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Master of Science in Engineering and Management

Master Thesis

“Patent Landscape on Hydrogen Technologies: a study on the generality and originality of hydrogen patents”

Tutors:
Prof. Giuseppe Scellato
Ph.D. Antonio De Marco

Candidate:
Oliviero Giacomo Vidoni

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INTRODUCTION

Climate change in recent years has emerged as the most critical threat to the stability of the earth and has forced governments of various countries to take urgent action to try to mitigate its negative effects to ensure prosperity and well-being for the future generations. CO2 emissions, mainly from the consumption of fossil fuels over the decade 2011-2020, caused a global temperature to rise of 1.09°C compared to pre-industrial levels (1850-1900), as highlighted in the 2020 report of the Intergovernmental Panel on Climate Change (IPCC, 2020). This temperature increase is accelerating the pace of climate change, with dramatic consequences such as extreme droughts, wildfires, more intense heat waves, melting glaciers and rising ocean levels and temperatures.

In 2015, 196 countries pledged to sign the Paris Agreements with the goal of limiting the increase in global average temperature well below 2°C thus limiting dramatic and irreversible effects on the planet. Countries set their sights on the ambitious goal of staying below a 1.5°C increase over pre-industrial levels (UNFCCC, 2015*: "Paris Agreement", United Nations*). To achieve these goals, it is strictly necessary to embark on a large-scale energy transition pathway, with an emphasis on the development and adoption of renewable energy sources on the one hand and the reduction and replacement of fossil fuel consumption on the other.

Within this perspective, hydrogen, in recent years, is emerging as a key element in facilitating the transition. Indeed, hydrogen represents a versatile substance with the potential to reduce CO2 emissions in many different industries. First, hydrogen as an energy carrier offers numerous advantages.

Hydrogen represents an inexhaustible resource and can be produced through the electrolysis of water, a process that breaks down the water molecule into hydrogen and oxygen molecules. If the energy used to promote the water electrolysis reaction comes from renewable sources, the hydrogen produced is a renewable resource (Ball and Wietschel, 2009). Specifically in this case, we speak of green hydrogen or clean hydrogen. Moreover, because of its versatility, hydrogen is an energy carrier that can be used in a variety of applications. First, hydrogen can contribute significantly to solving the problems related to energy storage and transportation, which, especially when considering renewable energy, pose major challenges. In fact, renewable sources such as solar and wind provide an intermittent supply that is not always in line with consumption needs. This means that the energy produced from these sources must be stored for later consumption to cover the time lapses in which energy production is low or nil. Batteries can store energy but have limitations in cost, useful life and storage capacity. Regarding transportation, renewable plants to date, are often located near the areas whose energy needs they cover. This is due to the difficulties of transporting energy for considerable distances without storing it. Hydrogen can be a solution to these challenges. Indeed, hydrogen has a high energy density, which implies that it can store a lot of energy in a small volume. It is also a relatively easy element to transport, either through pipelines or in specialized ships. Consequently, Hydrogen can facilitate the balance between energy production and demand, thus ensuring the integration and large-scale development of renewable energy resources.

In addition, hydrogen can be a sustainable solution for the transport industry. Hydrogen can be used in fuel cells to power light and heavy vehicles, offering an environmentally friendly alternative to fossil fuels. Hydrogen can also be used for domestic and commercial heating, providing a low-carbon alternative to fossil fuels.

Another sector that could benefit from hydrogen is the heavy industry, and in particular the iron and steel, which is a very high environmental impact industry. Hydrogen can replace natural gas as a heat source for blast furnaces and significantly reduce CO2 emissions.

However, although hydrogen holds all the necessary characteristics to become a key component of the energy system of the future, there are still major challenges to be overcome in the coming years. Hydrogen-related technologies still require improvements in cost, efficiency, and infrastructure. For example, the production of clean hydrogen is currently more expensive than hydrogen produced from fossil fuels and the infrastructure for hydrogen transport and storage is still under development. In addition, there are significant constraints at the geopolitical level that could hinder the global-scale development of the hydrogen value chain. Despite these challenges, forecasts, suggest an increase in hydrogen production and consumption in the coming decades; a trend driven by continuous scientific research, technological improvements, major investments, and favourable policies. At the European level, for example, the European Commission has recognized hydrogen's key role in the energy transition. The European Green Deal aims to increase ''green'' hydrogen production to 1 million tons per year by 2024 (European Commission, 2020*: "A hydrogen strategy for a climate-neutral Europe"*). This represents a significant step toward decarbonizing the European energy system.

To better understand the innovation landscape in the field of hydrogen, this master thesis aims to analyse in detail the patent data related to hydrogen and related technologies. Indeed, patents are an essential tool in the study of innovation output as they protect new inventions and processes in various fields, including energy (*OECD, 2020: "Patents and innovation: Trends and policy challenges"*). A patent provides the owner with the exclusive right to commercially exploit an invention for a specified period, normally 20 years. This exclusive right stimulates innovation because it gives inventors the security that their creative efforts will be protected and can be exploited economically. Furthermore, patents are an invaluable source of technical information, as each patent must describe the invention clearly and completely so that an expert in the field can reproduce it (European Patent Office, 2020*: "What is a patent?"*).

Analysis of patent data, known as patent landscaping, can reveal technology trends, identify market leaders, potential competitors, and possible collaboration opportunities. It can also provide insight into emerging research areas and key technologies in a specific field.

This work aims to use patent data as a tool to study innovation in the field of hydrogen. By integrating this information with statistical studies, a more comprehensive analysis of the domain will be possible and help to outline past and present trends, but also to anticipate future directions of innovation in the hydrogen field.

In conclusion, the goal of this thesis is to contribute to the understanding of the role of hydrogen in the energy transition through an analysis of the patent activity that has developed over the years. Consequently, this work will fit into all the research that aims to provide valuable insights to guide future research and development strategies, energy policies, and investments in the hydrogen sector.

This master thesis is structured into multiple chapters. Initially, the Literature Review will focus on why it is important to study innovation and innovative activities, which are at the basis for the development of economic development, growth and prosperity; secondly it will explain, through the analysis of previous studies how and why it is appropriate to study innovation through the output, and more specifically using patents, considering both advantages and disadvantages of using this method; last it will report studies that have been conducted, especially in recent years on green patented technologies and more specifically hydrogen technologies, illustrating their findings. Following the review of past literature, a chapter will be dedicated to the representation of the hydrogen value chain: from the production to the storage, distribution, transformation, and end-uses of this extremely versatile and promising resource. As the analysis that have been conducted, an individual paragraph will also be dedicated to explaining what patents are and how the patenting procedure of an innovation is conducted. Subsequently, the following chapter, "Data & Methodologies" will explain how the research perimeter of hydrogen technologies has been defined, how the dataset has been identified and extracted from the adopted database. After the cleaning and refinement of the dataset, a series of statistics and analysis have been run to better understand the nature, characteristics, and peculiarities of hydrogen technologies. More specifically, the studies that will be presented in the "Descriptive statistics of the Dataset" chapter reveal interesting insights regarding the evolution in time, value-chain development, geographical distribution and evolution, complexity, collaborative nature among innovators, top innovators, technological domain, and greenness/sustainability on hydrogen patented technologies. As the personal analysis conducted adopts citations, an introductory chapter will explain what citations are, how and why they can be useful to draw indicators and extract interesting information regarding the innovation practices in each area of study. This will be done with a particular interest for the generality and originality indexes, built from forward and backward citation information. respectively. At this point, inferential statistics (difference in means – ttests) have been conducted to investigate how hydrogen patented technologies compare to others, and more specifically assess their degree of generality and originality. Secondly, the analysis will present how the generality and originality has evolved over time. In conclusion, econometric analysis employed, including OLS and tobit models, will investigate the relationships between generality/originality of patents and some bibliometric patent data, including the hydrogen patent dummy. The last chapters are reserved for the conclusions, representation of the limits, potential improvements, and future developments of the present studies.

LITERATURE REVIEW

This chapter aims at investigating the previous literature with respect to the existing relationship between the development of economic growth and prosperity in the long term and innovation. While there may be more intuitive and immediate metrics to account for a country's (e.g., GDP pro capita, life expectancy) wealth and progress, it may be more challenging and complex to measure innovation. Previous literature suggests that an effective way to account for innovation is by measuring the research outputs, and more specifically, patents. Therefore, the second goal of this chapter is to present previous studies that explain why patents represent an accurate proxy of innovation activity. Since the main topic of this thesis is the analysis of sustainable hydrogen technologies, the third objective of this review will be to present some significant examples of studies of green innovations using data provided by patents. Finally, previous examples of patent analysis and patent landscape with specific reference to hydrogen and related innovations will be shown. As much as possible, scientific papers and articles will be presented in chronological order to highlight evolution and trends in research.

Section 1: Innovation and Economic Development

The first section of this literature review concentrates on studies that demonstrate the connection between innovation activities, studies, and investments with long-term growth and prosperity of nations. It is essential to investigate the various aspects of innovation and their effects on countries to gain a deeper understanding of the important economic growth and prosperity factors. Several prominent scientific papers in this field will be discussed, to cast light on their findings and establish a thorough understanding of the topic. In the beginning, it is significant to delve into the link between the role of innovation and its impact on the economic development of an industry or a country.

In this regard, a first meaningful example is provided by the Schumpeter's Theory of Economic Growth (1911). Schumpeter (1911), one of the greatest Austrian economists of the 20th century, widely regarded as the founding father and precursor of modern economic growth theories, introduced the concept of creative destruction, highlighting the role of innovation in propelling economic development (Schumpeter, 1911). According to Schumpeter, new innovations decimate old industries and spawn new ones, thereby fostering economic growth and prosperity. The work of Schumpeter (1911) established the groundwork for comprehending the importance of innovation in shaping the economic landscape.

Afterwards, the topic of innovation, was addressed by Solow (1956) who created the *Neoclassical Growth Model*. The model emphasized the significance of technological advancement in nurturing economic development (Solow, 1956). His model demonstrated that investments in physical and human capital could only result in transient development, whereas technological innovation was the true source of long-term growth. This seminal work had a significant impact on how economists comprehend and research economic growth. Among these economists stands Romer (1990), who extended the neoclassical growth model, proposed by Solow (1956), by integrating endogenous technological change, contending that investments in research and development and human capital also account as important growth drivers (Romer, 1990). Romer's model stresses the significance of knowledge spill overs and rising returns to scale, showing that public policy can play an important role in nurturing innovation and economic growth.

Solow's Neoclassical Growth Model (1956) also served as a baseline for Mankiw et al. (1992), which focused deeply on the influence of a specific factor. Indeed, Mankiw et al. (1992) added human capital as an additional factor of production to the neoclassical development model (Solow, 1956). Human capital, as proxied by education, has a significant impact on economic expansion, according to their empirical research. This study highlights the significance of investing in human capital and education as a mean to foster innovation and long-term economic prosperity.

Numerous studies have also been done regarding the determinants of the development of innovative activities and subsequent growth of the economy. Grossman and Helpman (1991) proposed a conceptual framework for comprehending the role of innovation in propelling global economic development (Grossman and Helpman, 1991). Their work highlights the significance of international trade and R&D investments, demonstrating how these factors contribute to technological advancement and economic expansion. Additionally, their findings underline the importance of international cooperation and policy coordination for fostering global innovation.

Instead, Aghion and Howitt (1990), taking up the concepts developed by Schumpeter (1956), constructed a new development theory (Aghion and Howitt, 1990) that illustrates how creative destruction stimulates economic development by encouraging firms to invest in R&D and innovate. The model believes that entrepreneurs can invest in research and development to come up with new technologies that are more efficient than the current ones. However, these new technologies are not quickly adopted by all companies. Instead, new firms with innovative technologies join the market and replace the current ones, leading to an increase in output and economic growth. In addition, the authors emphasize the role of competition in stimulating innovation, offering a determined view on the intricate relationship existing between market competition, innovation, and economic development.

Furthermore, Fagerberg (1987) carried out a country-level comparative analysis between growth rates. Fagerberg (1987) investigated the relationship between innovation, catching up, and economic development, emphasizing the significance of innovation in fostering growth in both developed and developing nations (Fagerberg, 1987). The author demonstrated that countries that invest in research and development, human capital, and technology adoption have a greater chance of catching up to dominant economies. The work of Fagerberg (1987) emphasizes the significance of innovation in reducing income disparities and fostering a path towards international inclusion.

Another countrywide comparative research was conducted by Hall and Jones (1999). The two American economists examined the role of social infrastructure in promoting economic development and argued that robust institutions and a supportive social infrastructure are essential for fostering innovation and technological advancement (Hall and Jones, 1999). Their empirical findings demonstrate the significance of factors such as property rights, the rule of law, and government efficacy in fostering innovation and long-term economic prosperity.

Acemoglu et al. (2001) also delved into the connection between institutions, innovation, and economic growth (Acemoglu et. al, 2001). The authors argue that inclusive institutions that level the playing field and encourage innovation led to long-term economic growth. Their research emphasizes the importance of institutions in nurturing an environment that is conducive to innovation, and thus, to economic growth.

Furthermore, previous literature also includes relevant studies regarding policies about innovation and the role of governments in fostering the establishment of innovative activities. Lundvall (1992) investigated the idea of a National Innovation System (NIS), focusing on the interactive learning process among system players (Lundvall, 1992). According to Lundvall (1992), a country's economic performance is dependent on its capacity for innovation, which is the product of collaborative learning amongst a variety of stakeholders, including businesses, governments, and academic institutions. The findings of Lundvall's study (1992) emphasize the value of group learning and information exchange in fostering innovation at the national level. Another meaningful analysis within this field is provided by Nelson (1993) who explored innovation and economic development (Nelson, 1993), by investigating how countries stimulate innovation and technical development using the National Innovation Systems (NIS) paradigm, previously illustrated by Lundvall (1992). By comparing NIS in Japan, Germany, and the United States, Nelson (1993) demonstrated the importance of coordinated innovation promotion by businesses, universities, and government institutions. Infrastructure, education, and political institutions determine the viability of a NIS, which can sustain economic development.

Considering the role of government institutions in promoting the development of an innovation ecosystem, a relevant contribution is given by the work of Arrow (1962) who emphasized the importance of government intervention in fostering innovation and generating economic welfare (*Arrow, 1962*). Arrow (1962) argued that market failures impede innovation because firms tend to underinvest in R&D due to the prevalence of externalities and the character of knowledge as a public benefit. In this study, the author also focused on the role of patents (as mentioned before, patents will be deepened in the next sections of the literature review) in incentivizing R&D and emphasized the importance of patents in providing firms with incentives to invest in R&D and engage in innovative activities. The research also highlights the limitations of the patent system, focusing on the trade-offs between disclosure and monopoly power. The influence of Arrow's work (1962) on innovation-related public policy has been significant, leading to the development of government policies and programs such as research grants, fiscal incentives, and funding for fundamental research. These initiatives seek to encourage innovation and provide firms with the resources and incentives necessary to invest in R&D, thereby contributing to economic growth and development.

The same topic was also addressed more recently by Mazzucato (2013). The author argues that the state can play a crucial role in advancing technological development by operating as an entrepreneurial actor (Mazzucato, 2013). The author suggests that public investments in research and development, infrastructure, and human capital, can foster innovation and thus long-term economic growth. The author also emphasizes the significance of public-private partnerships, which can help leverage public investments and facilitate collaboration between government, industry, and academia, to advance innovation.

To conclude, the first chapter of the literature review has provided an overview of the most significant scientific articles discussing the role of innovation, studies, and investments in innovation in promoting economic growth and prosperity among nations. These studies highlight the significance of technological advancement, human capital, institutions, and supportive policies in promoting long-term economic expansion. Moreover, governments play a crucial role in correcting market failures and fostering an environment conducive to innovation. As the global economy continues to evolve, it will be essential for policymakers and researchers equally to comprehend these relationships to shape a prosperous and equitable future.

Section 2: The use of patents in the analysis of innovative activities

As illustrated in the previous section, the study of innovation has long been of interest to academics, policymakers, and business leaders. Patent data is one of the most important sources of information on innovation, providing valuable insights into the character and patterns of technological change. Patent data and patent analysis have arisen as a popular and useful method for studying innovation, and a vast body of literature has accumulated on the subject. Indeed, since patents contain a lot of semi-structured data, researchers have been able to create and use a variety of quantitative indices and metrics to examine and compare patent data. This section of the literature review seeks to summarize the major contributions and debates in the field, as well as discuss the advantages and disadvantages of using patent data to research innovation.

To begin this second part of the literature review, the reasons why it is relevant to study innovation through patent data are presented by using a selection of notable publications. A primary argument for using patent data to study innovation is that patents are often adopted as indicators of innovation and innovative activity. This assumption is well supported by Griliches (1990), who examined the potential advantages and disadvantages of utilizing patent data in economic research (Griliches, 1990). The author emphasized the vast amount of valuable information that can be derived from patent data, and the data's capacity to offer valuable insights into the process of innovation, the economic ramifications of technological progress, and the competitive environment of diverse industries. The study also highlights the prospective uses of patent data in figuring out the connections between R&D expenditures, technological advancement, and productivity development, underlining the versatile applications of patent data in studying economic phenomena. The Griliches (1990) recognized that patent data are susceptible to biases and incongruities, including, but not limited to, variations in patent systems across nations, differences in the inclination to patent among different industries, and the impact of legal and institutional factors on patenting practices.

The value of patents in studying innovation was later addressed even by Hall et al. (2001). The authors published a scientific paper focused on the National Bureau of Economic Research (NBER) patent citations data (Hall et al. 2001). The NBER is a private, non-profit organization in the United States that conducts and spreads economic research for academics, public policymakers, and companies. Hall et. Al (2001) stressed the indispensable resource for patent analysis research of the NBER patent citations data file. The authors emphasized the role of patents in providing legal protection to inventors and encouraging information disclosure, which facilitates the systematic study of innovation. Hall et al. (2001) presented the various methodological tools and techniques used to construct the data file, including patent citation matching and cleaning procedures, and discussed the data's limitations and potential biases. Hall et al. (2001) also highlights several empirical applications of the NBER patent citations data file, demonstrating its utility in addressing a variety of research questions pertaining to innovation, technology diffusion, and the influence of public research.

Additionally, the interest in patents as an attractive source for investigating innovation is due to the easy availability, quality and potential insights provided by patent data. In this sense there are a variety of reports and studies available that analyze these aspects.

The World Intellectual Property Organization's annual report *"World Intellectual Property Indicators 2022"* (WIPO, 2022) provides, for instance, an exhaustive overview of global patent trends, highlighting the vast amount of information available on inventions, inventors, and the intellectual property landscape. The report underscores the increasing interest in studying innovation through patent data. According to this publication, the growing curiosity in analyzing patent data can be attributed to different factors:

1. *The ability to track technological progress*

   Patent data is an abundant source of information that can assist researchers, policymakers, and businesses in understanding the evolution of technology and innovation across multiple domains.

2. *The potential for cross-disciplinary analysis*

   Patent data can be used to examine the relationships between innovation, economic growth, and social development, making it a valuable resource for economists, managers, and sociologists.

3. *The opportunity for international comparisons*

The standardization of patent data permits cross-country comparisons and reveals the global distribution of innovation activities and technology transfer.

4. *The capacity to inform policy*

   Patent data may assist in the formulation and evaluation of innovation policies and strategies at the national, regional, and international levels, thereby assisting governments and organizations in fostering innovation-driven growth.

Furthermore, the *"OECD Patent Statistics Manual"* (OECD, 2009), from the Organisation for Economic Co-Operation and Development provides guidelines for the gathering, analysis, and interpretation of patent data. The manual underlines the standardized format of patent data, making comparisons and analyses across countries and time periods more straightforward. It also provides an overview of patent-based indicators and methodologies employed in the study of innovation, such as patent counts, citation analysis, and co-invention networks. In addition to delineating best practices for working with patent data, the manual discusses potential obstacles and hazards that researchers may encounter, including biases in patenting behaviour, data quality issues, and the limitations of certain patent-based indicators. The manual also emphasizes the significance of considering the legal, economic, and institutional contexts in which patents are granted and enforced, as these variables can impact the interpretation of patent data. The OECD Patent Statistics Manual (OECD, 2009) is an indispensable resource for researchers, policymakers, and practitioners who seek to better comprehend the dynamics of technological change and its impact on economic and social development.

Over the years, diverse methods have been established for analysing patent data and deriving innovation-related insights. Among the most prevalent methods there are: Patent Citation Analysis, Patent Co-classification Analysis and Network Analysis.

<u>Patent Citation Analysis</u>

Patent citation analysis is a widely employed technique that entails examining the references made by patents to previous patents. This method can assist scholars in comprehending the transfer of knowledge between inventions and identifying influential patents and emerging technologies. (OECD, 2009).

Narin and Noma (1985) introduced the concept of measuring the flow of knowledge and the relationship between science and technology using patent citations (Narin and Noma, 1985). The authors demonstrated the utility of patent citation analysis for comprehending the connections between scientific research and technological innovation, laying the groundwork for future studies employing this methodology. Narin and Noma (1985) analysed the patterns of scientific citations in patents and demonstrated how the extent of such citations reflects the integration of scientific knowledge into technological development.

An exhaustive overview of patent citation analysis, discussing numerous methods, applications, and empirical findings is given by Jaffe and Trajtenberg (2022). The authors highlighted the importance of patent citation analysis in the study of knowledge flows, technology diffusion, and the influence of public research on innovation. Jaffe and Trajtenberg (2022) covers a vast array of topics, including the theoretical foundations of patent citation analysis, the construction and validation of patent citation measures, and the econometric techniques used to analyze patent data. In addition, Jaffe and Trajtenberg (2022) examine the limitations and potential biases associated with patent citations, emphasizing the need for cautious interpretation of results.

