.g. EPO Family ID, earliest priority dates, International Patent Classification codes, assignees, inventors) as well as variables identifying the specific electrolysis process phase(s) of each patented technology. The latter was provided by an EPO expert examiner in the electrolyzer/hydrogen field together with IRENA experts tasked to identify and classify PFs through the content analysis of PF documents. Five groups of technologies relevant for the electrolysis were identified: cell operation conditions and structure, electrocatalyst materials, separators (diaphragms, membranes), stackability of electrolysers (stacks), and photo electrolysis. See https://intelligence.help.questel.com/en/support/solutions/articles/77000436699-coverage-of-the-fampat-database

citations. Among the information retrieved, I identified the date of first filing, assignee(s) and technological classes of the backward and forward citations.

Finally, I classified focal PFs and their citations as green and non-green by assessing whether at least one of their International Patent Classification (IPC) codes equals one of the IPC codes classified as green by the World Intellectual Property Organization (WIPO) green inventory (Rivera León et al., 2018).[10]

3.3 Variables

3.3.1 Dependent variables

I developed a set of three dependent variables to answer the research questions. All dependent variables are based on PF forward citations, as a common way to look at technological impact (e.g. Ahuja & Lampert, 2001; Aristodemou & Tietze, 2018; Fleming & Sorenson, 2001; Trajtenberg, 1990; Waltman, 2016). The basic assumption is that a patent that receives a higher number of citations has a higher impact on subsequent technological development, hence shaping technological change to a greater extent (Aristodemou & Tietze, 2018).

Following this rationale the dependent variables are as follows. First, I calculated the *Overall Technological Impact* (*OTI)* as the total number of forward citations received by the PF in the five years after its first application. The five-year window has been adopted given the difference in citation patterns among PFs applied in different time periods. Thus, a defined time window was needed because "directly comparing patent citations across patents from different years would be inappropriate" (Capaldo et al., 2017, p. 515). Second, I calculated the *Green Technological Impact (GTI)* as the total number of green forward citations (classified as green as indicated in the previous section) received by the PF in the five years after its first application. Third, I calculated the *GTI beyond organizational boundaries (GTI-BOB)* as the total number of green and non-self forward citations received by the PF in the five years after its first application. In sum, the first dependent variable looks at the overall impact of a technology, the second dependent variable looks at the impact in terms of development of new green technologies instead of new non-green technologies, and the third dependent variable looks at the impact in terms of development of new green technologies spanning organizational boundaries.

3.3.2 Independent variables

The first independent variable measures the extent to which the PF is based on green technologies

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[10] https://www.wipo.int/classifications/ipc/green-inventory/home

as the prior art by counting the number of green backward citations (*Green Prior Art).* The second independent variable instead, measures the extent to which the PF is based on non-green technologies as the prior art by counting the number of non-green backward citations (*Non-Green Prior Art).* The third independent variable is a dummy variable taking the value of one if the PF can be classified as green (*Green Technology)*, according to the WIPO Green Inventory, zero otherwise (Rivera León et al., 2018). Thus, it captures its nature as green or non-green. The two former independent variables assess the knowledge search and recombination process used to develop a technology.

3.3.3 Control Variables

I included in the model additional factors that could exert an influence on technological impact. First, I counted the number of different 4-digit IPC codes for each focal PF (*Scope)* (Fleming, 2001). Second, I calculated the *Originality* index proposed by Trajtenberg, Henderson and Jaffe (1997), a variable that reflects the heterogeneity of the knowledge sources underlying a technology. Third, I calculated the *Citation lag* as the average of the difference between priority year of focal and priority year of cited patents. Fourth, I considered the influence of the *Scientific knowledge* in technology development as the sum of the non-patent citations made the focal PF (Narin et al., 1997). Fifth, I counted the number of assignees of a PF *(Joint development)*. Sixth, I considered the size of the inventing team (*Team size)* by counting the number of inventors of the PF (Singh, 2008). Seventh, I included the number of independent claims (*Independent claims)* in the document (Nagaoka et al., 2010). Eight, I accounted for the *Family size* of the focal PF by counting the number of countries where the PF is protected (W. G. Park & Hingley, 2009). Ninth, I included a set of three dummy variables (Dummy applicant) to identify the types of applicants, distinguishing them among firms, research centres/governmental organizations, and individuals. Tenth, since temporal dimension is an important component for the technological impact (Park et al., 2023), I added a set of dummy variables capturing the period when the focal PF has been applied (Dummy period). I identified three time periods according to the diverse generations of the electrolyzers proposed by IRENA (International Renewable Energy Agency, 2020, p. 29), namely third generation (1981-2010), fourth generation (2011-2020), and the fifth generation (2021- beyond), each of which constituted a dummy variable[11]. Finally, a set of dummy variables (Dummy nations) was included to identify the area of origin of the focal PF, distinguishing among: Europe, USA, Asia, and Others.