Patent Co-classification Analysis

Patent co-classification analysis involves examining the distribution of patents across different technology classes. This method can be used to identify technological diversification and specialization patterns, as well as to monitor the evolution of technological fields. Researchers can gain insight into the development of new technological combinations and the convergence of formerly distinct disciplines by analysing the co-occurrence of technology classes within individual patents. (OECD, 2009)

Breschi et al. (2003) utilized patent co-classification analysis to investigate the technological diversification patterns of companies. The authors discovered that firms tend to diversify within related technological fields and emphasized the significance of knowledge-relatedness in determining firms' innovation strategies. In particular, Breschi et al. (2003) analysed a large dataset of patents filed by European and American companies, focusing on the distribution of patents across various technology classifications. The authors built a measure of knowledge-relatedness based on the co-occurrence of technology classes within patents and used it to examine the extent to which firms diversified their technological activities within or across related disciplines. The study revealed that firms were more likely to expand their technological portfolio into areas with a higher degree of knowledge-relatedness, indicating that existing technological capabilities played a substantial role in determining firms' diversification decisions.

Another significant work involving the usage of patent co-classification analysis to examine the development and structure of technological fields was carried out by Fleming and Sorenson (2001). The study demonstrated that technological fields exhibit the characteristics of a complex adaptive system in which the emergence of new fields is driven by the recombination and integration of prior knowledge. Fleming and Sorenson (2001) examined the distribution of patents across various technology classes and the relationships between them using a large dataset of patent data. The study showed that co-classification patterns were consistent with the concept of technologies as building elements that can be recombined in novel ways to produce new innovations. Additionally, Fleming and Sorenson (2001) discovered that technological innovation is characterized by both incremental advances within existing fields and the creation of completely new fields through the integration of previously distinct areas of knowledge. This finding emphasizes the significance of understanding the interplay between existing technologies and the potential for inter-disciplinary collaboration in fostering technological progress.

Network Analysis

Network analysis is a collection of methodologies designed to examine the interactions between entities, which are typically depicted as nodes, and the relationships or associations between them, which are depicted as edges or arcs. By applying network analysis to patent data, researchers have examined the connections between inventors, organizations, and technologies. In patent network analysis, nodes can represent several entities such as inventors, organizations, technology classes and so on, whereas edges can represent a variety of relationships, such as co-invention, co-assignment, citation connections, and shared technology classes. These techniques are useful for obtaining insights into the structure and organization of innovation networks, as well as for understanding the roles of various actors within these networks. By analysing the structure of these networks, researchers can identify patterns of collaboration, knowledge transmission, technological and innovative activity distribution among various actors and domains (OECD, 2009).

The effectiveness and the potential of network analysis techniques applied to patent data is showcased by Verspagen (2007). Indeed, by analyzing patent citation networks, Verspagen (2007) investigated the history of fuel cell research using network analysis techniques and identified key insights into the evolution of fuel cell technology and the roles performed by various organizations, inventors, and nations in determining the trajectory of this research field. Specifically, the author analysed patent data from various sources and constructed an exhaustive citation network to depict the intricate relationships between all the different entities involved in the technological development of fuel cells.

Moreover, an extensive overview of network analysis including its application to patent data and the study of innovation networks is available from Newman (2010). The author presented an in-depth examination of various network analysis methods, their theoretical foundations, and their practical applications, demonstrating their potential for examining innovation networks and revealing the structure and dynamics of the innovation process. Newman discussed a wide variety of topics, such as graph theory, centrality measures, community detection, and network evolution, as well as the application of these techniques to real-world problems, including the analysis of patent data. Newman (2010) emphasized the significance of understanding network properties and patterns to reveal the fundamental mechanisms that drive innovation and the factors that contribute to the success or failure of various technologies.

As widely demonstrated so far, the study of innovation and innovative activities through the use and analysis of patent data has many pros but at the same time as mentioned in a few articles, it also involves some limitations (Griliches, 1990). The following studies highlight the flaws arising from the use of patents in the analysis of technological development.

Levin et al. (1987) analysed the effectiveness of different mechanisms for appropriating the returns from industrial research and development. Levin et al. (1987) argued that patent data may not capture the complete scope of innovative activity since not all innovations are patentable due to factors such as the character of the invention or the strategic decisions of the inventing firm. In addition to patent data, the authors emphasized the importance of considering other innovation indicators, such as R&D expenditures, product announcements, and alternative forms of intellectual property protection. Thus, the findings of Levin et al. (1987) highlighted the need for a more comprehensive approach to measuring innovation than patent data alone.

The limitations of employing patents to study innovative activity have also been proved Cohen et al., (2000). The authors investigated the differences in patenting propensity across industries, countries, and companies, identifying potential biases and comparability issues in patent data, and thus, demonstrating the need for careful interpretation of patent-based innovation indicators. By analyzing survey data from U.S. manufacturing firms, Cohen et al., (2000) identified several factors that influence patenting behaviour, including industry-specific appropriability conditions, the efficacy of alternative mechanisms for protecting intellectual assets, and the strategic goals of individual firms. The study revealed that patenting propensity can vary considerably based on these factors, resulting in potential biases when comparing patent data across contexts.

In conclusion, patent data and patent analysis have emerged as important instruments for analyzing innovation, providing valuable insights into technological change's patterns, dynamics, and determinants. The literature on this topic is vast and varied, and the studies presented in this master’s thesis represent only a fraction of the significant contributions and debates in the field. Even though it has many advantages, researchers must be aware of the limitations of patent data utilization in investigating innovation, such as the incompleteness, the disparities in patent propensity and in the strategic patenting behavior. Despite these obstacles, patent data and patent analysis continue to be an indispensable resource for scholars, policymakers, and industry leaders attempting to comprehend and foster innovation in today's complex and quickly changing world.

Section 3: Patent Analysis of Green Technologies and Hydrogen-related Technologies

This third section of the literature review seeks to investigate the increasing volume of research that examines green technology using patent data, with an emphasis on hydrogen-related technologies. With the intensifying urgency to address climate change and achieve sustainable development, there is a growing interest in understanding the dynamics of green innovation, and hydrogen-based technologies have emerged as a promising pathway to ensure and facilitate the energy transition to carbon neutrality and a more sustainable future. Through an analysis of relevant scientific papers and articles, this section intends to provide a comprehensive overview of the main findings and trends in the study and analysis of patent data on green technologies, as well as hydrogen-related technologies such as green hydrogen production, storage, distribution, and end-use applications. By examining the methodologies, results, and implications of these studies, this third part attempts to shed light on the factors driving innovation in these fields and their potential contribution to a more sustainable future.

The first part of this third section will present studies on the progress of sustainable technologies using patent data while the second part will present significant studies on the status and development of hydrogen-related technologies again through patent analysis.

Green Technologies and Patent Analysis

To begin with, Barbieri et al. (2020) investigated the distinctions between green and non-green technologies in terms of their knowledge sources and their influence on future innovations. The authors used a citation-based methodology to trace the roots of both green and non-green patents, revealing significant patterns. Green technologies exhibited a distinct level of technological specialization, which likely reflects their multidisciplinary complexity. In addition, these technologies drew from a vast array of knowledge sources, indicating the diverse influences that shape green innovation. In contrast, non-green technologies were found to rely on a more uniform set of knowledge sources, indicating that their innovation process is more limited. Moreover, Barbieri et al. (2020) discovered that green patents produce a greater influence on subsequent inventions, highlighting their profound impact and the growing importance of sustainability in the domain of invention and innovation. The outcomes of Barbieri et al. (2020) emphasize the unique role of green technologies in propelling technological progress and the critical importance of supporting green innovation as a catalyst for sustainable and broad-based development.

Aldieri et al. (2019) conducted another interesting study concerning the analysis of patent data in the field of sustainability and green technologies (Aldieri et al., 2019). Specifically, the authors, using patent data, delved into the complex relationship between environmental innovation and sustainable development, concentrating on the crucial role of technological proximity between different industries. Aldieri et al. (2019) found out that industries with greater technological proximity demonstrated a greater propensity for environmental innovation. This finding suggests that technological origins that are similar or shared can facilitate collaborative innovation, leading to more sustainable solutions. Consequently, technological proximity appears to be a driving force behind the development of green technologies. In addition, the Aldieri et al. (2019) highlighted the significance of technological relatedness and knowledge spillovers in promoting the development and widespread adoption of environmentally friendly technologies. This suggests that the flow of knowledge between industries can substantially influence the rate and direction of sustainable innovation.

Green technologies using patent data have also been studied by Nomaler and Verspagen (2019). The authors, using an extensive patent citation network as their data source, presented a comprehensive analysis of the interaction between homophily and path dependence in the field of green technologies. Homophily, the tendency for similar entities to interact or congregate together, and path dependence, the idea that the possibilities of the present are influenced by the events of the past, are both essential concepts for comprehending the dynamics of technology development. The Nomaler and Verspagen (2019) discovered that green technologies exhibited a greater degree of homophily, indicating that they are more likely to reference other green technologies in their patent applications. This finding suggests that green technologies may be evolving along a distinct trajectory compared to non-green technologies. This study simultaneously highlights the significant path dependence observed in the development of green technologies. This indicates that the evolution of these technologies is heavily influenced by previous technological decisions and advancements, further directing their development along a distinct path. According to Nomaler and Verspagen (2019), a combination of robust homophily and path dependence can facilitate the transition to a more sustainable technological paradigm.

Later, the same authors published an additional significant work on patent analysis applied to the study of sustainable technologies (Nomaler and Verspagen, 2021), where they presented a novel methodology for patent landscaping. The new approach is based on green technological trajectories, with an emphasis on the evolution and development of green technologies over time. Specifically, through the usage of patent data, Nomaler and Verspagen (2021) showed that it is possible to trace the developmental paths of green technologies, providing a clear understanding of their evolution and possible future direction. Nomaler and Verspagen (2021) covered a broad spectrum of technologies and among them also presents the evolution of some hydrogen-related innovations. Their findings revealed distinct trajectories for every different technology, highlighting how each of these elements had a unique progression pattern, and thus, demonstrating the complex and multifaceted character of the development of green technologies.

Differently, Montresor and Quatraro (2020), analysed patent data, by specifically adopting the technology codes of the International Patent Classification, to investigate the nuanced relationship between green technologies and smart specialization strategies. Montresor and Quatraro (2020) investigated the technological relatedness of renewable technologies with the Key Enabling Technologies (KETs), within the context of European patent data, finding that the two are closely related. This correlation suggests a synergistic relationship in which advances in KETs can stimulate the development and enhancement of green technologies, and vice versa. The interdependent development of these two industries provides an essential basis for the implementation of smart specialization strategies. The smart specialization strategy concept emphasizes the need to concentrate resources on important fields where regions have a competitive advantage or potential.

Therefore, the co-evolution of green technologies and KETs can enhance regional competitive advantage in sustainable practices (Montresor and Quatraro, 2020).

Additionally, Chai et al. (2020), studying patents on green and sustainable technologies, provided an exhaustive and relevant analysis of the factors that substantially influence the citation performance of these green patents. Chai et al. (2020) focused on the examination of two crucial factors: inventor collaboration and technological relatedness, as well as their influence on the citation performance of green patents. The collaborative networks established by inventors appear to be a critical success and impact factor for green patents. These partnerships can facilitate the exchange of ideas and knowledge, thereby augmenting the potential and quality of ecological innovations (Chai et al., 2020). Similarly, the author investigated the role of technological relatedness in green patents, that is, the extent to which diverse technologies share common knowledge bases. Chai et al. (2020) showed that a green patent has a greater chance of being recognized and cited if it closely aligns with existing technological pathways. The findings indicate that both factors positively influence the citation performance of green patents and therefore this highlights the importance of fostering collaborative networks and leveraging technological relatedness to enhance the impact and diffusion of green innovations.

Hydrogen-related Technologies and Patent Analysis

An extremely meaningful study that addresses the technological development involving the hydrogen economy, using patents as a tool, was conducted by Sinigaglia et al. (2018), which presented a comprehensive analysis of patents related to the hydrogen economy from 1998 to 2018. Initially, utilizing the "Questel Orbit" platform for data collection, the authors meticulously identified and catalogued patents, focusing on their geographic distribution and their correlation with technological advancements in hydrogen production, storage, and usage. Sinigaglia et al. (2018) utilized keywords as a methodology to filter patents, ranging across various stages of the hydrogen economy, coupled with International Patent Classification (IPC) codes. The data analysis provided an effective approach for understanding the technological landscape and the leading countries and companies in the hydrogen economy. Sinigaglia et al. (2018) unveiled that Japan and the United States have made significant strides in hydrogen technology, leading the pack with the highest number of patent families. Toyota Motor and Honda Motor emerged as the leading companies in terms of patent ownership, indicative of their active involvement in this technology domain. Interestingly, the Sinigaglia et al. (2018) identified an overall increase in patent publications from 2001 to 2006, followed by a notable decline between 2012 and 2017. This decline might suggest a waning interest in certain technologies related to the hydrogen economy during that period. Despite this trend, the authors underscored the importance of hydrogen as a future energy source given its high energy density and potential for zero carbon emissions. Ultimately, Sinigaglia et al. (2018) indicated that patent analysis could serve as a valuable tool in comprehensively mapping the progress and direction of technological advancements.

More recently, Yu et al. (2022) developed a significant analysis that aimed to predict the future of the hydrogen supply chain by identifying the most promising technologies. The authors examined patent databases and research paper databases from Korea, the United States, Europe, China, and Japan, which enabled them to derive the key technologies for future hydrogen supply chains. By analysing the development of storage, transport, and charging technologies, Yu et. Al, (2022) utilized text mining and Generic Topographic Map (GTM) analysis to identify emerging technologies. This approach enabled the authors to bridge the 18-month blind spot in patent analysis, thus capturing the latest advancements in hydrogen technologies. As a matter of fact, patents often have an "18-month blind spot" or "blind period," which is a term that refers to the time from when a patent application is filed until it is published (Yu et. Al, 2022). This period is typically 18 months long, and during this time, the contents of the patent are not publicly available. From the patent analysis, the Yu et. Al, (2022) identified three promising technologies: the compression, cooling, and liquefaction processes for storing hydrogen in vehicle-mounted cylinders; the use of tanks for transporting stored hydrogen fuel; and the charging of transported liquid hydrogen to vehicles in stations. Finally, Yu et. Al, (2022) underlined the potential of three promising technologies: the use of Liquid Organic Hydrogen Carriers (LOHC) for storing hydrogen fuel energy; transportation by train or truck using containers; and the remodelling of existing train stations to supply hydrogen energy fuel to vehicles.

One of the most significant studies regarding the analysis of the status of hydrogen technologies with the help of patent data was conducted by Ampah et al. (2022), who provided an in-depth investigation into the trends and key contributors to hydrogen production technologies, utilizing a combined approach of patent-life cycle and econometric analysis. The emphasis on patent data offers a unique perspective on the technological progression in this field. Through the patent-life cycle analysis, Ampah et al. (2022) determined the technological maturity of different hydrogen production technologies and the analysis revealed that about 60% of patents were filed between 2000 and 2010, predominantly by companies from Japan, the US, and China. Additionally, Ampah et al. (2022) found that fossil-based technologies have a maturity rate of around 66%, indicating limited space for further growth. In contrast, renewable-based technologies, with a maturity rate of nearly 57%, show higher potential for technological advancement. The authors also employed econometric analysis to identify the key drivers of development in the hydrogen production technologies sector and their findings suggest that research and development expenditure, along with low carbon energy consumption, are significant positive contributors to the advancement of hydrogen production technologies. Also, Ampah et al. (2022) found an ascendant trend of renewable-based technologies in recent years, despite the existing challenges like high production costs and the lack of a sustainable clean hydrogen value chain. The study demonstrates that a committed push towards innovative technologies like water electrolysis, biomass gasification, and nuclear thermal pathways can overcome these challenges.

Furthermore, Zhang et al. (2023) conducted a further study of hydrogen technologies through the analysis of patent data that filled a knowledge gap in renewable energy literature by reviewing relevant US patents on hydrogen-based renewable energy systems and energy management strategies. Zhang et al. (2023) focused on hydrogen's industrial applications, given its attributes such as high efficiency and high energy density, which position it as a crucial component in renewable energy systems. To conduct this analysis, the authors performed an extensive search on “Google Patents” and “Free Patents Online” using keywords like hydrogen, management, and power system. They then filtered the gathered data and categorised the patents into three groups: renewable energy hydrogen production technology, the application of hydrogen-containing in renewable energy systems, and energy management of power systems with hydrogen energy storage. Zhang et al. (2023) found that the trend towards hydrogen production through wind power and photovoltaic electrolysis of water will be significant in the future, owing to the continuing decrease in the cost of electricity generation from renewable sources. However, issues such as system efficiency and economic feasibility still need to be addressed. Hydrogen energy storage presents a viable solution to the limitations of traditional energy storage methods, exhibiting multiple application values both on the load side and power supply side (Zhang et al., 2019). However, the authors recognize challenges, including lack of integrated development strategy, low energy conversion efficiency, and monitoring difficulties. They also note that there is no "one-size-fits-all" energy management strategy; the best scheme depends on the specific optimization objectives. Ultimately, Zhang et al. (2023) concluded that the future of energy management systems with hydrogen storage is promising and forecasted that research will shift towards multi-energy complementary energy management systems that incorporate big data and intelligent autonomous optimization design.

To conclude the review of hydrogen publications, it is also noteworthy to cast light on the findings of Chung et al. (2023). The authors employ patent analysis to explore the life cycle, commercial readiness, and technological advancements of Hydrogen Production Technology (HPT). In particular, the analysis utilized patents from the US Patent and Trademark Office (USPTO) database. Chung et al. (2023) found that HPT has progressed from its initial hype stage to a mature phase of development, signifying stabilized expectations and readiness for commercial dissemination. Trends in patent applications have shown a global hydrogen ecosystem, involving not just the US and Japan who led the early stages, but also the EU and emerging countries, fostering greater innovation. Also, Chung et al. (2023) highlighted the shift in technological competitiveness within HPT. Initially, reforming technology dominated, but as technology accumulation grew, the superiority transitioned to electrolysis. The competitive gap between these two technologies has subsequently expanded, and electrolysis is expected to play a vital role in a sustainable hydrogen economy. Furthermore, Chung et al. (2023) pointed out a strong correlation between HPT development trends and fossil fuel prices, implying that fossil fuel costs significantly impact HPT as an alternative technology. Despite the technological maturity and strengthening competitiveness of HPTs, their commercialization largely depends on cost efficiency (Chung et al., 2023). Currently, electrolysis, though technologically and environmentally suitable, lacks economic feasibility due to the high costs of catalysts like platinum, gold, and silver. Therefore, the authors emphasized the need for the development of cost-effective electrocatalysts with improved system efficiency for large-scale hydrogen electrolysis commercialization. Chung et al. (2023) also acknowledged the limitations of their study, above all the reliance on patents from USPTO, which could not represent technology development trends globally. Second, patent data doesn't reflect completely ongoing research trends or potential technologies developed at the laboratory scale. Despite these limitations, the Chung et al. (2023) provided valuable insights into the technological trajectory and commercial readiness of HPT.

In conclusion, this third section literature review provides an extensive exploration of green technologies and the use of patent analysis in uncovering trends, advancements, and challenges in the field of hydrogen technology. These studies collectively highlight the value of patent data in offering unique insights into technological progression, maturity, and readiness for commercialization of hydrogen technologies and renewable energy systems. Furthermore, they underline the promise and potential of hydrogen as a key component of future energy systems, a prospect that is evidently supported by the global shift towards sustainable and renewable energy sources. Despite evident challenges, such as economic feasibility and technology development constraints, the advancements and research trends reviewed here inspire confidence in the potential for significant growth and innovation in the hydrogen technology sector. On the broader perspective, previous literature illustrates the increasingly crucial role of green technologies in shaping the future of our energy landscape and their capacity to address urgent global issues such as climate change and energy sustainability.

THE HYDROGEN VALUE CHAIN

Hydrogen Production: Brown, Gray, Blue, Green Hydrogen and Other Colours of Hydrogen

Hydrogen can be obtained in various ways, from different input feedstocks and different sources of energies can be used in the transformation process. The different hydrogen generation methods carry along different environmental impacts, as well as different costs, which also largely depend on the cost of feedstock/resources in a specific geographical area.