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[11] First and second generations are not considered since our sample PFs do not include PFs applied before 1987.

3.4 Model specification

Given the characteristics of the dependent variables—specifically, their overdispersion (i.e., the standard deviation exceeds the mean) and their nature as nonnegative integer count variables—I employed Negative Binomial regression, a generalization of Poisson regression, in this study. Negative Binomial regression shares the same mean structure as Poisson regression but incorporates an additional parameter to account for overdispersion. This is necessary when the conditional variance of the main variables exceeds the conditional mean (Hilbe, 2011; Wooldridge, 2012). The model is particularly well-suited for count data that exhibit extra-Poisson variation, meaning the event occurrences are overdispersed (Hilbe, 2011, p. 2). To ensure accuracy, robust standard errors are applied.

4 Results

Table 1 shows descriptive statistics and pairwise correlations. Correlation values are below the threshold of 0.70, so limiting multicollinearity concerns (Cohen, 2013).

Table 2 presents results for *OTI.* Model 1 includes control variables only and suggests that all control variables exert a positive and significant influence on *OTI,* except for *Citation lag,* which exerts a negative effect (β=-0.003, $p<0.05$) and *Joint development,* which is not significant ($p>0.10$). In Model 2, I added the first independent variable (*Green Prior Art*); it positively influences OTI (β=6e-04, $p<0.001$). Model 3 includes *Non-Green Prior Art* only, revealing a positive and significant effect (β=0.006, $p<0.001$). Similarly, Model 4 includes *Green technologies* only, revealing a positive and significant effect (β=0.031, $p<0.05$). Finally, Model 5 includes all the independent variables, however not confirming the positive influence of *Green Technologies* (β=0.026, $p>0.10$).

Table 3 instead, offers the results for *GTI.* Model 1 takes into consideration control variables only and shows that all control variables exert a positive and significant influence on *GTI,* except for *Scope* (β =-0.031, $p<0.001$) and *Citation lag* (β=-0.004, $p<0.001$), which exert a negative effect, and *Joint development,* which is not significant ($p>0.10$). In Model 2, the first independent variable (*Green Prior Art*) positively influences *GTI* (β=0.029, $p<0.001$). Model 3 considers *Non-Green Prior Art* only, revealing a negative and significant effect (β=-0.002, $p<0.01$). Contrariwise, Model 4 includes *Green technologies* only, revealing a positive and significant effect (β=0.031, $p<0.05$). Finally, Model 5 considers all the independent variables, confirming the results of the partial models. Finally, Table 4 shows results for *GTI-BOB.* In Model 1, by considering only the control variables, it is possible to note that all these variables exert a positive and significant effect on *GTI-BOB* except for *Scope* (β=-0.020, p<0.01) and *Citation lag* (β=-0.005, p<0.05), which exert a negative effect, and *Joint development,* which is not significant (p>0.10). In Model 2, the first independent variable (*Green Prior Art*) positively influences *GTI-BOB* (β=0.026, p<0.001). Model 3 considers *Non-Green Prior Art* only, revealing a negative and significant effect (β=-0.001, p<0.10). Contrariwise, Model 4 takes into account *Green technologies* only, revealing a positive and significant effect (β=1.05, p<0.001). Finally, Model 5 considers all the independent variables, confirming the results of the partial models. For robustness, I included the quadratic terms of the independent variables, yet the results do not reveal the presence of curvilinear effects.