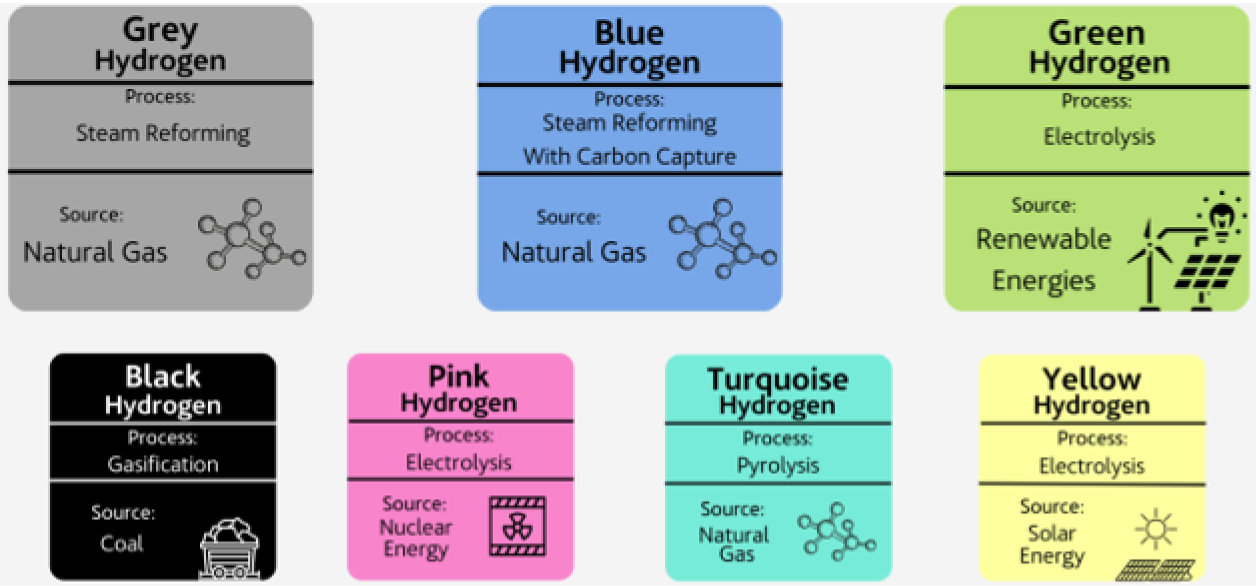

IMAGE 1: THE COLOURS OF HYDROGEN, SOURCE: ACCIONA ENERGIA

Black or Brown Hydrogen

The production of brown hydrogen involves utilizing coal in the gasification process. This method, which is on the opposite end of the spectrum from the green hydrogen's electrolysis process, is commonly used in various industries to convert carbon-rich materials into hydrogen and carbon dioxide. However, the emissions released during this process contribute to pollution and make it the second most harmful form of hydrogen for the environment, behind only grey hydrogen. Furthermore, brown hydrogen accounts for over 27% of global hydrogen production (World Economic Forum, 2021).

Grey Hydrogen

Currently, grey hydrogen production is the most common and cost-effective method of producing hydrogen. It is a source of propellant and accounts for 71% of the world's hydrogen production. However, its production does produce greenhouse gas emissions. Using steam methane reforming (SMR), which extracts hydrogen from natural gas, grey hydrogen is produced from natural gas. However, this process's technology does not retain the resulting carbon emissions, which are instead released into the atmosphere (World Economic Forum, 2021).

Blue Hydrogen

Steam reforming produces blue and grey hydrogen. However, unlike grey hydrogen, carbon emissions from the process are collected and stored using carbon capture and storage (CCS) technology, reducing atmospheric emissions but not eliminating them. Blue hydrogen is called "low-carbon hydrogen" because it stores greenhouse gasses during creation. Blue hydrogen's restrictions have limited its application. It uses limited resources, fluctuates fossil fuel costs, and doesn't provide energy security. Blue hydrogen needs CO2 storage, transport, and monitoring. Blue hydrogen can boost the hydrogen industry by upgrading current resources with CCS technology to reduce greenhouse gas emissions. CCS efficiency is predicted at 85-95%, therefore some CO2 will be discharged into the environment. Thus, blue hydrogen is a short-term solution for net-zero emissions. Green hydrogen is expected to replace blue hydrogen to accomplish carbon neutrality as renewable energy prices drop (World Economic Forum, 2021).

Green hydrogen

Green hydrogen is a form of hydrogen that is produced from renewable energy sources, making it the optimal means of transitioning to a completely sustainable energy system. It is produced by electrolysing water with electricity derived from renewable sources such as solar, wind, and hydropower. In the future years, the proportion of hydrogen produced from renewable resources is expected to increase significantly from its current level of less than 1%. Renewable energy cost reductions and technological advances are essential for lowering the price of producing green hydrogen and making it a financially viable and sustainable option (World Economic Forum, 2021).

Other Colours of Hydrogen

Numerous technological advancements in hydrogen production have emerged in recent years. Electrolysis powered by nuclear energy is used to produce pink hydrogen, which is one of these techniques. Another new technique, known as turquoise hydrogen, is undergoing research to determine its potential for wide-scale application. This variety of hydrogen is produced by the methane pyrolysis process, which employs heat to convert a material into hydrogen and solid carbon. Instead of being released into the atmosphere, the carbon produced is retained in solid form. In the event of success, turquoise hydrogen could be deemed a low-carbon option, provided the carbon is stored in an environmentally responsible manner. Last, yellow hydrogen is a less common term for hydrogen produced through electrolysis powered by solar energy (a subset of green hydrogen) (World Economic Forum, 2021).

Hydrogen Distribution

Distribution of hydrogen is a crucial aspect of the hydrogen value chain, which entails transporting hydrogen from production sites to end-users. Due to its unique characteristics, such as its low density, high flammability, and need for specialized infrastructure, the distribution of hydrogen presents several difficulties. There are numerous distribution methods for hydrogen, including pipelines, vehicles, and ships.

Hydrogen's low density is one of the most significant obstacles to its distribution. Hydrogen has a lower energy density than petroleum and diesel, meaning it occupies more space per unit of energy. This results in larger storage containers and transport vessels, making hydrogen distribution more difficult and expensive. Another difficulty is the excessive flammability of hydrogen. Hydrogen is more explosive than other fuels due to its low ignition energy and vast flammability limits, necessitating additional safety measures and specialized infrastructure to ensure its safe handling and distribution. In comparison to other fuels, the present infrastructure for hydrogen distribution is relatively underdeveloped. The hydrogen pipeline network is limited, and there are fewer hydrogen fuelling stations than petroleum stations. As the demand for hydrogen rises, more extensive infrastructure development is required to support its increased use. To address these obstacles, ongoing research and development efforts are being made to enhance the safety and efficacy of hydrogen distribution. For instance, efforts are made to develop materials that are resistant to hydrogen embrittlement and to optimize the compression and storage of hydrogen for transportation purposes. In addition, it may be necessary to develop new distribution methods, such as the use of hydrogen carriers such as liquid organic hydrogen carriers (LOHC) or metal hydrides (Hydrogen Europe, 2022).

Pipelines

Pipelines, which currently are most widely adopted distribution method, offer several benefits, including reduced costs, greater efficiency, and a more reliable supply. Hydrogen conduits are typically constructed from specialized materials that are resistant deterioration caused by hydrogen absorption. Hydrogen can also be mixed with natural gas and transported through existing natural gas conduits. Hydrogen can be separated from natural gas at the point of use, allowing for a gradual transition to a network of purified hydrogen without requiring significant infrastructure modifications. Hydrogen integration is a cost-effective strategy for incorporating hydrogen into the current natural gas infrastructure (Hydrogen Europe, 2022).

Trucks

Another method of hydrogen distribution is truck distribution, which entails compressing and storing hydrogen in high-pressure cylinders on board the trucks. This method is more adaptable than pipeline distribution, allowing hydrogen to be transported to regions lacking pipeline infrastructure. Due to the limited quantity of hydrogen that can be transported at one time, it is additionally more expensive and less efficient (Hydrogen Europe, 2022).

Ships

Hydrogen is still transported over vast distances via ship distribution, though it is less common. For transport aboard ships, hydrogen is chilled and compressed into liquid form, and upon arrival at the destination, it is heated and vaporized back into gas form. This distribution method is appropriate for transporting large quantities of hydrogen over long distances, but it is costly and requires specialized apparatus (Hydrogen Europe, 2022).

Hydrogen Storage & Transformation

The ability to store hydrogen is a key link in the hydrogen supply chain. Hydrogen, as a renewable energy transporter, might be essential in the shift to a low-carbon economy. However, because of its low density and high flammability, storing it can be difficult. To guarantee the secure and effective management of hydrogen, several storage technologies have been devised. There are several variables to consider while deciding on a storage technique, including the data type, the amount of space needed, and the budget. Most hydrogen is stored as compressed gas or as a liquid, although there are intriguing alternatives, such as solid-state storage and chemical storage (IEA, 2019).

Gaseous Storage

Compressed hydrogen gas is one of the most often used ways of long-term storage. High-pressure tanks composed of carbon fibre composite materials are commonly used to store compressed hydrogen gas because of their low weight and resistance to pressure. Tank pressures vary from around 350 bar to about 700 bar, depending on the use case. To guarantee the tanks' safety, they must be tested often and conform to strict safety regulations.

Liquid Storage

Liquid hydrogen is another way that hydrogen may be stored. The volume of hydrogen gas is reduced by a factor of around 700 when it is cooled to extremely low temperatures (-253°C) and turns into a liquid condition. After that, the liquid hydrogen is kept in insulated storage tanks. Since liquid hydrogen can carry more energy per unit volume than compressed hydrogen gas, it is a promising fuel for rockets and spacecraft that travel long distances. However, due to its low boiling point, liquid hydrogen necessitates special care when being handled and stored, which can be both time-consuming and costly.

Solid Storage

Solid-state materials, such as metal hydrides, can also be used to store hydrogen since they can absorb and release hydrogen through reversible chemical processes. Hydrogen may be stored in metal hydrides at low to high temperatures and pressures without harming the material. They are versatile, with several possible uses including fuel cells and portable power sources due to their large hydrogen storage capacity. However, their widespread application has been hampered by metal hydrides' slow hydrogen release rate and low capacity.

Chemical Storage

Chemical forms of hydrogen storage, such ammonia and methanol, are also on the rise as a means of energy conservation. Hydrogen is stored in these chemical compounds and then released as hydrogen gas as needed. Due to its high hydrogen density and its manageability, ammonia shows promise as a hydrogen transporter. The energy density of methanol is lower than that of ammonia, but it can also store hydrogen effectively. However, the value chain for hydrogen could become more expensive and complicated if chemical storage methods are used.

Geological Storage

Finally, geological structures like depleted oil and gas reserves or salt caverns can be used to store hydrogen. Hydrogen storage in underground geological formations (UGF) describes this technique. UGF is an attractive choice for hydrogen storage on a wide scale because of its high storage capacity and long-term storage stability. The danger of leakage and environmental damage must be carefully analysed and managed, and only certain sites should be used for UGF storage.

Hydrogen End-Uses

Hydrogen's potential in global decarbonization is strictly connected to the versatility of this resource. As a matter of fact, hydrogen can serve as a fuel for transport applications (road, rail, aviation and maritime) and power/electricity generation, as a source of heat in hard to abate industry sectors (steel, cement, paper and pulp, food and aluminium) and in residential and commercial buildings, and last as a feedstock for chemicals production (fertilizers, fuel refining, plastics) and products such as steel, glass, food and metallurgy. Currently, Hydrogen is primarily used as a raw material in the chemical and refining industries, with over 90% of hydrogen in Europe being used in the production of ammonia, methanol, and refining. However, it is expected that hydrogen will play a significant role in reducing carbon emissions in various sectors in the future, including the power system, industries, transportation, and buildings (IEA, 2021).

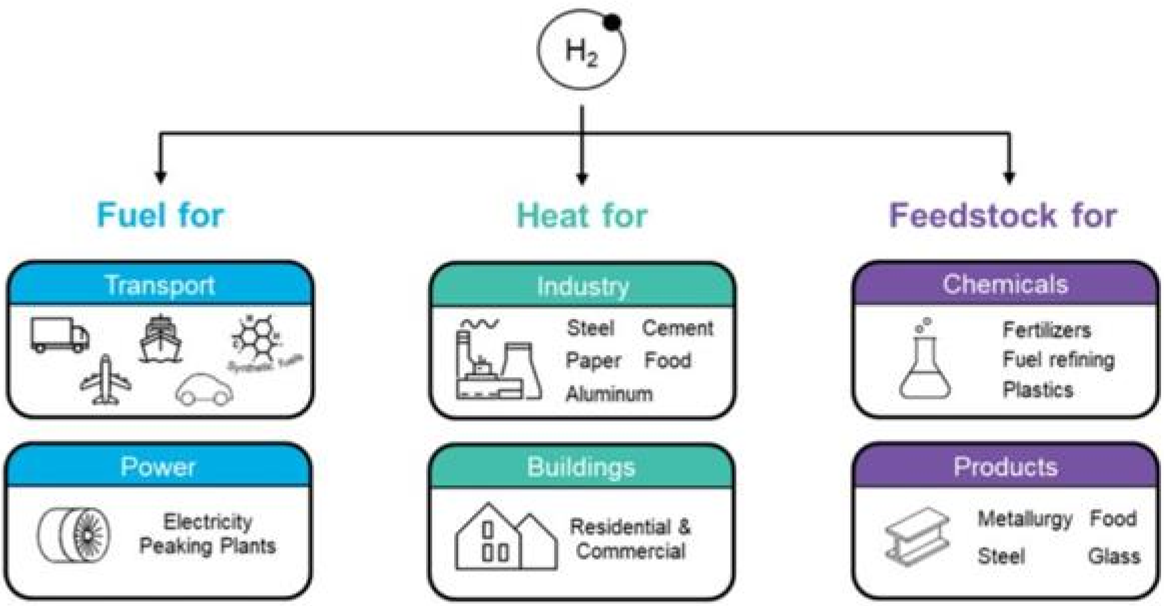

IMAGE 2: THE MANY USES OF HYDROGEN, SOURCE: BLOOMBERGNEF

Hydrogen as a Fuel

Road Transport

Hydrogen can be utilized as a vehicle fuel through the process of reverse electrolysis, in which hydrogen reacts with oxygen to produce electricity. Hydrogen is stored in onboard containers, while oxygen is extracted from the ambient air. This reaction generates only electricity, heat, and water vapor, rendering hydrogen-powered vehicles emission-free. Hydrogen can also be consumed in an internal combustion engine to generate power, albeit less frequently. Hydrogen-powered vehicles generate their own electricity via the fuel cell and do not require an external power source. The electricity produced by the fuel cell can either directly power the vehicle's electric motor or charge a smaller, lighter battery used for intermediate storage. Unlike the larger batteries used in pure electric vehicles, this traction battery is continuously supplied by the fuel cell. Like other electric vehicles, hydrogen cars can recuperate energy during deceleration by converting the vehicle's kinetic energy into electricity and storing it in the buffer battery (IEA, 2019).

Rail Transport

Hydrogen has demonstrated its viability as a rail transportation fuel. Since the early 2000s, the use of hydrogen and fuel cell technology in rail transportation has been demonstrated, with applications ranging from mine locomotives to trams. Multiple nations, including Germany, Austria, the United Kingdom, and the Netherlands, have developed and tested hydrogen fuel cell passenger trains over the past few years. Hydrogen fuel cell trains offer a clean, efficient, and dependable alternative to traditional diesel-powered trains and can contribute to the decarbonization of the rail sector in regions where electrification is difficult or expensive. For long-distance and freight applications, where battery-powered trains may not be practicable, fuel cell trains are particularly advantageous. In the rail transportation industry, hydrogen fuel cell technology has the potential to substantially reduce greenhouse gas emissions and enhance sustainability. As more nations invest in this technology, it is probable that hydrogen fuel cell trains will become more prevalent worldwide (IEA 2019).

Maritime Transport

Hydrogen is emerging as a viable fuel source for the maritime transportation sector due to its potential to provide a pure and sustainable alternative to conventional fossil fuels. Due to its low volumetric density, the direct use of hydrogen is presently restricted to short- and medium-range vessels. However, the use of hydrogen-based fuels, such as green ammonia, in larger oceangoing vessels is being investigated. Passenger ships, ferries, roll-on/roll-off ships, and tugboats are also adopting fuel cell technology at an increasing rate. These fuel cells convert hydrogen into electricity that can be used to power the ship's propulsion system, resulting in zero emissions of greenhouse gases and other contaminants. As the maritime industry continues to seek out healthier and more efficient sources of fuel, the development and use of hydrogen-based fuels and fuel cells are likely to play an important role in the propulsion of vessels of all sizes (IEA 2019).

Aviation Transport

To decarbonize the aviation industry, hydrogen is being considered as a potential solution. Potentially, fuel cell technology and hydrogen combustion could be used to power commercial flights and produce eco-friendly aircraft fuels. Even though hydrogen combustion could be utilized for extended flights, additional equipment would be required to reduce NOx emissions. Sustainable "drop-in" aviation fuels, such as hydrogen-based fuels and biofuels, will be required to decarbonize long-distance flights. However, additional measures may be required to address climate warming effects unrelated to CO2. The growing interest in utilizing hydrogen for aviation purposes underscores the need for sustained research and development in this area, as well as investment in the infrastructure required to support the adoption of hydrogen-based aviation technologies (IEA 2019).

Power Generation

Hydrogen's use in power generation is minimal at present, accounting for less than 0.2% of supply. Hydrogen can be utilized as a propellant in reciprocating and gas turbine engines. Currently, reciprocating gas engines can manage gases with a hydrogen content of up to 70% (on a volumetric basis), and several manufacturers have developed 100% hydrogen-powered engines that will soon be commercially available. Gas turbines can also operate on hydrogen-rich gases, and manufacturers are confident that by 2030, standard gas turbines will be able to operate on unadulterated hydrogen. Hydrogen can be converted into electricity and heat by fuel cells, which produce water but no direct emissions. Fuel cell systems can attain high electrical efficiencies (over 60 percent) and maintain high efficiencies even at partial load, making them suitable for flexible operations such as load balancing (IEA 2019).

Hydrogen as a Source of Heat

Iron & Steel Industry

The steelmaking industry is beginning to test the use of hydrogen to reduce emissions during the steelmaking process. Coal is commonly used for both high temperatures and chemical reactions in the steelmaking process, which necessitates a great deal of heat. In this process, hydrogen can be substituted for both the required heat and the chemical reactions. As steel is one of the fundamental building elements of modern structures and industrial processes, the use of pure hydrogen has the potential to reduce emissions significantly (Deloitte, 2023).

Cement, Paper, Food and Aluminium Industries

Additionally In the cement, paper, food, and aluminium industries, hydrogen can be utilized in a variety of methods to reduce emissions. Hydrogen can be used as a fuel source in the cement industry to substitute coal, which is the main source of energy for cement furnaces. Hydrogen peroxide is used as a bleaching agent in the paper industry, and it can be produced using hydrogen as a feedstock, thereby reducing the use of chlorine-based compounds that emit hazardous contaminants. Hydrogen produced from renewable energy sources can be used for hydrogenation in the food industry to reduce emissions associated with the production of hydrogen. Hydrogen can be employed as a reducing agent in the production of aluminium from bauxite ore, thereby minimizing the quantity of energy required and emissions (IRENA, 2021).

Heating of Residential & Commercial Buildings

The use of hydrogen as a thermal source for residential and commercial buildings is a promising decarbonization strategy for the building sector. However, it confronts obstacles due to the high efficacy of electricity-based solutions and the energy losses associated with hydrogen conversion and transportation. In addition, the expense and complication of assuring safe operations and converting gas infrastructure make it difficult to decarbonize this sector. Despite these obstacles, the localized use of hydrogen in existing building energy systems could support decarbonization in specific contexts with existing gas infrastructure. Incorporating hydrogen with other heat production technologies can increase the flexibility of the electricity grid, especially in extremely frigid regions where other storage options may not be adequate. Hydrogen reactors, fuel cells, hybrid heat pumps, and gas-driven heat pumps are the four major categories of technologies that can operate on hydrogen at the building level. Each technology has advantages and disadvantages, and the optimal solution depends on the building's particular context and needs (IRENA, 2021).

Hydrogen As a Feedstock

Oil Refining & Synfuel Production (Chemical Sector)

The oil refining industry, which converts crude oil into various end-use products such as transportation fuels and petrochemical feedstocks, is currently the largest consumer of hydrogen, consuming approximately 40 million metric tons of hydrogen per year (IEA, 2019). Hydrogen is primarily used for hydrotreating and hydrocracking in refineries. Hydrotreatment is used to remove impurities from crude oil, specifically sulphur, whereas hydrocracking is a refining procedure that uses hydrogen to transform heavy residual hydrocarbons into more valuable oil products. With the rising demand for light and intermediate distillates (including the upgrading of oil sands and the hydrotreatment of biofuels) and the falling demand for heavy residual oil, hydrocracking is gaining in significance. Another potential remedy is the production of low-carbon footprint synthetic hydrocarbon fuels (synfuels). These fuels are referred to as "drop-in" fuels because they can be used to replace current oil-derived fuels and the same distribution networks and end-use equipment can be utilized without modification (IRENA, 2021).

Ammonia Production (Chemical Sector)

Ammonia (NH3) is presently the second greatest consumer of hydrogen with approximately 31 million metric tons per year (IEA, 2019). Hydrogen and nitrogen are combined through the Haber-Bosch process to produce ammonia. The remainder is used in industrial applications such as explosives, synthetic fibres, and other specialty materials. With an increasing drive toward decarbonization across industries, novel ammonia applications are emerging. Ammonia, which is well-known in the freight shipping industry as a sustainable shipping propellant, can also serve as a transport vector for hydrogen. Currently, ammonia is the preferable method for long-distance hydrogen transport. This is because the cost of energy storage is less for ammonia than for hydrogen or liquefied petroleum gas, and because ammonia can store more hydrogen by volume than either hydrogen pipelines or liquid hydrogen. In addition, ammonia is already utilized globally as a fertilizer, so its transportation and storage infrastructure are already in place. Due to its extensive use, there are already established regulations governing its production, transportation, and application (Deloitte, 2021)

Methanol Production (Chemical Sector)

Methanol (CH3OH) is presently the third greatest consumer of hydrogen with approximately 12 million metric tons per year (IEA, 2019). Like ammonia, methanol has multiple uses as a chemical, basic material, hydrogen transport, and electronic fuel. Utilizing CO2 and hydrogen as inputs to produce methanol significantly reduces the CO2 emissions that are typically generated during the manufacturing process. Additionally, e-methanol can help reduce emissions during its use. By procuring the CO2 used as a feedstock through direct air capture, e-methanol used in internal combustion engines can be carbon neutral. Furthermore, methanol has numerous industrial applications, including as a solvent, antifreeze, and in construction materials. Methanol is also used in the production of other industrial chemicals and in the methanol-to-gasoline process, which converts natural gas and coal into gasoline and has attracted interest in regions with an abundance of coal or gas but limited or no domestic oil production. This is one of the uses of methanol as a fuel, accounting for roughly a third of its global consumption, whether in its unadulterated form or after further conversion. In addition, the development of methanol-to-olefins and methanol-to-aromatics technology has created an indirect path from methanol to high-value chemicals (HVCs) and, by extension, plastics (Deloitte, 2021).