Table 1

		Min	*Max*	*Mean*	*S.D.*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*
1	Overall Technological Impact (OTI)	0	550	5.234	11.946	1													
2	Green Technological Impact (GTI)	0	330	2.614	7.083	0.852*	1												
3	GTI beyond organizational boundaries (GTI-BOB)	0	282	2.028	5.737	0.948*	0.827*	1											
4	Green Prior art	0	400	5.639	14.762	0.436*	0.480*	0.415*	1										
5	Non Green Prior art	0	1167	5.455	18.479	0.457*	0.289*	0.395*	-0.002	1									
6	Green technologies	0	1	0.459	0.498	0.124*	0.247*	0.113*	0.222*	0.657*	1								
7	Scope	0	41	2.435	1.576	0.283*	0.258*	0.280*	0.273*	0.230*	0.214*	1							
8	Originality	0	1	0.576	0.323	0.179*	0.153*	0.179*	0.115*	0.184*	0.180*	0.295*	1						
9	Citation Lag	0	102	7.743	6.269	0.063*	0.043*	0.060*	0.023*	0.105*	0.124*	0.124*	0.517*	1					
10	Scientific knowledge	0	485	4.001	15.685	0.438*	0.372*	0.405*	0.090*	0.537*	0.554*	0.273*	0.134*	0.073*	1				
11	Joint development	1	20	1.285	0.731	0.196*	0.190*	0.192*	0.122*	0.181*	0.142*	0.190*	0.145*	0.074*	0.172*	1			
12	Team size	1	31	3.395	2.274	-0.006	-0.030*	-0.011*	-0.052*	-0.023*	0.006	-0.042*	0.051*	0.027*	0.002	0.07*	1		
13	Independent claims	1	41	1.611	1.196	0.206*	0.201*	0.206*	0.159*	0.167*	0.138*	0.196*	0.171*	0.102*	0.154*	0.097*	-0.048*	1	
14	Family size	1	347	3.785	6.212	0.463*	0.449*	0.430*	0.187*	0.436*	0.369*	0.390*	0.205*	0.1153*	0.465*	0.351*	-0.033*	0.154*	1

N= 43,832
*p<0.05

Table 2. Overall Technological Impact (OTI)

	Model 1	*s.e.*	*Model 2*	*s.e.*	*Model 3*	*s.e.*	*Model 4*	*s.e.*	*Model 5*	*s.e.*
Green prior art	-		6e-04****	7e-04	-		-		0.005****	8e-04
Non-green prior art	-		-		0.006****	7e-04	-		0.003****	9e-04
Green technologies	-		-		-		0.031**	0.0153	0.026	0.016
Scope	0.030****	0.005	0.032****	0.005	0.031****	0.005	0.029****	0.0053	0.030****	0.005
Originality	0.821****	0.030	0.800****	0.030	0.798****	0.030	0.821****	0.0301	0.795****	0.030
Citation lag	-0.003**	0.0001	-0.004***	0.001	-0.004***	0.001	-0.003*	0.0014	-0.004***	0.001
Scientific knowledge	0.007****	0.001	0.005****	6e-04	0.005****	0.001	0.007****	0.0005	0.004****	7e-04
Joint Development	0.006	0.010	0.004	0.0100	0.002	0.010	0.005	0.0101	0.002	0.010
Team size	0.031****	0.003	0.031****	0.003	0.031****	0.003	0.031****	0.0031	0.031****	0.003
Independent claims	0.081****	0.008	0.819****	0.008	0.082****	0.008	0.081****	0.0079	0.812****	0.008
Family size	0.085****	0.003	0.814****	0.003	0.084****	0.002	0.085****	0.0025	0.813****	0.003
Dummy applicant	yes		yes		yes		yes		yes	
Dummy period	yes		yes		yes		yes		yes	
Dummy nations	yes		yes		yes		yes		yes	
Wald χ^2	14651.6		14646.31		14475.2		14651.6		14627.1	
Log pseudolikelihood	-103997.38		-103913.97		-103929.85		-103997.28		-103894.19	

*p<0.10; **p<0.05; ***p<0.01; ****p<0.001

Table 3 Green Technological Impact (GTI)

	Model 1	*s.e.*	*Model 2*	*s.e.*	*Model 3*	*s.e.*	*Model 4*		*Model 5*	
Green prior art	-		0.029****	0.002	-		-		0.019****	0.001
Non-green prior art	-		-		-0.002***	5e-04	-		-0.006****	0.001
Green technologies	-		-		-		1.112****	0.020	1.01****	0.021
Scope	-0.031****	0.007	0.041****	0.006	0.032****	0.006	-0.031****	0.006	-0.020***	0.007
Originality	0.836****	0.038	0.639****	0.041	0.727****	0.040	0.836****	0.038	0.787****	0.038
Citation lag	-0.004***	0.002	-0.007****	0.002	-0.005***	0.002	-0.004**	0.002	-0.004*	0.002
Scientific knowledge	0.006****	6e-04	-0.002***	0.001	0.006****	0.0007	0.006****	0.001	0.002***	0.001
Joint Development	0.01	0.013	0.013	0.012	0.021	0.0132	0.01	0.013	0.005	0.012
Team size	0.017****	0.004	0.011***	0.004	0.011**	0.0042	0.017****	0.004	0.017****	0.004
Independent claims	0.096****	0.010	0.113****	0.009	0.119****	0.0093	0.096****	0.010	0.096****	0.010
Family size	0.086****	0.003	0.084****	0.003	0.109****	0.0030	0.086****	0.003	0.076****	0.003
Dummy applicant	yes		yes		yes		yes		yes	
Dummy period	yes		yes		yes		yes		yes	
Dummy nations	yes		yes		yes		yes		yes	
Wald χ^2	18779.48		12815.9		13111.17		18779.48		18702.53	
Log pseudolikelihood	-70942.789		-72648.355		-73163.146		-70942.789		-70654.03	