Products

Hydrogen is a versatile element that can be used as a raw material in a variety of industries, including the metallurgical, food, steel, and glass industries. Hydrogen is used as a reducing agent in the metallurgy industry to extract metals from their ores, such as iron from iron oxide. Hydrogenation is a process in the food industry that entails adding hydrogen to unsaturated lipids to make them more saturated, thereby extending their shelf life. Hydrogen is used as a reducing agent in the steel industry to remove impurities from iron ore and produce clearer, stronger steel. In the glass industry, hydrogen is used as a fuel source for high-temperature furnaces that shape glass into various shapes by melting it (IEA, 2019).

INNOVATION AND INTELLECTUAL PROPERTY

The Importance of Innovation for Organizations and Intellectual Property Rights

The protection of innovation's value is of paramount importance to the inventor. Innovation is the propelling force behind economic expansion, competitiveness, and societal progress. It propels technological advancements, encourages innovation, and produces novel solutions to complex problems (Grossman and Helpman, 1991). By safeguarding the value of innovation, businesses can defend their investments in R&D, encourage additional innovation, and create incentives for continuous improvement (Aghion and Howitt, 1990). Thus, especially in markets characterized by a high degree of technological specialization, innovation becomes an essential element for gaining competitive advantages over competitors. Therefore, intangible value plays a significant strategic function in complex economic systems and consequently, the exploitation of intangible assets becomes essential for the creation of value.

Nonetheless, innovation needs a suitable preservation strategy. In this regard, numerous context variables (such as the nature of the investment, the presence of complementary assets, and eligibility schemes) can impact the management of innovation and can lead to significant effect on its economic outcome (Schilling, 2013). Consequently, various strategies can be used to safeguard the value of innovation:

- Industrial secrecy (practice of keeping proprietary information and trade secrets confidential).
- Intellectual property rights (i.e., patents, trademarks, copyrights, industrial designs)
- Knowledge learning curves (keeping ahead from competitors by delivering continuous innovation and retaining knowledge)
- Exploitation of complementary assets: (e.g., large-scale production capabilities, distribution channels, access to key resources…)
- Lock-in of customers: (e.g., network externalities, industry standards, high switching costs for consumers...).

It is necessary to focus on Intellectual Property Rights and, more specifically, on patents to comprehend the evolution of the inquired technology. Intellectual Property (IP) refers to mental creations such as inventions, literary and artistic works, commercial symbols, identities, and images. IP is divided into two main categories:

- Copyright, which encompasses artistic and creative forms, such as literary works, films, music, works of art (such as drawings, paintings, photographs, and sculptures), and architectural designs. Copyright also includes rights pertaining to live performances of artists, recordings of music producers, and radio or television programs. Therefore, this privilege is applied automatically to all unpublished works at the time of their creation.
- Industrial Property consists of patents for inventions, trademarks, industrial designs, and geographical indications; unlike Copyright, this right does not arise automatically, but there is an application and publication process for patents and a registration process for trademarks and designs.

Intellectual Property Rights, like any other property rights, enable the creators or proprietors of patents, trademarks, or patented works to profit from the investment made or the labour performed in creating the work. Particularly, the author has the right to enjoy the protection of his own moral and material interests deriving from any of his works (Art. 27 Universal Declaration of Human Rights). The Paris Convention for the Protection of Industrial Property (1883) and the Bern Convention to Protect Literature and Artistic Works (1886) acknowledged for the first time the significance of intellectual property. The World Intellectual Property Organization (WIPO) administers both agreements.

There are numerous justifications for promoting and defending intellectual property rights (IPR). First, the progress and welfare of humanity are dependent on its capacity for creativity and innovation in the domains of culture and technology. Second, the protection of new inventions encourages the allocation of additional resources for future innovations. Third, the promotion and protection of IPRs stimulates economic growth, generates new employment and industries, and enhances the quality of life. An effective and equitable system of innovation protection can benefit all nations by fostering economic growth and social and cultural prosperity. As a matter of fact, the intellectual property system serves to strike a balance between innovators' and the public's interests by providing a protected environment in which creativity and innovation can flourish for the benefit of all.

Patents

Characteristics of a Patent

A patent is a contract between an inventor and a state that grants an exclusive right to an invention, product, or process that offers a novel technical solution to an existing problem. A patent is also a technical-legal document that contains a detailed technical description of the subject of the patent itself as well as its claims of protection. Thus, a patent must include a summary of the prior state of the art (i.e., the technology known at the time of filing, the problem that the invention is intended to address, and a description of how to implement the invention). For an invention to be patented, it must meet the following requirements:

- Must be original/novel. The invention being submitted is not part of the current state of the art and is therefore not yet available to the public or patented. In the EU, everything that is publicly available in any form before the filing date is not considered new (i.e., any disclosure made by the inventor generates prior art). On the other hand, in other patent systems, the inventor has some additional time (i.e., the so-called grace period) to file a patent application after disclosure (e.g., 1 year in the US)

- Must be inventive/non-obvious. It is not possible to obtain a patent for an idea or invention that is considered obvious or falls within the realm of common knowledge. An invention is deemed to be inventive when it is not obvious to a person skilled in the art in view of the state of the art. The person skilled in the art is a skilled practitioner in the relevant technical field who has access to the entire state of the art, is aware of technical knowledge, and capable of routine work.
- Must be useful. The invention being submitted must serve some purpose or have some use that would be desired, such as solving a technical problem and/or having an industrial application.

The assignee, the individual or entity that has been granted the rights to a patent, can decide to whom to grant the right to use it by licensing it based on agreements between the parties or also to transfer his patent rights to third parties. A patent provides assignees with guaranteed protection for their inventions for a limited period, typically twenty years, to enable the return of sustained investment in research and development and to consolidate market position and competitiveness. As the inventor has the right to exclude others from making, using, selling, and importing the patented invention for a limited time, any use of a patented product or process without the owner's permission constitutes a patent infringement.

From the perspective of the state, patents are a highly efficient means of achieving several essential objectives. Patents facilitate the dissemination of new technical knowledge, to begin with. By granting exclusive rights to inventors, patents encourage them to disclose their innovations so that others can learn from and build upon them. This dissemination of knowledge is beneficial to society, as it enables further innovation and advancement. Second, patents prevent R&D efforts from being duplicated. Through the patent system, inventors receive a transitory monopoly on their inventions in exchange for their R&D investments. This exclusivity encourages inventors and companies to invest in hazardous and expensive research, knowing that if their innovations are successful, they can recoup their investments and receive the rewards. As a result, duplicate R&D efforts are reduced, optimizing resource allocation, and nurturing more effective innovation. Last, patents play a crucial role in promoting innovation. Patents encourage inventors and companies to invest in the development of ground-breaking technologies and solutions by providing legal protection and exclusive rights. Individuals and organizations are motivated to stretch the limits of knowledge and develop inventive solutions by the potential for financial gain and market advantage. This, in turn, generates a dynamic and competitive marketplace, which fuels innovation and economic expansion.

In complex industries where products and services are susceptible to intricate variations, a single patent may not provide adequate protection for an invention. Businesses may employ patent fencing strategies to maximize economic benefits and prevent imitation. These strategies entail obtaining distinct patents for each variant of the invention, with the intention of establishing a dense network of intellectual property rights. By doing so, businesses can effectively thwart imitation attempts and maximize the value of their innovations. Patent fencing enables businesses to derive greater economic benefits by assuring comprehensive protection and control over diverse aspects and variants of their inventions.

Patenting Procedure

As a patent consists of a contract between an inventor and a state, each country will have a national office where it is possible to apply for a patent. However, in today's global business environment, companies and organizations require protection beyond national borders for their innovations. Patent rights can be extended internationally or continentally by submitting applications with organizations such as the European Patent Office (EPO) or the World Intellectual Property Organization (WIPO) to address this need. By utilizing international patent organizations and adhering to established patenting procedures, businesses can protect their innovative assets beyond national borders and ensure the proper defence and enforcement of their intellectual property rights.

The patenting procedure begins on the Application Date, date on which the patent application is officially submitted to the competent patent office. Aside from signifying the beginning of the patenting procedure, the Application Date carries significant legal importance as it establishes the invention's priority by determining the order in which patent applications are evaluated for the granting of rights. As patent rights are typically granted based on the "first-to-file" principle in most jurisdictions, it is vital for inventors to file their applications promptly to secure an early priority date. Once the Application Date has been established, the inventor or applicant has a period, typically twelve months, to request territorial rights extensions. This permits them to pursue patent protection in additional countries or regions beyond the jurisdiction of the initial filing. Requests for extensions may be submitted through a variety of channels, including national patent offices, regional patent organizations (e.g., the European Patent Office), and international patent systems (e.g., the Patent Cooperation Treaty administered by the World Intellectual Property Organization).

During the 18-month period preceding the publication of the patent, research is carried out. The patent office conducts a thorough search for relevant prior art. Examining existing patents, scientific literature, and technical publications, this search seeks to determine the novelty and non-obviousness of the invention. The results are compiled into a search report that contains a list of prior art documents with citations and summaries. This report aids the patent examiner in assessing the patentability of the invention and provides the applicant with an understanding of existing technologies. It assists the applicant in revising or strengthening the patent application's claims. Overall, the search period and search report play a significant role in determining the patentability of the invention and informing the subsequent examination procedure.

Following the search period, the patent application enters the publication phase, where it typically becomes accessible to the public 18 months after its filing. The publication permits the dissemination of invention details and establishes a period of provisional protection. After its publication, the patent application enters the phase of examination. The application is reviewed by a patent examiner who considers its novelty, inventive step, and industrial applicability. The examiner may ask the applicant for additional information, amendments, or clarifications. Examining the claims, description, and prior art references cited in the search report is part of the examination procedure. A patent is granted if the examiner determines that the application fulfils the criteria for patentability. Nevertheless, if issues are identified, the applicant can resolve them via arguments or amendments. Depending on factors such as the complexity of the invention, the congestion at the patent office, and the jurisdiction's practices, the examination procedure can last anywhere from several months to several years. Once granted, the patent grants the inventor exclusive rights to the invention for a specified period, typically twenty years from the date of filing, allowing them to prohibit others from producing, using, or selling the invention without permission.

Following patent grant, there is a nine-month period for appealing the decision. If there are objections, interested parties can file an appeal by presenting evidence and arguments against the patent. Objections must be pursued through civil proceedings, typically in a court of law once the appeal period has expired. In civil proceedings, parties may file petitions to contest the validity of a patent. The outcome of these proceedings will determine whether the patent is maintained in its current form, modified, or invalidated. This assures a comprehensive evaluation of the granted patent and permits interested parties to challenge its validity or seek necessary modifications.

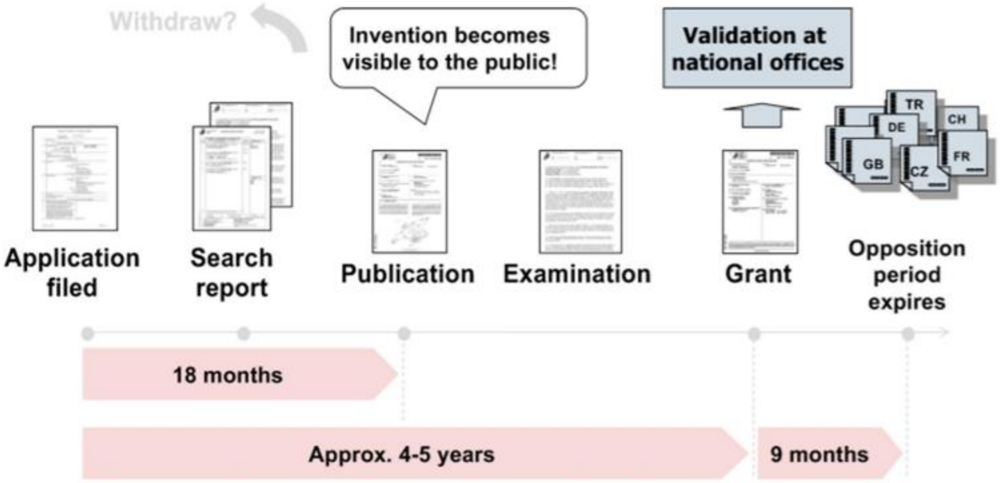

IMAGE 3: PATENTING PROCEDURE MILESTONES AND TIMELINE

Technological Classifications

To facilitate research and grouping patents according to universal criteria, technological classifications have been developed, the most prominent of which is the International Patent Classification (IPC), which was established in 1971 by the Strasbourg Agreement. The IPC code appears on the front of the patent document and divides patentable technologies based on their functional properties into eight sections, denoted by letters from A to H, until descending into ever-greater levels of detail; each patent is therefore marked by at least one code indicating the main class of belonging, followed by additional codes if the invention belonged to multiple classes. In addition, depending on the jurisdiction of deposit, additional classifications occur, such as the European Classification (ECLA) in Europe or the United States Patent Classification (USPC) in the United States.

Patenting offices

The procedure of obtaining intellectual property rights for an innovation through patenting differs depending on the country where the patent application is submitted. Most of the time, registering a patent with a national patent office ensures that it is protected in the nation where it was filed. This indicates that only inside that specific jurisdiction are the patent rights legitimate and enforceable.

A different strategy is provided by filing a patent with international bodies like the European Patent Office (EP) or the World Intellectual Property Organization (WIPO). A single worldwide patent application may be submitted by applicants under the Patent Cooperation Treaty (PCT), which is administered by WIPO. This method makes the initial filing process simpler by enabling applicants to look for patent protection across several member nations. A "worldwide" patent is not, however, granted. Instead, a PCT application goes through an international search and preliminary review before the applicant can decide whether to move on to the national or regional phase in the nations or regions of their choosing.

Through a centralized process, applicants may request patent protection in the nations that are parties to the European Patent Convention (EPC) through the European Patent Office (EP). An approved European patent offers defence in numerous European nations chosen by the applicant.

Inventors primarily obtain protection within a particular country by filing at a national patent office. By contrast, international agencies like WIPO or regional offices like the European Patent Office simplify the process of obtaining patent protection across numerous nations or regions. It is essential for inventors to consider the desired geographic breadth of protection and assess the best strategy when registering their patents.

DATA & METODOLOGIES

Selection and Description of the Research Perimeter

The objective of this master's thesis is to provide a comprehensive overview of the current state of the technologies related to the hydrogen industry, through the analysis of patent data. To conduct a complete analysis of the topic, the entire hydrogen value chain (production, transformation, storage, distribution, and end uses) was selected as a research perimeter. Thus, to identify patent classes, the report "*Hydrogen patents for a clean energy future - A global trend analysis of innovation along hydrogen value chains*" (IEA, 2023), was utilized as a benchmark to construct a taxonomy for the patent landscape. This report provides a thorough perspective of all patented technologies across the entire hydrogen technology value chain. As indicated by the report, within the research perimeter that incorporates the entire value chain, the analysis carried out will focus on the most patent-intensive technologies. Thus, it is worth to precise that not all hydrogen related worldwide patented technologies will be included in this analysis, but only the most significant ones. These identified hydrogen value-chain-related technologies are listed in *Table 1* and described into details in this section. Each technology was highlighted in yellow if it represents a *process innovation*, counter wise it was highlighted in green if it accounts for a *product innovation*.

Hydrogen Value Chain	Category	Technology
1.Hydrogen Production	1.1 Low-carbon Technologies for Hydrogen Production (from Light Hydrocarbons)	1.1.1 Steam Methane Reforming: with CCUS (Blue Hydrogen)
		1.1.2 Steam Methane Reforming: Electrically Heated (Grey Hydrogen)
		1.1.3 Steam Methane Reforming: Sorption-enhanced (Grey Hydrogen)
		1.1.4 Steam Methane Reforming: Plasma Reforming (Grey Hydrogen)
		1.1.5 Methane Pyrolysis (Turquoise Hydrogen)
	1.2 Water Electrolysis (Green Hydrogen Production)	1.2.1 Alkaline Electrolysers (AEL)
		1.2.2 Polymer Electrolyte Membrane (PEM) or Proton Exchange Membrane Electrolysers (PEMEL)
		1.2.3 Solid Oxide Electrolysers (SOEL)
		1.2.4 Anion Exchange Membrane Electrolysers (AEMEL)
2. Hydrogen Transformation, Storage & Distribution	2.1 Transformation into Hydrogen-Based Fuels (also part of Hydrogen End Use for the Chemical Sector)	2.1.1 Transformation of Pure Hydrogen into Low-emission Hydrogen-based Synthetic Fuels: Synthetic Methane & Others
		2.1.2 Transformation of Pure Hydrogen to Ammonia & Low-temperature Ammonia Cracking (from Ammonia to Pure Hydrogen)
		2.1.3 Transformation of Pure Hydrogen to Liquid Organic Hydrogen Carriers
	2.2 Hydrogen Storage & Distribution	2.2.1 Gaseous Storage (Fuel stations, Terminals or Platforms, by Burying Tanks, by Digging Cavities, by using Natural Cavities, Deep Sea, Offshore)
		2.2.2 Liquid Storage (Fuel stations, Terminals or Platforms, by Burying Tanks, by Digging Cavities, Deep Sea, Offshore)
		2.2.3 Solid storage (Hydrides/Adsorption)
3. Hydrogen End-Uses	3.1 Fuel Cells and ICE	3.1.1 Proton-exchange membrane fuel cells (PEMFC)
		3.1.2 Alkaline Fuel Cells (AFC)
		3.1.3 Phosphoric Acid Fuel Cell (PAFC)
		3.1.4 Molten Carbonate Fuel Cell (MCFC)
		3.1.5 Solid Oxide Fuel Cell (SOFC)
		3.1.6 Direct Methanol Fuel Cell (DMFC)
		3.1.7 Internal Combustion Engine (ICE)
	3.2 Iron & Steel Manufacturing	3.2.1 Direct Reduced Iron
		3.2.2 Blending in Blast Furnaces
		3.3.3. Smelting Reduction

TABLE 1: LIST OF HYDROGEN VALUE-CHAIN-RELATED TECHNOLOGIES FOCUS OF THE STUDY

1.1.1 Steam Methane Reforming: with CCUS (Blue Hydrogen)

Steam methane reforming with carbon capture and utilization (CCUS) is a process that converts natural gas into hydrogen while capturing and storing the carbon dioxide (CO_2) emitted during the conversion. Using steam and methane, SMR with CCUS produces a chemical reaction that produces hydrogen gas, carbon monoxide, and carbon dioxide. The captured CO_2 emissions are then redirected to other industrial operations or buried underground. This technology is acquiring popularity as a low-carbon alternative to conventional SMR, also known as grey hydrogen, which lacks carbon capture. SMR with CCUS has the potential to substantially reduce greenhouse gas emissions associated with hydrogen production by capturing and storing CO_2 emissions (IEA, 2023).

1.1.2 Electrically Heated Steam Methane Reforming (Grey Hydrogen)

An option for reducing the two-fifths of SMR emissions that result from thermal requirements is substituting electricity for natural gas combustion. Innovation in this field has centred on the design of compact reformers that eliminate the need for a large gas furnace with an array of hundreds of reformer tubes that are each longer than 10 meters and contain a catalyst. In contrast to the gas-based heating system, which necessitates flame temperatures above the reaction temperature to account for heat transfer losses, an electrical resistance heating system can use much more precise and efficient heating, varied in real time according to the chemical reaction profile, to achieve greater methane conversion ratios. If such systems were applied to all SMRs utilizing renewable or nuclear energy, it would be possible to reduce global CO_2 emissions by 1%.9 Because an eSMR can be operated with some degree of flexibility, it is possible that it could be derated when renewable electricity is in limited supply if incentives are in place to incentivize "system-friendly" operation (IEA, 2023).

1.1.3 Sorption-enhanced Steam Methane Reforming (Grey Hydrogen)

In the SMR process, methane is initially reformed with steam to separate its carbon and hydrogen components. The resulting carbon monoxide (CO) is then reacted with additional vapor in a second step to extract additional hydrogen from the water molecules. This two-step procedure is hampered by the need for high temperature and pressure (800–1000°C and 1.53 MPa) as well as the inability to achieve extremely high conversion rates. SE-SMR combines these stages into a single phase with more moderate operating conditions and a potential output containing up to 98% H_2 and significantly reduced levels of CO and CO_2. Therefore, it requires less natural gas, less energy to purify the H_2 product, and inexpensive reactor materials that do not need to withstand such extreme conditions. In addition, CO_2 separation is considerably more straightforward with CCUS. In addition, the high-temperature, high-alloy steels required for the reforming reactor can be substituted with less expensive building materials (IEA, 2023).

1.1.4 Steam Methane Reforming through Plasma (Grey Hydrogen)

The creation of a plasma of heated ionized gas, in which the reaction occurs, is a more radical method for transitioning to electricity-based reforming heating. There is no need for water inputs; the equipment can be very compact; it can process biomass, heavy hydrocarbons, and natural gas to produce hydrogen; smaller amounts of catalyst can potentially be used, with the plasma's free radicals helping to achieve higher yields; the reaction conditions could potentially be modified so that the hydrogen product is converted to synthetic fuels using the same equipment (IEA, 2023).

1.1.5 Methane Pyrolysis (Turquoise Hydrogen)

Methane pyrolysis is the high-temperature decomposition of methane into its constituent elements, predominantly hydrogen and carbon. Typically, the process takes place in a reactor at temperatures above 800°C, with or without a catalyst. The process can also be performed in the presence of a catalyst, which can reduce the required temperature for the reaction to occur and increase the hydrogen yield. The main benefit of methane pyrolysis is that it can produce highly pure hydrogen without additional purification and CO_2 is not produced as a by-product. However, methane pyrolysis is still a relatively new and developing technology, and it faces challenges in terms of scalability, energy efficiency, and cost-effectiveness in comparison to other hydrogen production methods such as steam methane reforming and electrolysis (IEA, 2023).

1.2.1 Alkaline Electrolysers (AEL)

Alkaline electrolysis (AELs) is the most mature and widely used technology for stationary and/or continuous applications, accounting for approximately 70% of the market for green hydrogen production. It has a low cost and a long operating life, but continuous operation is required, or the apparatus may be damaged. Applications requiring flexible operation and intermittent electrical production employ AELs less frequently. The electrolyte is typically a liquid solution of KOH or NaOH that is circulated between two Ni-alloy electrodes. This method transfers OH^- ions between the cathode and anode at temperatures between 60 and 80 degrees Celsius. A permeable diaphragm is used to prevent the mingling of hydrogen and oxygen and to maintain their separation on the cathodic and anodic sides. Two liquid-vapor separators receive the gas and electrolyte fluxes departing the cathode and anode. The residual electrolyte is recirculated, while the purified gases are sent for external use (IEA, 2023).

1.2.2 Polymer Electrolyte Membrane (PEM) or Proton Exchange Membrane Electrolysers (PEMEL)

Polymer Electrolyte Membrane (PEM) or Proton exchange membrane electrolysis (PEMEL) are also commercially available, but their industrialization and experimentation are not as advanced as alkaline electrolysers. PEM employs a polymer membrane electrolyte that facilitates the transfer of protons (H+ ions) in the presence of water, producing hydrogen with a near-zero oxygen concentration. The hydrogen is stored between metal electrodes at temperatures between 50 and 70 degrees Celsius. Due to the reduced thickness and high current density, medium-high pressure operation, and rapid response to electrical power transients, the design of PEM/PEMEL electrolysers allows for the development of compact stacks. The requirement for precious materials such as catalysts (Platinum, Iridium) is a significant disadvantage of this technology, and ongoing research focuses on reducing the quantity of catalyst required and making them entirely recyclable. PEM/PEMEL electrolysis can produce hydrogen of a higher quality and can operate intermittently, but it is more expensive and has lower production rates than alkaline electrolysis (IEA, 2023).

1.2.3 Solid Oxide Electrolysers (SOEL)

Solid oxide electrolysis (SOEL) is a technique that uses elevated temperatures to produce hydrogen from water vapor. The technology is in the pre-commercial stage of development now. SOEL cells employ solid oxide ceramic electrolytes that permit oxygen exchange and have high electrical efficiencies, ranging from 80 to 95% depending on thermal integration. These cells are desirable for use in high-temperature industrial processes such as steel manufacturing and refining. However, SOEL cells lack operational flexibility due to their high operating temperatures and the consequent thermal inertia. They cannot withstand frequent on/off cycles due to their high operating temperatures and thermal inertia. Moreover, while increased production is anticipated to reduce investment costs, the longevity of the cells still needs to be enhanced. Solid oxide electrolysis has the potential to accomplish high efficiency at a low cost, but it still requires increased adaptability and extended component lifetimes (IEA, 2023).

1.2.4 Anion Exchange Membrane Electrolysers (AEMEL)

Anion exchange membrane electrolysis (AEMEL) is a relatively novel technology that operates at low temperatures (30 to 60 °C) and has recently made significant advancements. Although these cells are less well-known than other technologies, several companies are already producing at a pre-commercial level. They have several advantages over other technologies, such as the use of an alkaline environment, which reduces the need for costly materials, and solid polymer electrolyte membranes that are capable of transferring OH- ions selectively. This technology reduces the presence of corrosive fluid and has reduced membrane and material costs in comparison to PEMEL (IEA, 2023).

2.1.1 Transformation of Pure Hydrogen into Low-emission Hydrogen-based Synthetic Fuels: Synthetic Methane & Others

The manufacture of low-emission synthetic fuels derived from hydrogen, such as synthetic methane and others, is a crucial aspect of the transition to a sustainable energy future. Power-to-gas technology combines hydrogen with carbon dioxide captured from industrial processes or the atmosphere to produce synthetic methane. This method utilizes renewable electricity to produce hydrogen, which is then combined with carbon dioxide to produce methane. The resultant synthetic methane can be used as a low-emission transportation fuel or injected into the natural gas infrastructure for energy generation and heating. Other hydrogen-based synthetic fuels, such as methanol, may also function as carbon-neutral energy carriers and chemical feedstocks (IEA, 2023).

2.1.2 Transformation of Pure Hydrogen to Ammonia & Low-temperature Ammonia Cracking (from Ammonia to Pure Hydrogen)

The conversion of pure hydrogen to ammonia and its conversion back to pure hydrogen via low-temperature ammonia cracking, is essential to the development of a hydrogen economy. The Haber-Bosch process combines nitrogen from the air with hydrogen from natural gas or renewable sources, such as electrolysis, to produce ammonia. Ammonia can be used in transportation as a low-emission propellant, as a fertilizer, and as a chemical feedstock. Low-temperature ammonia cracking is the process of separating ammonia into nitrogen and hydrogen, which can be used as a source of purified hydrogen for fuel cells and other applications. This process can be conducted at substantially lower temperatures than traditional steam methane reforming, reducing energy consumption and carbon emissions (IEA, 2023).

2.1.3 Transformation of Pure Hydrogen to Liquid Organic Hydrogen Carriers

Important to the development of hydrogen-based energy storage systems is the transmutation of purified hydrogen into liquid organic hydrogen carriers (LOHCs). Through reversible hydrogenation and dehydrogenation reactions, LOHCs can absorb and release hydrogen. In the hydrogenation process, hydrogen is added to LOHC, which can be transported as a liquid at ambient temperatures, allowing for the safe and efficient storage of large quantities of hydrogen. The process of dehydrogenation releases hydrogen that can be used as fuel in a fuel cell or combustion engine. LOHCs can be produced from a variety of organic compounds, such as hydrocarbons and alcohols, and can be used to store and convey hydrogen in regions where hydrogen infrastructure is not yet complete. This technology offers a promising solution for the safe and efficient storage and transport of hydrogen, thereby facilitating the incorporation of renewable energy sources into the energy balance (IEA, 2023).

2.2.1 Gaseous Hydrogen Storage

High pressure storage of hydrogen is one method to increase its storage density. At 700 bar, the density of hydrogen is 42 kg/m3, allowing a 125-liter storage vessel to store up to 5 kg of hydrogen. However, high-pressure storage containers are expensive to manufacture and require special materials that can withstand the pressure. There are also safety concerns associated with high-pressure storage, as the abrupt discharge of hydrogen can result in powerful explosions. Hydrogen is stored using gaseous storage technologies at gas stations, terminals, and platforms by burying containers, excavating cavities, utilizing natural cavities, deep sea, and offshore (IEA, 2023).

2.2.2 Liquid Hydrogen Storage

Liquid hydrogen storage involves retaining liquid hydrogen at cryogenic temperatures to prevent its evaporation into gas. At -252.87°C and 1.013 bar, liquid hydrogen has a higher energy density than its gaseous form, with a density of approximately 71 kg/m3. However, the procedure of transforming hydrogen vapor into liquid state is costly. In addition, cryogenic liquid hydrogen storage containers and facilities must be adequately insulated to prevent evaporation caused by conduction, convection, or radiation. The energy density per unit volume of liquid hydrogen is roughly four times less than that of gasoline and other hydrocarbons. Liquid hydrogen storage can be utilized in a variety of applications, including gas stations, terminals or platforms, subterranean containers, excavated cavities, deep sea, and offshore facilities (IEA, 2023).

2.2.3 Solid Hydrogen Storage

Solid hydrogen storage entails the use of substances that can absorb or adsorb hydrogen via chemical reactions. By reacting hydrogen with specific metal alloys, solid metallic hydrides, such as magnesium and alanates, can be produced. Hydrogen is stored through a reversible chemical reaction with the elements of the material. Solid hydrogen storage is advantageous because it eliminates the need for cryogenic temperatures and high-pressure storage. To remain solid, hydrogen must be stored at specific temperatures and pressures (typically below -253 degrees Celsius or at high pressures, depending on the storage material). Typically, only 2% to 3% of the total weight of the storage material consists of hydrogen, which is the most significant disadvantage of this technology. Therefore, additional research is necessary to optimize critical parameters such as the efficacy of the storage material, the temperature and pressure during the hydrogen charge and discharge cycles (IEA, 2023).

3.1.1 Proton-exchange membrane fuel cells (PEMFC)

Proton Exchange Membrane Fuel Cells were invented in 1960 and have nowadays become the most prevalent fuel cell technology. In contrast to the direct combustion of hydrogen and oxygen gases to produce thermal energy, a proton exchange membrane fuel cell converts the chemical energy liberated during the electrochemical reaction of hydrogen and oxygen into electrical energy. PEMFCs currently are the most promising fuel cell design for transportation for a number of reasons: it operates at a relatively low temperature range of 100°–180°C; it can quickly vary its output; it is smaller in volume and size than most other types; it has a good supply of membranes (e.g., NAFION or CELTEC, produced in large quantities); and it has a simple, scalable production process. PEMFC membranes must be able to conduct hydrogen ions (protons) for them to function; however, this requires rather expensive platinum catalysts (IEA, 2023).

3.1.2 Alkaline Fuel Cells (AFC)

Alkaline fuel cells, also known as alkaline membrane fuel cells (AMFCs) or alkaline anion exchange membrane fuel cells (AAEMFCs), function by transporting alkaline anions – typically hydroxide (OH) – between electrodes. Initially, aqueous potassium hydroxide (KOH) was used as the electrolyte in AFCs. In the 1960s, NASA utilized AFCs for the Apollo and Space Shuttle programs. As it is responsible for the transport of OH– ions, the anion exchange membrane (AEM) has been the focus of numerous recent advancements, as it is an essential component of AFCs. This contrasts with PEM, which is an H+ conductive membrane, and is the primary reason why this type of fuel cell is less popular (IEA, 2023).

3.1.3 Phosphoric Acid Fuel Cell (PAFC)

Phosphoric Acid Fuel Cells are a form of fuel cell whose electrolyte is aqueous phosphoric acid. They were the first commercially available fuel cells. Developed in the mid-1960s and field-tested since the 1970s, their stability, performance, and cost have significantly increased. Due to these qualities, the PAFC was an excellent candidate for early stationary applications. Due to the risk of corrosive acid, they are utilized less frequently for transport (IEA, 2023).

3.1.4 Molten Carbonate Fuel Cell (MCFC)

Molten Carbonate Fuel Cells operate at temperatures above 600 degrees Celsius and are designed to directly convert natural gas or biogas. Due to the required high temperatures, less rare metals can be used as catalysts, resulting in significant cost savings compared to PAFCs. MCFCs do not require an external reformer to transmute more energy-dense fuels into hydrogen, unlike PAFCs, AFCs, and PEMFCs. Due to the high temperatures at which MCFCs operate, these hydrocarbons are converted to hydrogen within the fuel cell itself via a process known as internal reforming, which reduces costs. Before MCFCs can be used for transportation, additional investigation on the employed materials is necessary due to their still-huge size. However, they have tremendous potential due to their durability. Presently, MCFCs are discussed primarily in terms of stationary use (IEA, 2023).

3.1.5 Solid Oxide Fuel Cell (SOFC)

Solid Oxide Fuel Cells are distinguished by their electrolyte material, which is either a solid oxide or a ceramic. SOFC employ the simplest fuel cell design, consisting only of gas and particulates. This type of fuel cell features a high combined heat and power efficiency, long-term stability, fuel versatility, low emissions, and a relatively low cost. The greatest drawback is the high operating temperature (500–1000°C), which necessitates prolonged start-up times and causes mechanical and chemical compatibility problems. In the 1990s, SOFCs were utilized in automobiles, but have since been supplanted by PEMFCs. They are still the subject of intensive research for multiple transport applications, particularly shipping and rail (IEA, 2023).

3.1.6 Direct Methanol Fuel Cell (DMFC)

A Direct Methanol Fuel Cell is a variety of fuel cells that converts the chemical energy of methanol directly into electrical energy without requiring a separate reformer device. DMFCs were first developed in 1955, but their potential use in portable electronic devices and as a secondary power source for buildings has garnered significant attention in recent years. In a DMFC, two electrodes, an anode and a cathode, are separated by a polymer membrane. At the anode, methanol undergoes a chemical reaction with water to generate protons, electrons, and carbon dioxide. Protons pass through the membrane to the cathode, whereas electrons travel through an external circuit to generate electricity. Oxygen is supplied at the cathode, where it reacts with protons and electrons to form water. As methanol is a liquid fuel that can be readily stored and transported, DMFCs offer the benefit of a high energy density. However, they have several disadvantages, including low efficacy and a sluggish reaction time. To enhance the efficacy and durability of DMFCs for commercial applications, ongoing research is being conducted (IEA, 2023).

3.1.7 Internal Combustion Engines (ICE)

Hydrogen-powered internal combustion engine vehicles are distinct from hydrogen fuel cell vehicles, which use electrochemical hydrogen utilization as opposed to combustion. Instead, the hydrogen internal combustion engine is merely a modified variant of the conventional internal combustion engine propelled by gasoline. The absence of carbon means that no CO2 is produced, which eliminates the principal greenhouse gas emission of a conventional petroleum combustion. Carbon-based pollutants such as carbon monoxide (CO), carbon dioxide (CO2), and hydrocarbons are absent from the exhaust, as pure hydrogen is carbon-free. In an atmosphere containing nitrogen and oxygen, the combustion of hydrogen can produce oxides of nitrogen known as NOx. In this fashion, the combustion process is comparable to that of other high-temperature fuels, such as kerosene, gasoline, diesel, or natural gas. Hydrogen combustion engines are therefore not considered zero emission (IEA, 2023).

3.2.1 Direct Reduced Iron

Direct reduced iron (DRI) is a process that entails reducing iron oxide pellets or masses with a reducing gas, typically natural gas, hydrogen, or syngas. In a vertical shaft furnace or rotary kiln, iron ore is heated to between 800 and 1050 degrees Celsius, and reducing gas is introduced to convert iron oxide into metallic iron. The reduced iron product is commonly known as "sponge iron" and has a maximum purity of 98%. Due to its high purity and minimal residual elements, DRI is becoming an increasingly popular feedstock for electric arc furnaces (EAF). In addition, the use of hydrogen as a reducing agent in DRI production has the potential to substantially reduce carbon emissions in comparison to conventional blast furnace processes, making it an attractive option for sustainable steel production (IEA, 2023).

3.2.2 Blending in blast furnaces

Blending in blast furnaces is a prevalent practice in the iron and steel industry, in which various types of iron ore and additives are mixed to produce the desired chemical composition for a blast furnace feed. Traditionally, anthracite or coal is burned to produce carbon monoxide, which acts as a reducing agent and converts iron oxide in the ore to metallic iron. Nonetheless, there is a growing interest in using hydrogen as a reducing agent in blast furnaces to reduce carbon emissions. The concept is to heat the iron ore mixture to between 1200 and 1300 degrees Celsius and add hydrogen gas to reduce the iron oxide to metallic iron. Despite the potential benefits of hydrogen, this technology is still in its early phases of development, and its ubiquitous use is likely to be limited by the high cost of producing hydrogen at scale relative to coal (IEA, 2023).

3.3.3. Smelting Reduction

Smelting reduction is a process involving the direct reduction of iron oxide with carbon, which yields a heated metal product that is refined in an electric arc furnace or basic oxygen furnace. Various reducing agents, such as hydrogen, methane, and coal, can be utilized to complete the procedure. However, hydrogen's potential to reduce carbon emissions makes it an appealing option. In this procedure, iron ore is elevated to between 1,200 and 1,400 degrees Celsius and hydrogen gas is introduced to convert iron oxide to metallic iron. The use of hydrogen in smelting reduction has the potential to reduce carbon emissions considerably compared to traditional blast furnace processes, making it an essential technology for the transition to more sustainable steel production. However, the technology is still in its infancy, and substantial investment and innovation will be required to make it commercially viable (IEA, 2023).

Identification of the Dataset

Derwent Innovation[1] was utilized to identify and download patents related to each subcategory of the taxonomy. *Derwent Innovation* is a robust database of patents that provides several advantages over other databases. First, it encompasses numerous jurisdictions, including the United States Patent and Trademark Office (USPTO), European Patent Office (EPO), and World Intellectual Property Organization (WIPO). This ensures that a diverse range of patents are included in the inquiry, thereby providing a more comprehensive view of the patent landscape. In addition, *Derwent Innovation* provides sophisticated search capabilities, such as truncation (*), logical operators (AND, OR), and proximity operators (NEAR), which permit precise and targeted searching when developing the research queries. Moreover, *Derwent Innovation* provides a vast array of search filters that enable precise and targeted searches (Title/Abstract/Claim, IPC or CPC Classification, Text Fields, Assignee/Applicant, Citations, Priority Data, etc.). Furthermore, the

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[1] Derwent Innovation is a global patent search and analysis utility that provides access to more than 50 million patents and patent applications.

platform also contains some advanced tools that allow the user to create customized fields and easily export patent data in Excel format. Overall, *Derwent Innovation* is its intuitive and user-friendly interface. Throughout the search procedure, plain instructions are provided to facilitate platform navigation, making it accessible to users with varying degrees of patent searching experience and expertise.

Multiple phases and an iterative strategy were required to identify patents for each leaf of the taxonomy. The procedure began by conducting research to identify the technology's most important keywords and synonyms. Using these to refine results, a query was then modelled that accounted for all these variations. This required trial and error as various search criteria were evaluated and the query was modified as required. Various search tools, including truncation (*), logical operators (AND, OR), and proximity operators (NEAR/ADJ), were used to ensure that the search was exhaustive and accurate. Truncation permitted the incorporation of variations of a specific keyword, whereas logical operators enabled the combination of multiple search criteria to refine results. Finally, proximity operators enabled the identification of patents where two keywords appeared near together in the text, resulting in a more precise search. It is worth noting that the 'NEAR' operator allows for a bidirectional search between two parts of text. This means that the command will consider matches even if the order of the parts is inverted. On the other hand, the 'ADJ' operator is more stringent and considers the exact order as written. If the second part of text appears before the first, the result will be filtered and dropped.

As shown in *Table 2* in *Annex*, the main search fields adopted to identify each patented technology were: ("CTB" filter) and eventually the IPC codes ("IC" filter). It is important to precise that adopting Title/Abstract/Claim search filter leads to the identification of a wide range of patents, that at first sight may not seem exactly pertaining to the scope of research. For instance, a technology grouped under the "Fuel Cell" category, may not be a fuel cell itself, but most likely it will refer to components, systems and/or other complementary technology, necessary for the functioning of the "Fuel Cell". Being the Claims section far more expanded than the Title and the Abstract of a given patent, most references will be found in this section.

The patent research was carried out at a worldwide level, with no country code restrictions, meaning that the patent could have been filed or granted anywhere. To broaden the search for patents related to specific technological fields such as "Fuel cells" and "ICE", *Derwent Innovation* incorporates the use of International Patent Classification (IPC). IPC is a standard methodology for classifying patents according to their technical subject matter. It provides a hierarchical classification structure that facilitates the efficient organization and retrieval of patent information across countries and patent offices. By employing IPC ("IC" filter), it was possible to improve the research for patents within targeted technological areas, by considering a broader range of relevant patents and access comprehensive information for research and analysis.

Table 2 illustrates the search queries utilized to investigate patents within a particular technological category of the hydrogen value chain. Information regarding the number of individual documents, applications, and patent families for each technology are also provided. First, the various records contain all the various papers and entries linked with a patent application or issued patent, such as bibliographic data, claims, descriptions, drawings, legal status, and related communications. Each patent application or awarded patent may contain several unique records indicating various phases, changes, and events within the patent process. The application number, on the other hand, is a unique identifier assigned to a specific patent application at the time of filing. It is used to track and distinguish distinct patent applications by serving as a reference number. Each patent application is normally assigned a single application number. Last, Patent Families group together patents with the same priority application that are related. Priority applications are the first patent applications submitted for an invention. If a single applicant submits multiple patent applications for the same invention in different countries, those applications are regarded as members of the same patent family. The family view provides an overview of the patents that belong to the same family, such as granted patents, pending applications, and related documents.

The search queries identified a substantial number of records, applications, and families associated with hydrogen technologies. There was a total of 150,778 individual records, 119,380 applications, and 79,962 families discovered. It is essential to observe that these numbers may comprise more than one hydrogen technology. This is because a single patent typically contains multiple claims, each of which may potentially cover various processes or technologies within the broader hydrogen domain. Consequently, these numbers reflect the overall scope and extent of hydrogen-related patents, which incorporate numerous innovations in the field. These aspects will be better explained in the next chapter of this Master thesis.