*p<0.10; **p<0.05; ***p<0.01; ****p<0.001

Table 4. Green Technologies Impact Beyond the Organizational Boundaries (GTI-BOB)

	Model 1	*s.e.*	*Model 2*	*s.e.*	*Model 3*	*s.e.*	*Model 4*	*s.e.*	*Model 5*	*s.e.*
Green prior art	-		0.026****	0.002	-		-		0.018****	0.001
Non-green prior art	-		-		-0.001*	5e-06	-		-0.006****	0.001
Green technologies	-		-		-		1.05****	0.020	0.949****	0.021
Scope	-0.020***	0.006	0.047****	0.006	0.041****	0.006	-0.020***	0.006	-0.01	0.006
Originality	0.875****	0.040	0.687****	0.042	0.771****	0.042	0.875****	0.040	0.825****	0.040
Citation lag	-0.005**	0.002	-0.007****	0.002	-0.006***	0.002	-0.005***	0.002	-0.005**	0.002
Scientific knowledge	0.006****	6e-04	-0.002***	7e-04	0.005****	0.001	0.006****	6e-04	0.003****	7e-04
Joint Development	0.021	0.013	0.021	0.013	0.029***	0.014	0.021	0.013	0.014	0.013
Team size	0.016****	0.004	0.011**	0.004	0.011***	0.004	0.016****	0.004	0.016****	0.004
Independent claims	0.092****	0.010	0.109****	0.009	0.114****	0.009	0.092****	0.010	0.093****	0.009
Family size	0.076****	0.003	0.074****	0.003	0.095****	0.003	0.076****	0.003	0.067****	0.003
Dummy applicant	yes		yes		yes		yes		yes	
Dummy period	yes		yes		yes		yes		yes	
Dummy nations	yes		yes		yes		yes		yes	
Wald χ^2	16820.76		11766.1		12098.41		16820.76		16695.42	
Log pseudolikelihood	-64090.577		-65443.808		-65856.617		-64090.577		-63855.665	

*p<0.10; **p<0.05; ***p<0.01; ****p<0.001

5 Discussion, implications and conclusion

This study draws on the notion that technological impact varies and that this is especially true in the green domain given its complex nature. In detail, it recognizes that technological impact can be assessed in various forms, hence focusing on the overall technological impact of a technology, the impact on subsequent green technologies, and the impact on subsequent green technologies. This finds its roots in the fact that a technology, apart from its impact on subsequent technologies in general, may exert an influence within or beyond the domain in which it initially emerged (Abernathy & Utterback, 1978; Phene et al., 2006; Pironti et al., 2010; Sood & Tellis, 2005) as well as within or beyond the organizational boundaries of the innovating organization (De Noni et al., 2017; Harpaz & Meshoulam, 1997). Such distinction is particularly relevant in the green domain as it is more pervasive in nature and involves a wide range of organizations (Guadagno et al., 2024; Moreno-Brieva et al., 2023; Petruzzelli et al., 2011). In this vein, I based on a sample of 43,832 granted PFs applied from 1987 to 2021 (European Patent Office & The International Renewable Energy Agency, 2022) in the electrolysis field, and then studied the factors that most influence the impact on subsequent technologies, both in general and specifically in green innovation. Additionally, I investigated the factors that can break the initial organizational and technological domain boundaries of a technology. As a result, I found that a higher adoption of green technologies as prior art is consistently beneficial in terms of technological impact, suggesting that following green technological trajectories is advantageous. Conversely, a higher adoption of non-green technologies has a detrimental effect on technological impact, indicating that green prior art is more relevant than non-green prior art. However, this does not imply that non-green prior art is generally harmful. While the green nature of the technology is important for developing new green technologies, its impact on overall technological advancement is not fully substantiated. These insights offer several theoretical and practical implications.