Download, Cleaning and Refinement of the Dataset

After having identified and refined the research queries across all patent classes, a custom category was created in *Derwent Innovation* to enable the export of all patents pertaining to hydrogen technologies. Within this custom field, a list of values corresponding to the various categories of the hydrogen technologies taxonomy were inserted. Each value represents a single leaf in the taxonomy, enabling patents to be easily categorized. The distinct queries for each technology were then imported into a custom field. This populated the custom field with all hydrogen-related patents, which were now separated by value/category. Subsequently, it was possible to download the dataset in Excel in a more streamlined and effective manner, by tagging each patent to its related category. The final download of the dataset was conducted on 12/05/2023. During the download procedure from *Derwent Innovation*, the database was filtered by publication date to adhere to the 30,000-record limit. Various time periods, including until 2004, 2005-2010, 2010-2015, 2015-2020, and beyond 2020, were filtered using the Publication Year of each patent ("PY" filter). This strategy enabled retrieval of patent records within the specified time ranges, ensuring a targeted and manageable data extraction from the platform. After having united the entire dataset, all patents with a Publication Date prior to 1978 were removed. This operation was conducted as older patents lacked some important information such as technological codes (IPC). The threshold year was chosen for a precise reason: the analysis that will be represented in the next chapter of this master thesis involves the use of *PATSTAT*[2] to seek for EPO patents, of which data is available starting from 1978, thus this date is useful for a purpose of comparability. For the same reason, data only until the end of 2022 was considered. Overall, around 10% of the observations were lost in this passage. As described above, the extraction from the *Derwent Innovation* database after the cleaning and refining operations identified a final sample consisting of 101.834 applications.

DESCRIPTIVE STATISTICS OF THE DATASET

Once the new dataset was created, a wide range of descriptive analyses of the sample were ran to investigate the nature and characteristics of Hydrogen Value-Chain-Related Technologies. Among others, the following section will focus on analysing the evolution, main trends, occurrence, geography, inventors, assignees, innovators, technological areas (IPC Codes), and share of green technologies ("Y" CPC Section) among hydrogen patents.

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[2] PATSTAT is a global patent database managed by the European Patent Office (EPO), providing comprehensive patent information for worldwide analysis and research on intellectual property, innovation, and technology trends

The Evolution of Hydrogen Patents

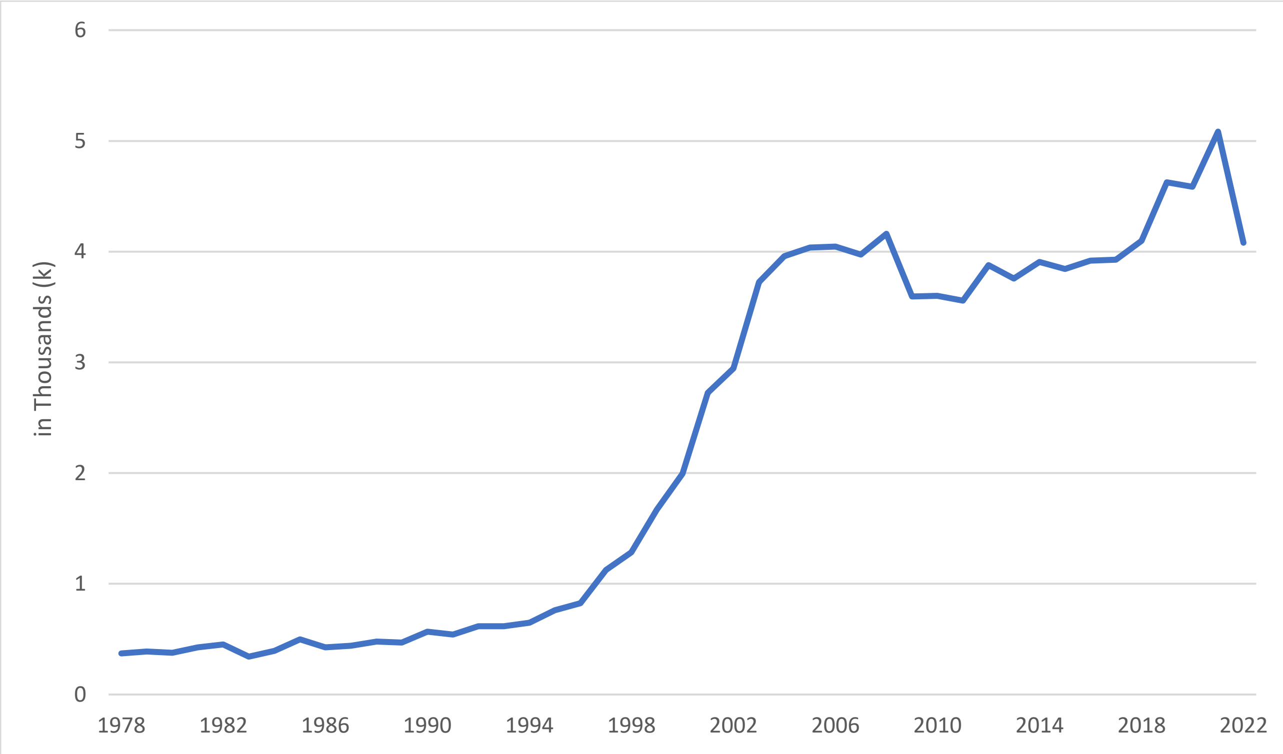

FIGURE 1: THE EVOLUTION OF HYDROGEN PATENTS BY APPLICATION YEAR

Figure 1 depicts the number of hydrogen technology patents from 1978 to 2022, revealing a remarkable trend that reflects the increasing prominence of Hydrogen technologies in last two decades. Over the entire period, there is a discernible upward trajectory in patent counts, indicating a growing interest and investment in hydrogen-related research and innovation. However, the most remarkable aspect of the graph lies in the years ranging from 1998 to 2006, where the curve demonstrates a steep and exponential rise. Such a sharp rise highlights a significant surge in patent filings and suggests an increased focus on developing and commercializing hydrogen technologies. Following a noticeable decrease in hydrogen patent filings after the 2008 crisis, the graph displays a rather stable trend up to 2018, followed by a new steep rise to 2021. It is imperative to notice that the apparent decline in 2022 does not reflect the true patenting activity, but it is because patents become visible to the public only after their publication date. As explained in the section above, on average it takes 18 months from when the application of a patent is filed to when they are published. Therefore, it is likely that both 2022 and 2021 may suffer from distortion bias, as the actual number of patent applications in these years is expected to be significantly higher in 2022 and slightly higher in 2021. Overall, the data presented is consistent with the findings of Sinigaglia et al. (2018), which identified an overall increase in patent publications from 2001 to 2006, followed by a period of stagnation from 2012 to 2017.

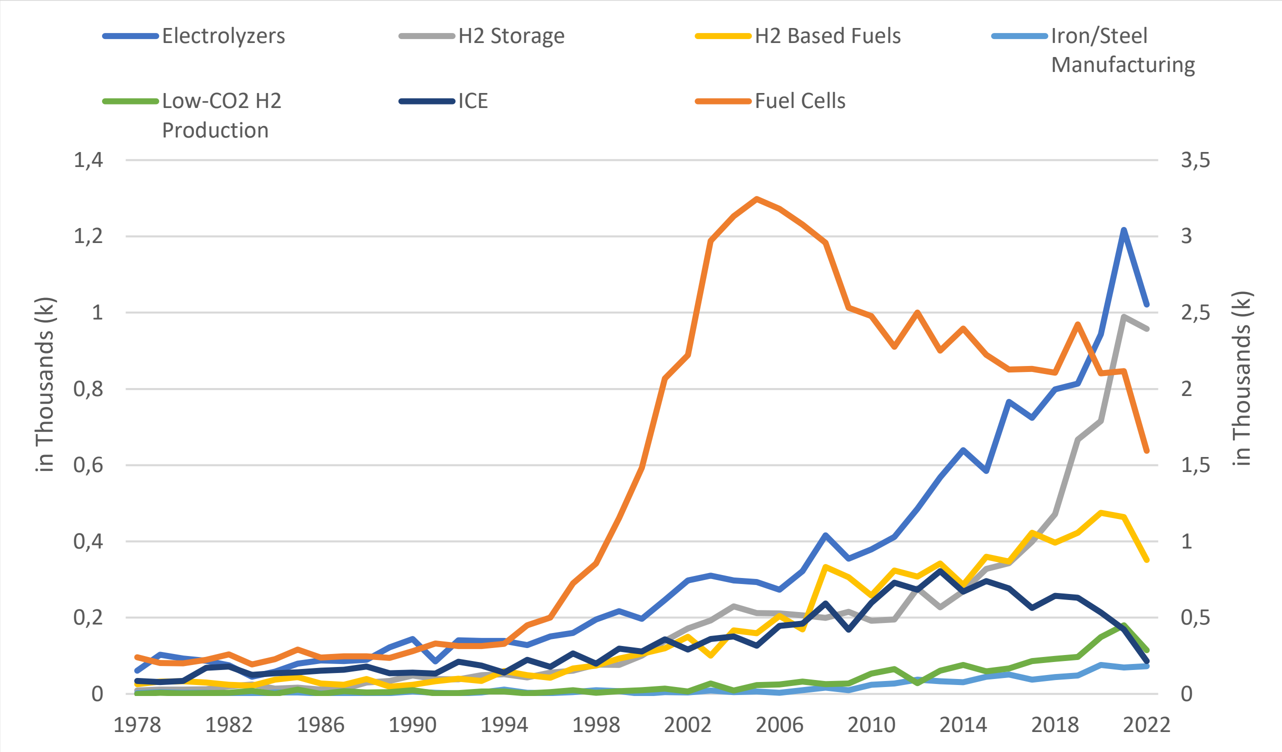

FIGURE 2: THE EVOLUTION OF HYDROGEN PATENTS BY APPLICATION YEAR PER MACRO CATEGORY OF THE HYDROGEN VALUE CHAIN (FUEL CELLS SCALED ON RIGHT AXIS, ALL OTHER CATEGORIES SCALED ON LEFT AXIS)

Above, *Figure 2* displays the number of hydrogen patents divided by macro group of the value chain, revealing important insights into patenting trends. Fuel cells stand out as the most patent-intensive technology, with 63,649 patents filed from 1978 to 2022. The graph indicates a significant rise in fuel cell patenting around 1998, but a rather declining trend after 2008. In contrast, electrolysers, storage technologies, and Hydrogen based fuels experienced a visible increase in patents throughout their entire lifetime. The graph clearly suggests that fuel cells are the most mature technology across the hydrogen value chain and that even though they remain at the forefront of innovation activity, other complementary technologies are rapidly catching up, indicating a wider expansion of interest and investment in their development. This demonstrates the expanding focus on advancing hydrogen technologies across various sections of the value chain.

Breakdown of Hydrogen Technologies across the Value-Chain

Figure 3 illustrates the distribution of patented technologies across the entire hydrogen value chain.

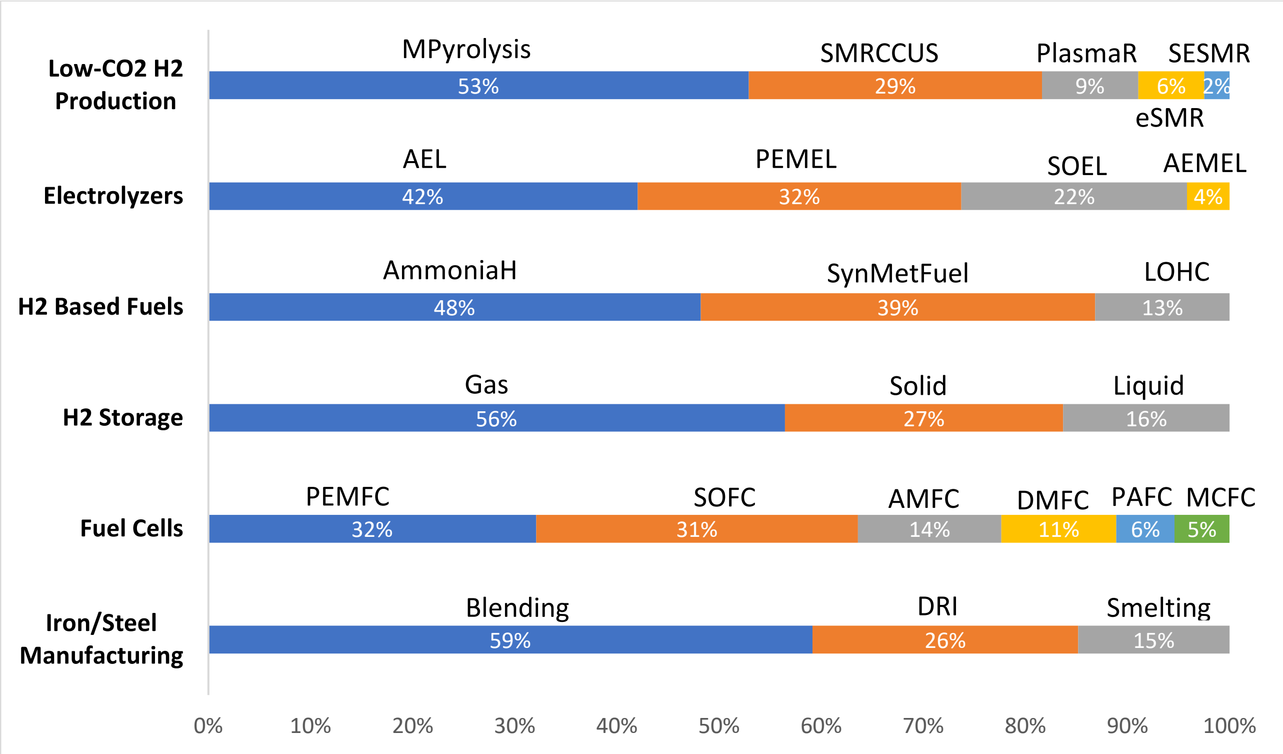

FIGURE 3: BREAKDOWN OF PATENTING ACTIVITY ACROSS THE HYDROGEN VALUE CHAIN

Regarding the patent distribution of emergent hydrogen production technologies with low carbon emissions, Methane Pyrolysis is the most prevalent technology, accounting for 52.9% of all patents. It is followed by Steam Methane Reforming with CCUS (28.7%), Electrically Heated Reforming (6.5%), Sorption-Enhanced Steam Reforming (2.5%), and Plasma Reforming (9.5%). As depicted in the graph, the distribution of emergent low carbon emission hydrogen production technologies is closely aligned with the respective technology readiness levels defined in the report "*Hydrogen Patents for a Clean Energy Future*" (IEA, 2023). The fact that Methane Pyrolysis accounts for 52.9% of all patents validates the report's claim that this technology has reached the pre-commercial stage, indicating its advanced state of development. Likewise, the prevalence of Steam Methane Reforming with CCUS, which accounts for 28.7% of the patents, corresponds with its classification as a pre-commercial stage in the report. In addition, the classification of Electrically Heated Reforming as a significant prototype is consistent with its 6.5% patent share. In addition, a 9.5% patent share of Plasma Reforming is consistent with the report's description of the technology as being in the conceptual stage. These correlations emphasize the congruence between patent distribution and the technology readiness levels reported by the IEA, confirming the ongoing advancement of low-carbon hydrogen production methods.

Secondly, the distribution of patents depicted in *Figure 3* provides insight into the proportional distribution of electrolysers to produce green hydrogen. AEL (Alkaline Electrolysis) holds the largest market share with 42.0%, followed by PEMEL (Polymer Electrolyte Membrane Electrolysis) with 31.7%, SOEL (Solid Oxide Electrolysis) with 22.1%, and AEMEL (Anion Exchange Membrane Electrolysis) with 4.2%. Overall, the patent distribution corresponds to the readiness levels reported in the report "*Hydrogen Patents for a Clean Energy Future*" (IEA, 2023), reinforcing the correlation between patent activity and the technological advancement of electrolysers to produce green hydrogen. Alkaline Electrolysis's patent share dominance is consistent with its characterization as having market penetration. This demonstrates that the technology has acquired traction and is currently being utilized in the industry. Similarly, the substantial patent share of Polymer Electrolyte Membrane Electrolysis correlates with its classification as a market-accepted technology, further validating its maturity and market presence. Solid Oxide Electrolysis, which represents a significant proportion of patents, corresponds to its technology readiness level classification as a pre-commercial demonstration stage technology. This indicates that the technology is undergoing testing and demonstration for real-world applications as it advances toward commercial viability. Lastly, Anion Exchange Membrane Electrolysis's lower patent share is consistent with its classification as a large prototype, indicating that it is still undergoing development and evaluation.

In addition, *Figure 3* depicts the patent shares of various hydrogen-based fuel technologies, including 38.6% for Synthetic Methane and Other Synthetic Liquid Hydrogen-based Fuels, 13.1% for Liquid Organic Hydrogen Carriers (LOHC), and 48.2% for the Transformation of Pure Hydrogen to Ammonia & Low-temperature Ammonia Cracking (from Ammonia to Pure Hydrogen). Notably, the corresponding technology maturity levels from the report *"Hydrogen Patents for a Clean Energy Future"* (IEA, 2023) may contribute to erroneous interpretations for this category. This is due to the inherent difficulty of accurately distinguishing patents involving technologies that convert hydrogen to ammonia from those involving technologies that convert ammonia back to hydrogen. Due to the overlap in patent categories, it is difficult to assign specific readiness levels to each technology. Despite this challenge, the substantial patent share indicates ongoing research and development efforts to utilize ammonia as a hydrogen carrier. Due to its high hydrogen content and well-established infrastructure for storage and transport, ammonia has gained attention as a potential energy carrier. The significant patent share for Synthetic Methane and other liquid hydrogen-based fuels suggests that innovation is also occurring in this field.

Furthermore, *Figure 3* provides a breakdown of hydrogen storage and distribution technologies. Gaseous storage technologies account for 56.4% of the market, whereas liquid storage technologies account for only 16.3%. Hydrides and adsorption account for 27.3% of the total solid storage technologies. Reflecting the present state of the hydrogen industry, the dominance of gaseous storage indicates its broad applicability and well-established infrastructure. The extensive use of gaseous storage methods, such as fuel stations and terminals, demonstrates the existing infrastructure for hydrogen storage and distribution in its gaseous form. Although liquid storage technologies have a reduced market share, they still play a significant role, especially in applications or locations where gaseous storage may not be as practicable or effective. The existence of liquid storage options illustrates the versatility and diversity of hydrogen storage requirements. Hydrides and adsorption, which represent solid storage technologies, occupy a significant portion of the storage distribution of patents. The prospective benefits of these methods include a higher volumetric density and the capacity for long-term storage. Inclusion of solid storage technologies indicates ongoing research and development efforts to discover innovative and alternative hydrogen storage solutions.

Moreover, *Figure 3* depicts the proportion of patents developed for various fuel cell technologies. Proton Exchange Membrane Fuel Cells (PEMFC) possess the dominant share of patents with 32.1% (22,326 patents), followed by Solid Oxide Fuel Cells (SOFC) with 31.5% (21,887 patents). Alkaline Fuel Cells (AFC) account for 14.1% (9,778 patents), while Direct Methanol Fuel Cells (DMFC) account for 11.2% (7,817 patents). At 5.7% (3,974 patents) and 5.4% (3,734 patents) respectively, Phosphoric Acid Fuel Cells (PAFC) and Molten Carbonate Fuel Cells (MCFC) possess lesser shares. The provided patent data aligns with the findings illustrated in the report "Hydrogen fuel cells in transportation" (WIPO*,* 2022). Both studies classify Proton Exchange Membrane Fuel Cells (PEMFC) as the technology with the most intensive patenting activity. According to the report, the considerable patent share of Solid Oxide Fuel Cells (SOFC) in the dataset reflects its position as one of the most patent-intensive technologies. Direct Methanol Fuel Cells (DMFC) and other direct or reforming fuel cells with significant patent shares in the dataset validate the ongoing research and development efforts cited in the report. The lesser patent shares of Phosphoric Acid Fuel Cells (PAFC) and Molten Carbonate Fuel Cells (MCFC) in the dataset correspond to their representation in the report as technologies with relatively fewer patents. This correspondence between the dataset and the report provides assurance that the collected patent data are consistent and relevant.

Last, *Figure 3* depicts the patent allocation for numerous hydrogen-based iron and steel manufacturing technologies. Blending in Blast Furnaces holds the largest patent share at 59.2%, followed by Direct Reduced Iron (DRI) at 26.0% and Smelting Reduction at 14.8%. Examining the corresponding technology preparedness levels from the report *"Hydrogen Patents for a Clean Energy Future"* (IEA, 2023), we can establish a relationship between the proportion of patents and the readiness levels. With the highest patent share, Blending in Blast Furnaces is classified as pre-commercial demonstration, indicating that substantial research and development efforts have been made to advance this technology toward commercialization. The patent share of Smelting Reduction correlates with its classification as an early prototype in the readiness levels. The patent activity indicates ongoing research and innovation in this field, with the goal of optimizing the technology further. Direct Reduced Iron (DRI), despite having a lower patent share than Blending in Blast Furnaces, is a complete prototype according to the preparation levels. This indicates that substantial progress has been made in the development and demonstration of this technology, paving the way for its possible commercial application.