5.1 Theoretical and practical implications

From a theoretical standpoint, first, research has indicated that technological impact could be better investigated by analyzing its diverse manifestations, yet only a few studies have considered such diversity and offered wider comprehension of technological impact (e.g. Messeni Petruzzelli et al., 2015). I instead provide additional results to this relevant, but limited, line of inquiry. Second, by seeking to offer a deeper comprehension of technological impact, I specifically focused on the green domain. Studies dealing with the green domain have hinted at a consistent difference between the adoption of green and non-green technologies in their development (Ardito, Messeni Petruzzelli, & Albino, 2016; Barbieri et al., 2020) as well as their pervasive nature (Fusillo, 2023; Guadagno et al., 2024; J. Li et al., 2022). I have therefore extended previous studies by specifically analyzing how the reliance on green versus non-green prior art affect technological impact in its diverse manifestations as well as how the nature of a technology of being green affects technological impact in its diverse manifestations. In detail, it appears that the higher the adoption of green technologies as the prior art is always beneficial with regard to technological impact, hence suggesting that following green technological trajectories pays off. Conversely, the higher the adoption of non-green technologies leads to detrimental effects in terms of technological impact, suggesting that green prior art is more relevant than non-green ones. Still, this result cannot imply that non-green prior art is detrimental in general. Indeed, as pointed out by previous literature (Barbieri et al., 2020, 2023), green technologies are the results of the integration of both green and non-green prior art. Therefore, both these knowledge sources are important in the development path of green technologies. At the same way, the green nature of the technology is relevant for developing new green technologies, but its impact on the overall technological impact is not fully supported in this study.

From a practical perspective, this study offers more specific guidance to managers and policymakers regarding the features influencing the technological impact in green electrolysis technologies. Specifically, I emphasize that organizations should prioritize green prior art when developing green technologies, rather than relying on non-green prior art. The findings indicate that a greater reliance on green prior art tends to result in more impactful technologies, particularly in the green sector. These issues are confirmed by the nature of hydrogen process. Indeed, the overwhelming majority of hydrogen produced today is from fossil fuels, and around 60% of it is produced in "dedicated" hydrogen production facilities, meaning that hydrogen is their primary product (International Energy Agency, 2019).

This insight can assist managers in selecting the most effective knowledge sources when developing green technologies. Likewise, policymakers may create some innovation platforms where make easier the generation of green network and the access to a green prior art. In doing so, they may provide ad hoc financing to speed up the development of green knowledge. Finally, considering also the role of the green nature of the technology towards a higher technological impact, managers may set R&D teams able to identify the most promising green technologies upon which built new technologies. Similarly, policymakers may identify some offices of expert in term of green technologies to choose the most potential technologies.

5.2 Limitations, future research directions, and conclusion

As with most research, this study has some limitations that may lead to future research opportunities. First, I have considered the electrolysis technologies, thus, the general domain of the hydrogen-based technologies may be investigated to corroborate the findings. However, I believe that the results will remain consistent. Second, I have only considered patented innovations, excluding those that are not yet included in patents or are not patented at all. Future studies could take into account innovations that are still immature or unpatented to further validate the results obtained. Third, I have not taken into account the practical applications of the technologies studied. This could lead to a paradox where a green technology is used in non-green applications. Therefore, it may be valuable to assess the subsequent use of the technologies to further validate the results.

In conclusion, this study aims to understand the technological impact of green technologies by analyzing two key components, the odds that an invention will move from its initial technological domain, and its ability to cross organizational boundaries. The results show that for both components, green prior art has a positive influence in achieving a higher technological impact.

Conclusion

This thesis has delved into the topics of technical change (Dosi, 1982) and technological impact (Veugelers & Wang, 2019) in the green domain. Indeed, green technologies are being considered a driving force for the technological progress in the next future (Guo et al., 2020; Longden et al., 2022) but are more complex in comparison to non-green ones since their inherently heterogeneity (Barbieri et al., 2020, 2023; Guadagno et al., 2024; Tan et al., 2021). These features make understanding the development and knowledge flows of green technologies a highly complex and resource-intensive endeavour. In addition, technological impact varies, and this is especially true in the green domain given its complex nature. This finds its roots in the fact that a technology, apart from its impact on subsequent technologies in general, may exert an influence within or beyond the domain in which it initially emerged as well as for the organizational boundaries (De Noni et al., 2017; Ning & Guo, 2022b), but previous studies have not deepened these issues. This thesis has tried to face these challenges in three distinct chapters.

First, due to the lack of a comprehensive overview of the hydrogen technology chain, I have studied the technological developments of hydrogen-based technologies (HBTs) by investigating patenting trends in the first chapter, 'Mapping Hydrogen-Based Technologies Progress Through Patent Analysis. To do so, I have collected patent families (PFs) related to HB production technologies (317.089 PFs from 1930 to 2020) and PFs regarding HB storage technologies (62.496 PFs from 1930 to 2020) granted by multiple patent authorities, hence identifying a more comprehensive set on data, in comparison to previous studies. Patent analysis technique have been used providing an overview of the technological landscape of HBTs in terms of magnitude and geographical distribution of the global inventive efforts on these technologies, while at the same time contextualizing these trends within national policies, historical events, and corporate initiatives. In doing so, this study has advanced on previous research efforts (Chanchetti et al., 2016; Chen et al., 2011; European Patent Office & The International Renewable Energy Agency, 2022; Ursúa et al., 2011) by expanding the analysis on the production and storage HBTs, which I observed over a relatively long period. In detail, I have underlined that patenting activity is significantly influenced by government strategies and energy programs, with countries like the US and Japan leading due to strong governmental support in the hydrogen sector (European Patent Office & The International Renewable Energy Agency, 2022; International Energy Agency, 2019). Second, I have found evidence that, although global enterprises are investing in HBTs, there is no clear dominant model for hydrogen production and storage technologies yet, since there are several companies and countries involved in the patenting activity (Dehghanimadvar et al., 2020; European Patent Office & The International Renewable Energy Agency, 2022; Hirscher, 2010; Sazali, 2020; Van Den Berg & Areán, 2008). Third, this study sheds light on the most active countries in the patenting of HBTs. Japan leads in the total number of patents, while the US holds the most highly-cited patents. Europe also plays a notable role in both patent quantity and impact, though BRIC countries (Brazil, Russia, India, China) have been slower but are making progress, particularly in hydrogen storage. Some implications emerge from this chapter. Firstly, from a technological perspective, analysis of the HBT-related patenting activity and the highly-cited PFs, suggests the absence of a dominant design (Abernathy & Utterback, 1978; Srinivasan et al., 2005), while also highlighting the economic potential of these technologies. Therefore, there seems to be space to create policy instruments that can support the emergence of a dominant design able to facilitate the development and diffusion of HBTs (Tushman & Murmann, 1998). Second, the US and Japan hold the majority of PFs related to HBTs, while European firms hold the highest number of highly-cited PFs. This may suggest that Europe and Japan have extremely effective organizations conducting highly impactful R&D as compared to the US and Asian countries, where the development of highly cited PFs is lower. Third, the dominant position of a few countries (i.e., US and Japan) in terms of HBTs development could generate a supremacy of knowledge (Pachauri et al., 2012) and, consequently, concrete difficulties for other nations in achieving widespread access to advanced energy technologies (Pachauri & Spreng, 2004). Therefore, given the significance of HBTs in shaping a new energy-economic design, there is a potential risk of encountering energy justice issues (Healy & Barry, 2017; Heffron & McCauley, 2017; Jenkins et al., 2016; Sovacool & Dworkin, 2015) and of leaving out other nations from the possibility to contribute to the establishment of a dominant design for HBTs. A potential solution to these issues is to enhance international cooperation through new agreements, building on frameworks like the Kyoto Protocol and the Paris Agreement. By leveraging Research and Technology Offices (RTOs) (Albors-Garrigos et al., 2010) within governments, innovations from other countries can be integrated, harmonizing knowledge sources. With rising patent activity in countries like BRIC nations, global policymakers could facilitate technology transfer by activating RTOs and using the expertise of leading nations (e.g., the US and Japan). This approach could also help establish a dominant design in hydrogen-based technologies (HBTs) worldwide.

In the second chapter, “Unveiling the Trajectories of Green Energy Technologies: The Case of Electrolysis”, considering the absence of a dynamic study of the green technologies, I have proposed an analysis of the technological trajectories of electrolysis technologies to dig into the evolutionary dynamics that may characterize green energy technologies (Xu et al., 2016; Xu & Ni, 2017). Drawing on the literature on technological trajectories (Dosi, 1982; Hung et al., 2022; Verspagen, 2007), this chapter have identified and analysed the knowledge flows underlying electrolysis technologies to identify key solutions and trace their development stages. To do so, I have relied on a sample of