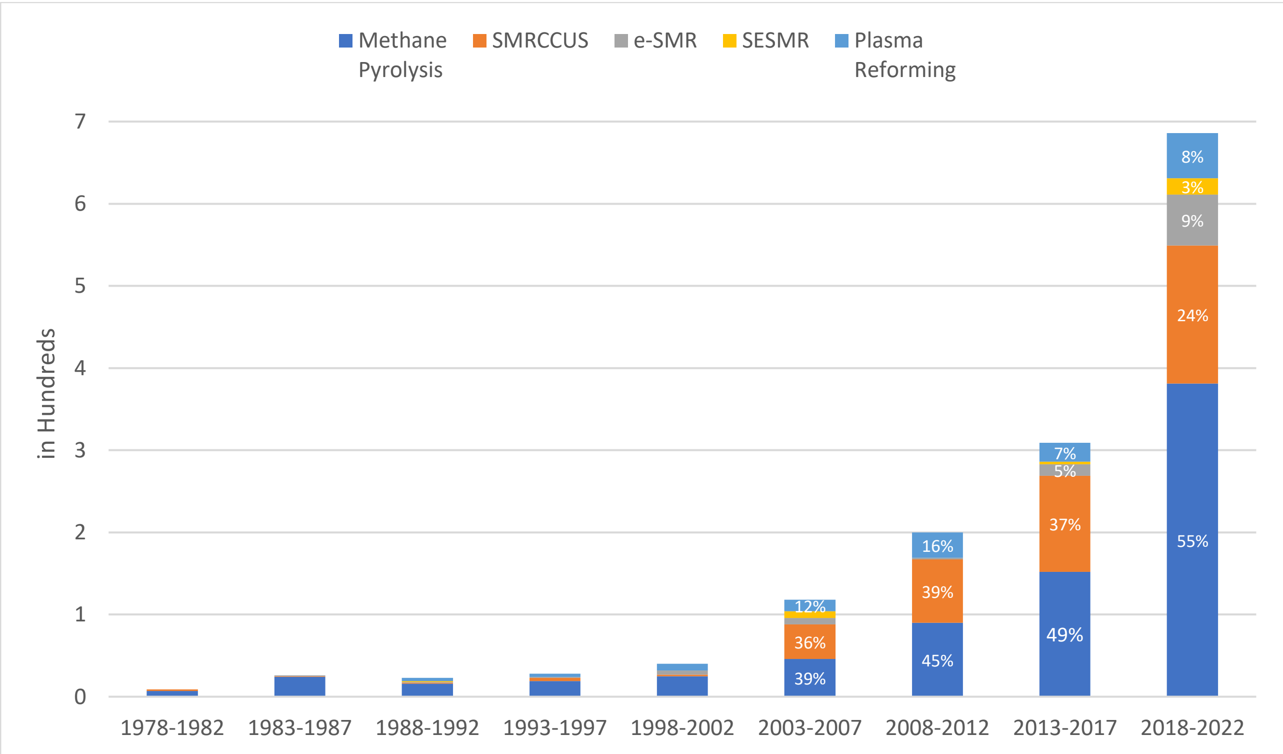

Figure 4: The Evolution of Patents related to Hydrogen Production Technologies with Low-Carbon Emissions

Figure 4 shows the patent counts for various low carbon emission hydrogen production technologies. Analysing the trends reveals significant growth rates and a growing interest in these technologies. For instance, Methane Pyrolysis has had a large growth in patent numbers, rising from 7 in 1978-1982 to 381 in the most recent period (2018-2022). The dominant position of this technology demonstrates a considerable industrial focus on developing methane pyrolysis as a low carbon emission hydrogen generating method. Additionally, Steam Methane Reforming with Carbon Capture and Storage methods have maintained a relatively strong share in the last 4 periods. Last, it is possible to see that Electrically Heated Steam Methane Reforming, as well as Plasma Reforming, are newer emerging technologies that are gaining increasing attention.

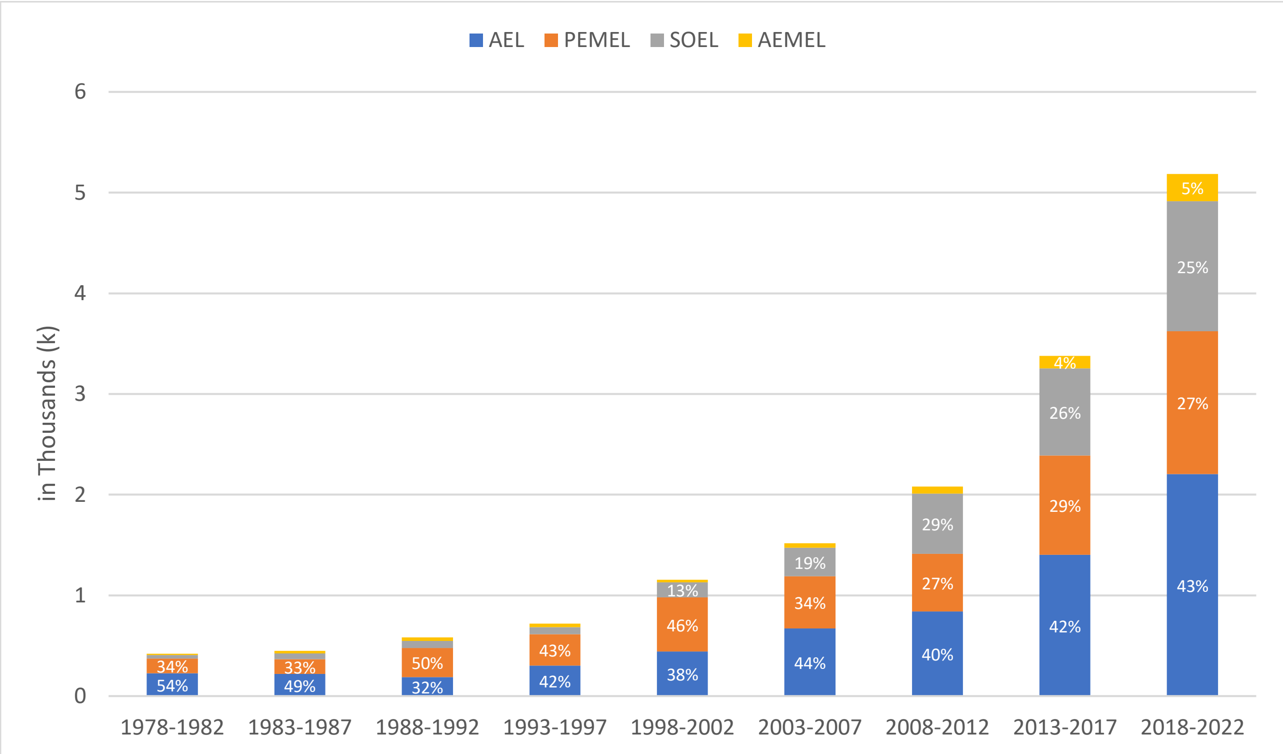

FIGURE 5: THE EVOLUTION OF PATENTS RELATED TO ELECTROLYSERS FOR THE PRODUCTION OF GREEN HYDROGEN

Figure 5 shows the patent counts for the four types of electrolysers (AEL, PEMEL, SOEL, and AEMEL) through time. Analysing the trends reveals interesting patterns, and compound annual growth rates (CAGR) for each electrolyser type can be estimated. AEL exhibits significant growth from 1978 to 2022, with its patent count increasing from 228 to 2204, resulting in a CAGR of nearly 10.5%. PEMEL has also grown significantly, from 145 to 1.418 patents, representing a CAGR of roughly 9.6%. SOEL has increased moderately, from 34 to 1.292 patents, resulting in a CAGR of around 11.2%. AEMEL, which began with fewer patents, has had amazing growth, increasing from 14 to 270 patents with a strong CAGR of around 15.3%.

These statistics demonstrate a general upward trend in patent applications for all types of electrolysers over the selected period. AEL and PEMEL are the most prominent technologies, with consistent and sustained growth. The faster CAGR of AEMEL in recent years indicates a growing interest in and possible developments in this specific electrolyser technology. Although SOEL has a reduced growth rate, it nevertheless reflects a consistent degree of innovation.

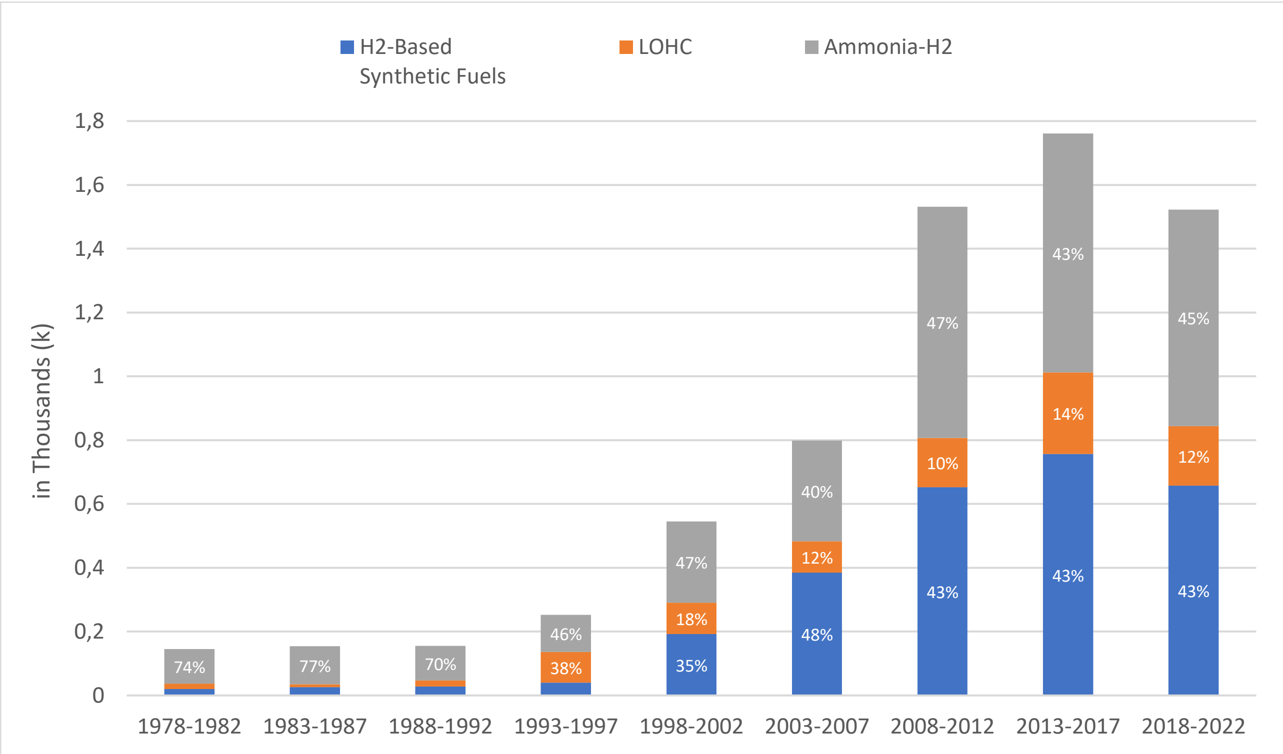

FIGURE 6: THE EVOLUTION OF PATENTS RELATED TO HYDROGEN-BASED FUEL TECHNOLOGIES

The temporal variations in patent activity across several hydrogen-based fuel concepts are presented in *Figure 6*. The areas of Transformation of Pure Hydrogen to Ammonia and Low-temperature Ammonia Cracking have maintained a dominant and growing position in hydrogen conversion technologies. The growth of Synthetic Methane is extremely pronounced in the past 25 years, gaining considerable attention since the 1998-2002 period. On the other hand, Other Synthetic Liquid Hydrogen-based Fuels display a much slower growth trend in terms of number of patents pertaining to that specific area.

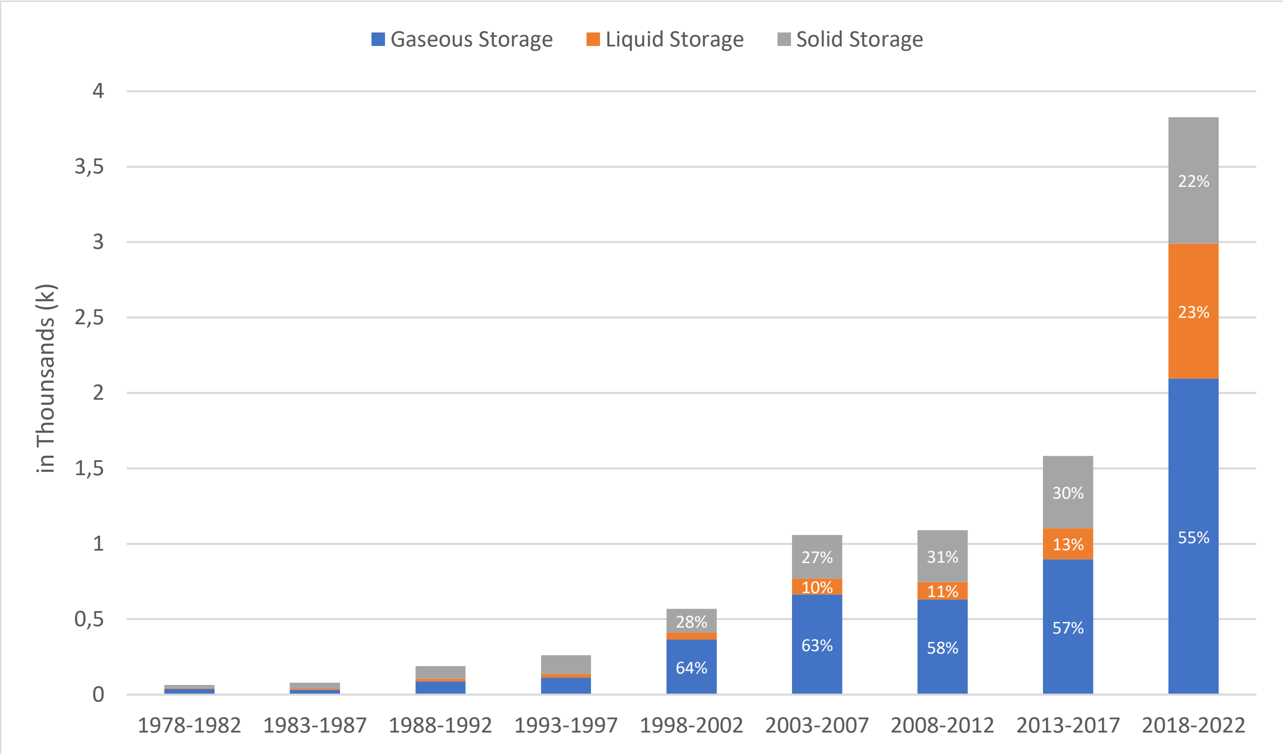

FIGURE 7: THE EVOLUTION OF PATENTS RELATED TO HYDROGEN STORAGE AND DISTRIBUTION TECHNOLOGIES

Figure 7 represents the patent counts for three distinct categories of hydrogen storage technologies: Gaseous Storage, Liquid Storage, and Solid Storage, spanning multiple time periods. From the graph, it is possible to notice that Gaseous Storage experienced a significant surge in patent counts, soaring from 39 in the initial period (1978-1982) to 2096 in the latest period (2018-2022). This remarkable growth corresponds to an impressive CAGR of approximately 35.87%. Such a substantial increase and the dominant share of this technology suggests a continued industry focus and dedication to developing efficient and effective hydrogen storage solutions utilizing gaseous materials. Likewise, Liquid Storage experienced substantial growth, with patent counts rising from 5 to 894 over the analysed period, indicating a CAGR of approximately 40.04%. The category demonstrated steady progress, particularly in recent years, gaining a significant share of all storage technologies, which, by 2018-2022, accounted for 23% of the total storage patent counts. Solid Storage, another crucial category in the realm of hydrogen storage, witnessed a substantial rise in patent counts from 19 to 837 between 1978-1982 and 2018-2022 (45% CAGR approximately), however its trend highlights how it is losing share in favour of other storage solutions.

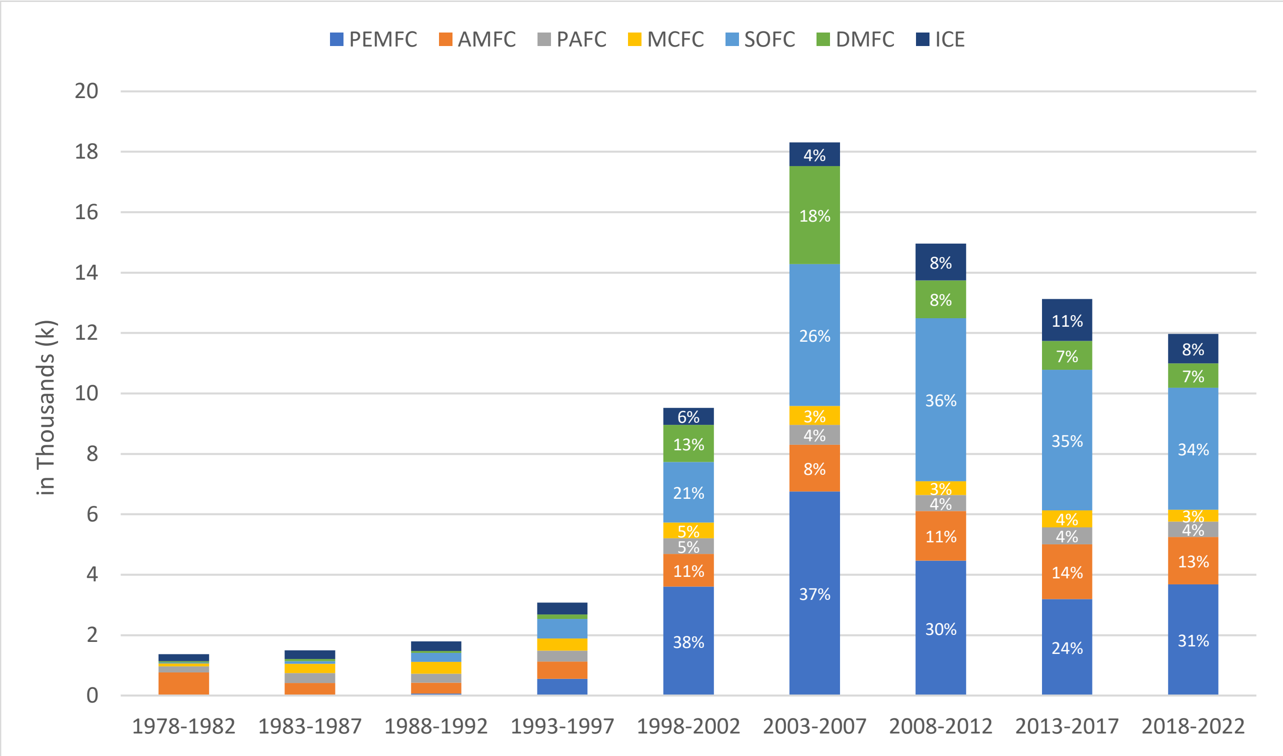

FIGURE 8: THE EVOLUTION OF PATENTS RELATED TO FUEL CELLS

A summary of the evolution of patent activity for several fuel cell technologies and the hydrogen internal combustion engine (ICE) is shown in *Figure 8*. Notably, Solid Oxide Fuel Cells (SOFC) and Proton Exchange Membrane Fuel Cells (PEMFC) both exhibit a notable increase in patent activity beginning in 1998-2002. Direct Methanol Fuel Cell (DMFC) patent activity shows an increasing interest between in 1998-2002 and 2003-2007, followed by downward trend in favour of alternative technologies. Hydrogen internal combustion engines (ICE) patenting activity presents a rather stable trend. On the other hand, and the Alkaline Membrane Fuel Cells (AMFC), Molten Carbonate Fuel Cells (MCFC), Phosphoric Acid Fuel Cells (PAFC), and display sustained but relatively sluggish development in patent activity. Overall, it is possible to infer that patenting activity related to Fuel Cells technologies has reached its peak in the 2003-2007 period.

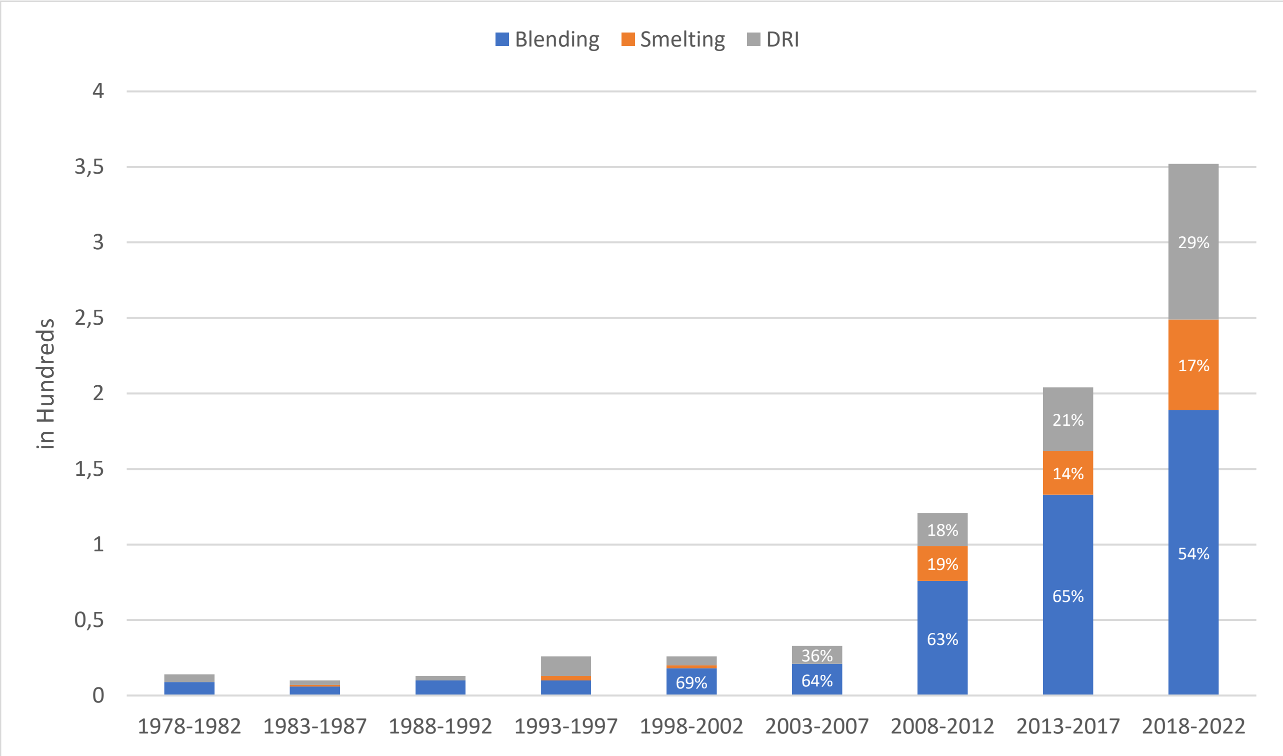

FIGURE 9: THE EVOLUTION OF PATENTS RELATED TO HYDROGEN-BASED IRON AND STEEL MANUFACTURING TECHNOLOGIES

Figure 9 depicts the development of patent activity in hydrogen use technology in the iron and steel production sector. According to the data, there has been a noticeable increase in interest in these technologies starting from 2008. All the subcategories have seen an uptick in patent activity since then. Particularly, a large and accelerating increased tendency may be seen in the blending of hydrogen in blast furnaces. Direct reduced iron (DRI) technologies are next, and they too show a significant increase in patent activity. Smelting reduction, on the other hand, exhibits a considerably slower growth tendency. The information demonstrates the increased interest in and innovation surrounding the use of hydrogen in the iron and steel production sector, with the integration of blast furnaces and DRI technologies leading the way.