43,832 PFs from 1987 to 2021 provided by the IRENA and the European Patent Office (EPO)[12], along with related citation data retrieved on Orbit Intelligence, to build a citation network that I have analyzed through MPA. In this way, I have identified four key sets of solutions and contextualize them within the different phases of the TLC model proposed by Taylor & Taylor (2012) – (i) solutions about membranes and hydrogen separation and (ii) electrochemical systems (application phase of the TLC model), (iii) inventions about hydrogen production through water electrolysis (paradigm phase of the TLC model), (iv) inventions about electrocatalysis (generation phase of the TLC model). The results obtained show that, in the application phase of the TLC model, the technical solutions that feature in the main development path of electrolysis technologies aim to reduce membrane thickness, thereby increasing efficiency and consequently reducing electricity consumption (Peters et al., 2017). At the same time, inventions related to electrochemical systems aimed at creating an efficient process for energy conversion are present. The combination of gas separation technologies and electrochemical systems lays the groundwork for the establishment of the paradigm phase, namely the development of water electrolysis. In this phase, major inventive effort targeted the optimization of electrolyzers. Finally, in the generation phase, main technical solutions deal with technologies of optimization of the technological paradigm, specifically describing the innovations required to a cheaper electrocatalysis (Eftekhari, 2017). These findings offer some relevant implications for both theory and practice. From the theoretical perspective, this study advances the understanding of green energy technologies (Barbieri et al., 2020, 2023) by offering a view on their technological trajectories and evolutionary paths. Indeed, on the one hand, extant research has demonstrated that green energy technologies present a higher degree of novelty in comparison to non-green energy technologies (Barbieri et al., 2020; Gallagher et al., 2012) since they are the result of the integration of heterogeneous technologies and knowledge sources (Nemet, 2012b, 2012a; Petruzzelli et al., 2011). On the other hand, this initial evidence is based on invention-level studies that do not consider the evolutionary dynamics that have led to a given (green) technology and do not follow their technological trajectories. Results obtained demonstrate that green energy technologies are more present in the evolutionary path in comparison to non-green energy technologies when considering technological trajectories over time despite what the odds suggest. Therefore, it could be reasonable to sustain that green energy technologies are more impactful and pervasive in subsequent

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[12] The dataset was compiled by querying the EPO's Espacenet database – queries (based on patent classification codes and keywords) are provided in the supplementary material of the corresponding report (European Patent Office & The International Renewable Energy Agency, 2022). For each PFs, the dataset includes a range of metadata (e.g. EPO Family ID, earliest priority dates, International Patent Classification codes, assignees, inventors) as well as variables identifying the specific electrolysis process phase(s) of each patented technology. The latter was provided by an EPO expert examiner in the electrolyzer/hydrogen field together with IRENA experts tasked to identify and classify PFs through the content analysis of PF documents. Five groups of technologies relevant for the electrolysis were identified: cell operation conditions and structure, electrocatalyst materials, separators (diaphragms, membranes), stackability of electrolysers (stacks), and photo electrolysis. See https://intelligence.help.questel.com/en/support/solutions/articles/77000436699-coverage-of-the-fampat-database

technological developments as reported by Barbieri and colleagues (2020) and present a pivotal role for the instauration of a dominant paradigm. Specifically, I have delved into the development paths of a set of technologies that have been widely examined from a technical perspective but less from the perspective of their evolution, neglecting more dynamic approaches over more conventional invention-level statistics (e.g. Medeiros Araújo de Moura et al., 2024). From the practical perspective, I shaped the boundaries of the evolution phases of the electrolysis technologies within the TLC model, hence informing practitioners and policymakers, especially in the energy domain, of which are the key electrolysis technologies that have set the technological trajectory in such domain and that are, hence, those on which it is probably safer to invest private and public money for the greening of the energy sector and run businesses. Thereby, policymakers could deepen the TRL associated with the technological solutions of the MPA to obtain insight into their market potentiality and to adopt the appropriate financing measure (Carfora & Scandurra, 2024; Suzuki et al., 2023). Lastly, the results obtained through MPA could help managers to formulate their strategies regarding the choice of innovation of a given technology. Indeed, this study could help R&D managers to choose what specific technological domain of electrolysis shell be deepened. For instance, results obtained seem to suggest that electrocatalysis is the current technological topic. Therefore, to obtain a technological advantage, it could be useful to deepen the knowledge related to this technology.

Finally, to offer a new insight of the technological impact of electrolysis technologies, in the third chapter, "Assessing the impact of the green technologies: analysis of the electrolysis setting", I have addressed a gap in the literature regarding technological impact by focusing on multiple aspects. First, this study examines the broader-scale impact of green technology compared to non-green technology. Second, this study explores the factors that enhance the impact of green technology beyond the innovating organization and within the green domain. Based on the same sample used in the second chapter[13], I have shown that the *Green prior art* exerts an important influence in *Overall Technological Impact*, in *Green Technological Impact* and in *Green Technological Impact Beyond Organizational Boundaries*. Results obtained show a consistent difference between green and non-green technologies in their development. For green technologies, the presence of *Green prior art* in their development path is crucial for enhancing their technological impact, while the use of *Non-green prior* art tends to reduce this impact. Although existing research explains that green

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[13] The dataset was compiled by querying the EPO's Espacenet database – queries (based on patent classification codes and keywords) are provided in the supplementary material of the corresponding report (European Patent Office & The International Renewable Energy Agency, 2022). For each PFs, the dataset includes a range of metadata (e.g. EPO Family ID, earliest priority dates, International Patent Classification codes, assignees, inventors) as well as variables identifying the specific electrolysis process phase(s) of each patented technology. The latter was provided by an EPO expert examiner in the electrolyzer/hydrogen field together with IRENA experts tasked to identify and classify PFs through the content analysis of PF documents. Five groups of technologies relevant for the electrolysis were identified: cell operation conditions and structure, electrocatalyst materials, separators (diaphragms, membranes), stackability of electrolysers (stacks), and photo electrolysis. See https://intelligence.help.questel.com/en/support/solutions/articles/77000436699-coverage-of-the-fampat-database

technologies are often a recombination of both green and non-green technologies (Barbieri et al., 2020; Fusillo, 2023), the results suggest that green technologies play a more significant role in their development compared to non-green technologies. Furthermore, also the condition of *Green Technology* exerts a positive influence in *Overall Technological Impact*, in *Green Technological Impact* and in *Green Technological Impact Beyond Organizational Boundaries*. From a theoretical standpoint, this study expands on the limited research analyzing the diverse manifestations of technological impact, contributing to a deeper understanding of this topic. Prior research has acknowledged the value of studying these varied impacts but has rarely explored them in depth. This study builds on that by specifically focusing on the green domain, which has been shown to differ from non-green technologies in terms of development and adoption. However, despite the detrimental impact of non-green prior art observed in this study, both green and non-green knowledge sources remain important for the development of green technologies, aligning with previous literature (Ardito, Messeni Petruzzelli, & Albino, 2016; Barbieri et al., 2020). Finally, while the green nature of a technology fosters the development of further green technologies, this study does not fully support the idea that it has a significant impact on overall technological advancement. From a practical standpoint, this study provides some guidance for managers and policymakers on how to enhance the technological impact of green electrolysis technologies. It stresses the importance of prioritizing green prior art over non-green prior art when developing green technologies. The findings show that greater reliance on green prior art leads to more impactful innovations, especially in the green sector. This insight can help managers select the most effective knowledge sources for green technology development. Policymakers, in turn, could create innovation platforms that facilitate the creation of green networks and improve access to green prior art. They could also provide targeted funding to accelerate green knowledge development. Moreover, recognizing the role of green technologies in achieving higher technological impact, managers could task their R&D teams with identifying the most promising green technologies to build upon. Similarly, policymakers could establish expert offices focused on green technologies to identify and support the most promising innovations.

In summary, in the first chapter, I have studied HBTs by tracing their technological trajectories using patent analysis. Results offer a complete overview of the hydrogen chain and describe their geographical context of development. The second chapter digs into deep the evolutionary trajectories of the green technologies by studying the electrolysis solutions through the Main Path Analysis and by corroborating the results within their Technology Life Cycle. The insights obtained could help managers or policymakers to identify the most promising technological phase within the electrolysis technologies domain. Finally, in the last chapter, I have focused the attention on the impact that the green technologies may exert. To do so, I have considered the impact as a force to divide in two main components, first, the broader-scale impact of green technology compared to non-green technologies, and second the impact that a green technology exerts beyond the innovating organization and beyond the green domain.

In summary, this work, through a wide analysis of HBTs and a vertical study on ETs, offers insights about the promising of HBTs particularly considering the chance to obtain green hydrogen through electrolysis technologies. Managers and policymakers could follow the results proposed to identify the technologies required to obtain greater technological impact and the safer stage of development within ETs to invest. Finally, the preponderant role of US and Japan in the development of HBTs could generate some energy justice issues that could be solved through international collaboration (RTO, or Innovation Consortia).

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