Geographical Distribution of Hydrogen Patents

Figure 10 presents a compelling overview of the geographical distribution of all patented hydrogen technologies until the end of 2022 across various patent offices.

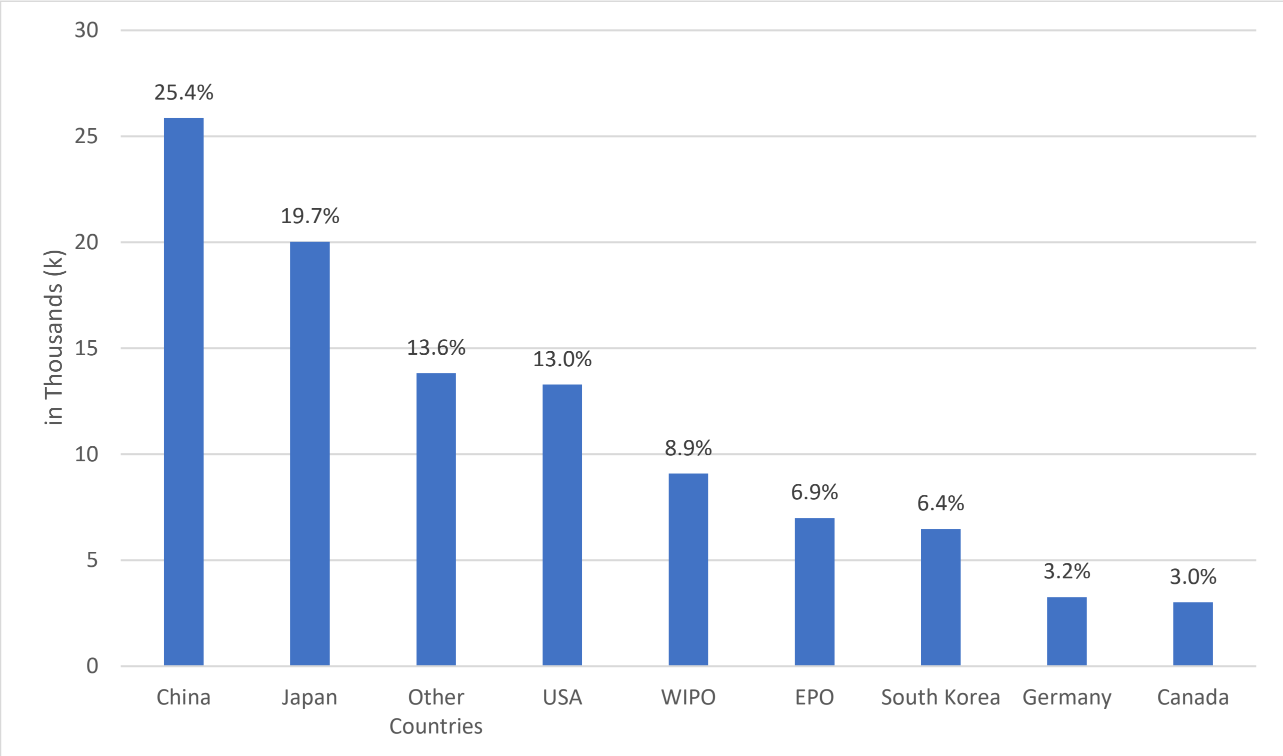

FIGURE 10: GEOGRAPHICAL DISTRIBUTION OF HYDROGEN PATENTS BY PATENT OFFICE

It is straightforward to notice that China, which holds a stunning 25.4% of all hydrogen technology patents, emerges as the front-runner. This sizeable proportion highlights China's continuous dedication to promoting research and innovation connected to hydrogen. With a respectable 19.7% share, Japan (JP) comes in second place, demonstrating its considerable contributions to the hydrogen industry. United States (US) patents represent 13.0% of the total hydrogen technology patents, highlighting the country's ongoing efforts and investments to advance hydrogen-related innovations. Similarly, South Korea, Germany and Canada demonstrate a notable contribution of 6.4%, 3.2% and 3.0%, respectively.

The European Patent Office (EP) region, represented by the code EP in the data, showcases a patenting activity share of 6.9% in hydrogen technology. It's important to note that the EPO Patent distribution may not fully reflect the extent of patenting activity within Europe, as many patents related to hydrogen technologies may have been filed directly at national patent office rather than through the European Patent Office. Therefore, the actual patenting activity in Europe is undoubtedly higher than the indicated percentage. Moreover, the World Intellectual Property Organization's (WIPO) patenting activity accounts for 8.9% of the total data. Notably, many of these WIPO-registered patents may have originated from countries with a high patent intensity, such as Japan, China, or the United States. Filing with the WIPO permits inventors to pursue international protection for their inventions, ensuring broader coverage beyond the borders of a single nation. This highlights the strategic approach adopted by innovators to secure global intellectual property rights through a WIPO-facilitated centralized and efficient process. Notably, a wide variety of countries make up the "Other Countries" group, which together account for 13.6% of the total number of patents on hydrogen technology. This emphasizes that the development of hydrogen-based technologies is a worldwide effort in which many nations are actively involved.

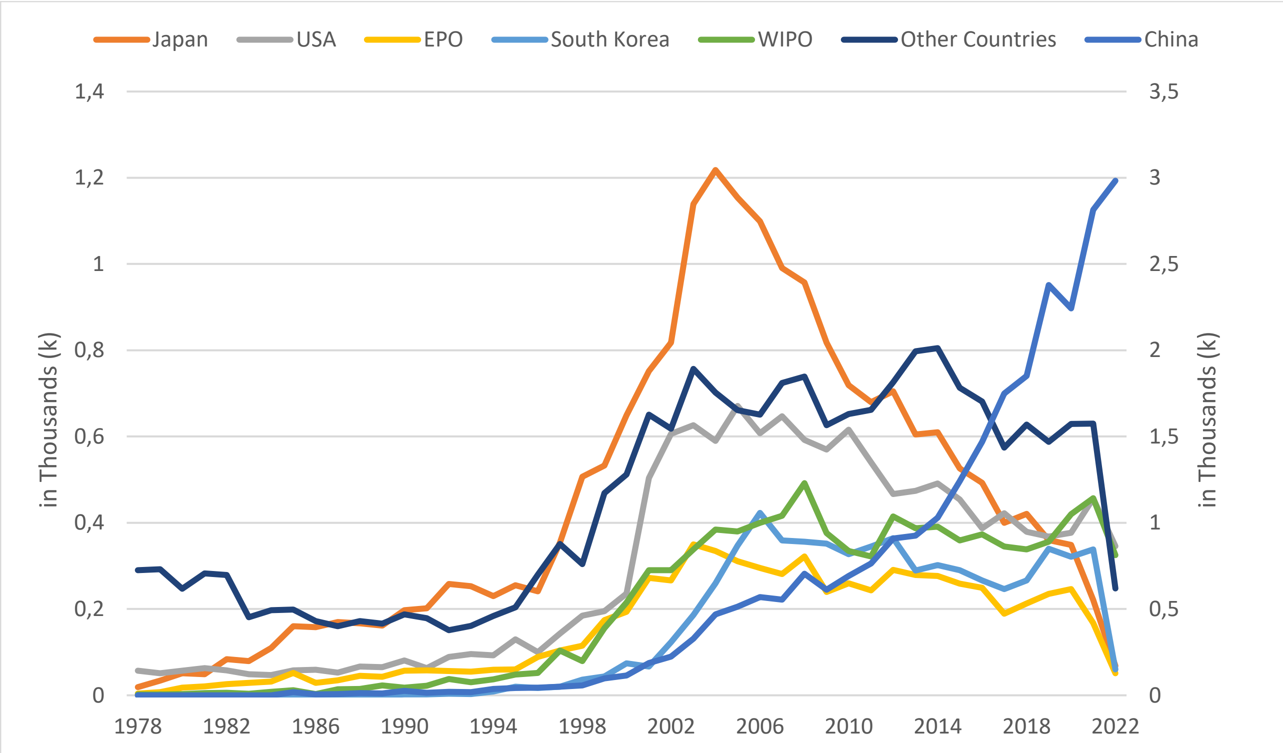

FIGURE 11: THE EVOLUTION OF HYDROGEN PATENT APPLICATIONS BY PATENT OFFICE CHAIN (CHINA SCALED ON RIGHT AXIS, ALL OTHER COUNTRIES SCALED ON LEFT AXIS)

Figure 11 provides a representation of the evolution of hydrogen patents registered at each patent office. Notably, China experiences an exponential increase in hydrogen patents beginning in the early 2000s (CAGR approximately equal to 23% from 2000 to 2022), leading it to become the undisputed leader of hydrogen patents from 2010 onwards. On the opposite end, Japan demonstrates a mountain-shaped trend: after displaying initial exponential growth in patenting activity (23% CAGR over the 1978-2005 period) and dominating innovation in the field of hydrogen technologies, hydrogen patent count starts a rapid decline after 2006, indicating a potential shift in research focus or shifting priorities within the Japanese hydrogen industry. Concerning hydrogen patenting activity, it is straightforward that Japan, followed by the United States, which display a comparable trend, exhibited a remarkable period of growth and dominance in this field from the late 1990s up to 2010. In subsequent years, however, hydrogen patenting activity in both countries sharply declines. Again, these results align with the findings of Sinigaglia T. et al. (2018), previously cited in the Literature Review section. As a matter of fact, both studies confirm a dominant position in patenting activity of hydrogen related technologies for both countries in the first decade and a relatively declining trend in the second decade of the twenty-first century. Overall, from the conjunct patent filings across all countries, it is possible to infer that hydrogen innovation has seen an increasing trend starting from 1998, which has quite stabilized in the last years (see EPO, WIPO, South Korea, and other countries).

It is imperative to mention that, for the same reasons previously illustrated, 2022 displays a representation patenting activity that is not free from bias and therefore should not be considered.

The Complexity of Hydrogen Patented Technologies

The number of inventors associated with a patent is seen as an indicator of the underlying technology's complexity. In other words, the greater number of inventors in the same patent indicates a higher level of complexity and technical knowledge necessary to produce innovation (Broekel, 2019). This is because sophisticated technologies frequently require multidisciplinary knowledge, collaboration among specialists from many fields, and elaborate problem-solving method. Analysing the number of inventors provides a more in-depth insight of the complexity nature, level and transversality of competence and knowledge needed to advance in a particular technological subject.

It is important to mention that of the 101.834 patent applications that make up the dataset, 9.675 patents (less than 10% of the total) showed no inventors. Logically, this represents a misinformation and therefore all these patents were removed from the panel of data exclusively for the purpose of the following considerations.

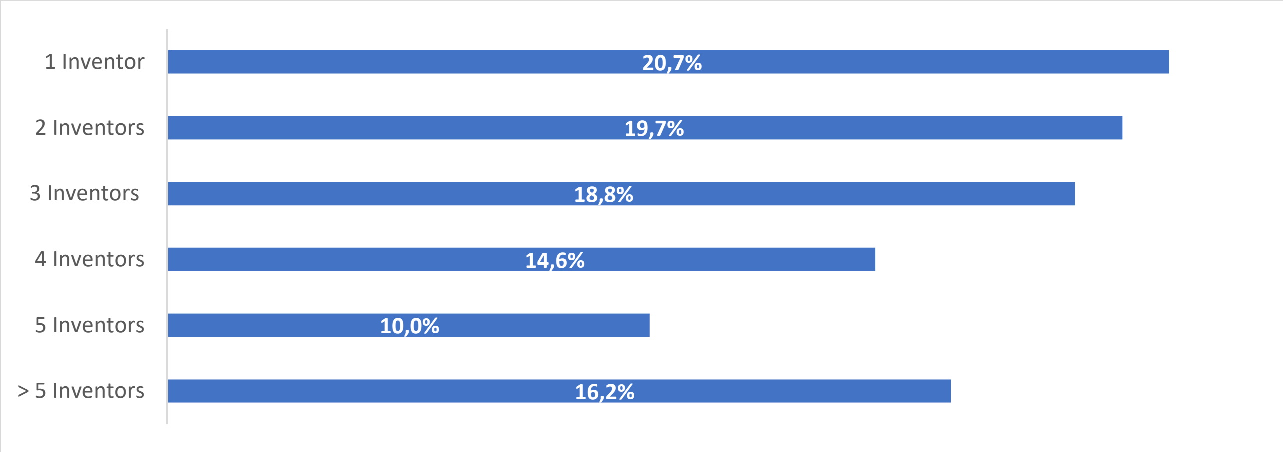

FIGURE 12: HYDROGEN PATENTS BREAKDOWN BY NUMBER OF INVENTORS

Figure 12 provides insights regarding the complexity of hydrogen related patented technologies. The distribution of inventors in hydrogen patents demonstrates different levels of joint efforts. Most patents (20.7%) had only one inventor, showing that individual contributions were made. However, a sizable fraction has several inventors, with 19.7% having two and 18.8% having three. The patent share drops as the number of inventors grows, indicating larger teams or more sophisticated technology. This highlights the complexity and interdisciplinary nature of hydrogen innovation.

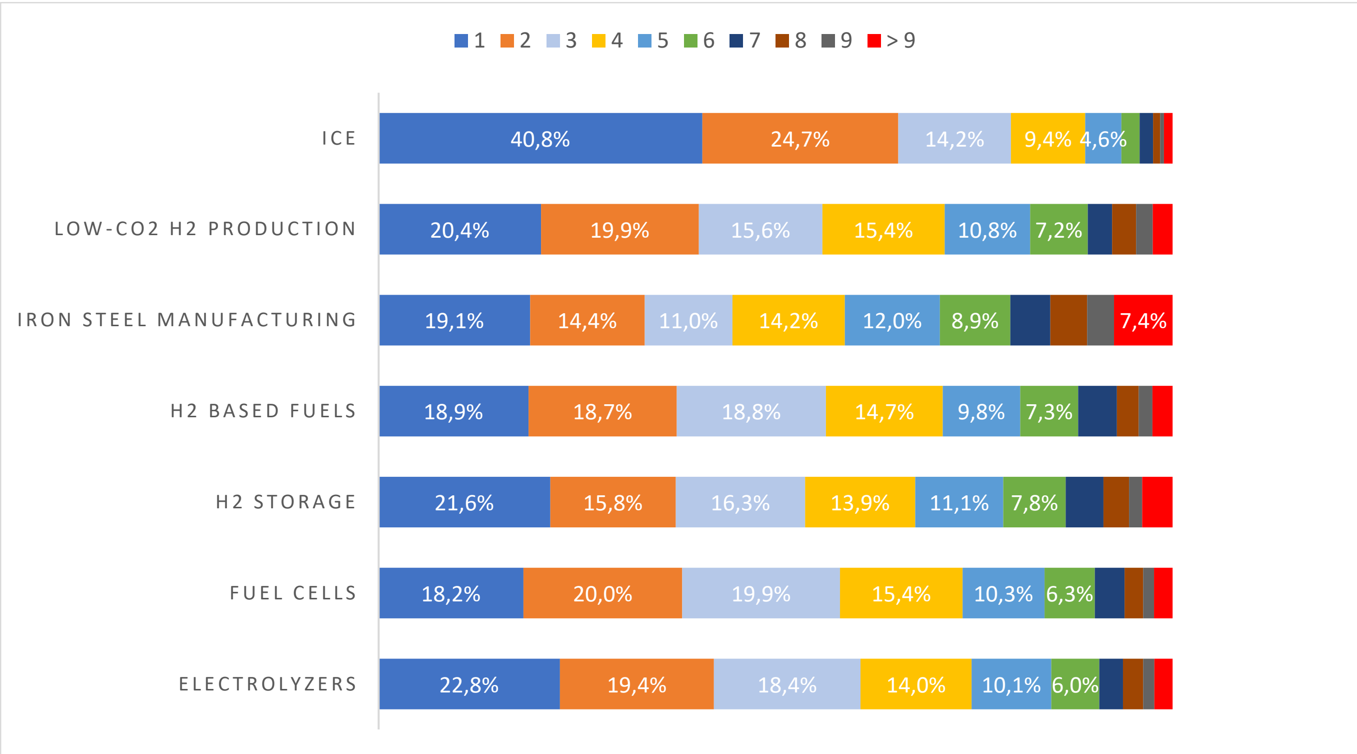

FIGURE 13: DISTRIBUTION OF INVENTORS PER PATENT BY SECTION OF THE HYDROGEN VALUE CHAIN

Figure 13 shows that while most technological macro categories across the hydrogen value chain have similar inventor levels per patent class, hydrogen ICE-related innovations appear to be technologically easier. This discovery could be related to the existing amount of combustion engine knowledge and skill obtained from other industries, which can be easily transferred and applied to the hydrogen industry. This familiarity with combustion engines may have sped up the innovation process and contributed to the relative simplicity of hydrogen ICE-related technology.

Additionally, it is interesting to track the evolution of complexity of hydrogen patented technologies over time. Thus, *Figure 14* illustrates the average number of inventors per patent year on year from 1978 to 2022 for the entire population of hydrogen-related patents.

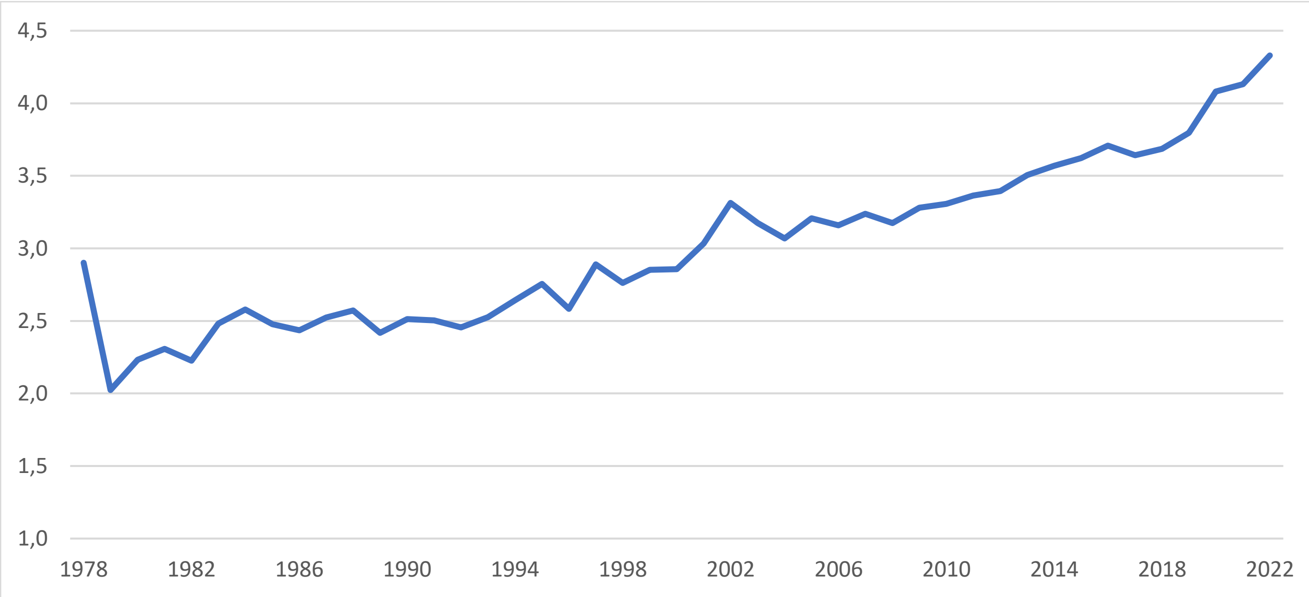

FIGURE 14: THE EVOLUTION OF THE COMPLEXITY IN HYDROGEN TECHNOLOGIES: AVERAGE NUMBER OF INVENTORS PER HYDROGEN PATENT

It is easy to notice that, over the years, the average number of inventors per patent has shown a consistent upward trend, indicating a complexity in hydrogen-related research and development. In 1979, the average number of inventors per patent was 2.02, and by 2022, it had increased to 4.33. As a result, excluding 1978, which appears as an outlier year, the CAGR for the average number of inventors per patent from 1979 to 2022 is 1.8%. The rising average number of inventors per patent suggests that hydrogen-related innovation has become more complex and interdisciplinary over time, necessitating the knowledge and participation of several innovators. Similar results are observable also when accounting exclusively for three of the main macro technology groups of the hydrogen value chain (electrolysers, fuel cells and hydrogen storage technologies). From *Figure 15* it is interesting to note that even though each of the three technologies follow comparable trends, hydrogen storage solutions have had the steepest increase in average number of inventors per patent over the last fifteen years, surpassing even fuel cells, which have long been the most complex technology of the hydrogen value chain.

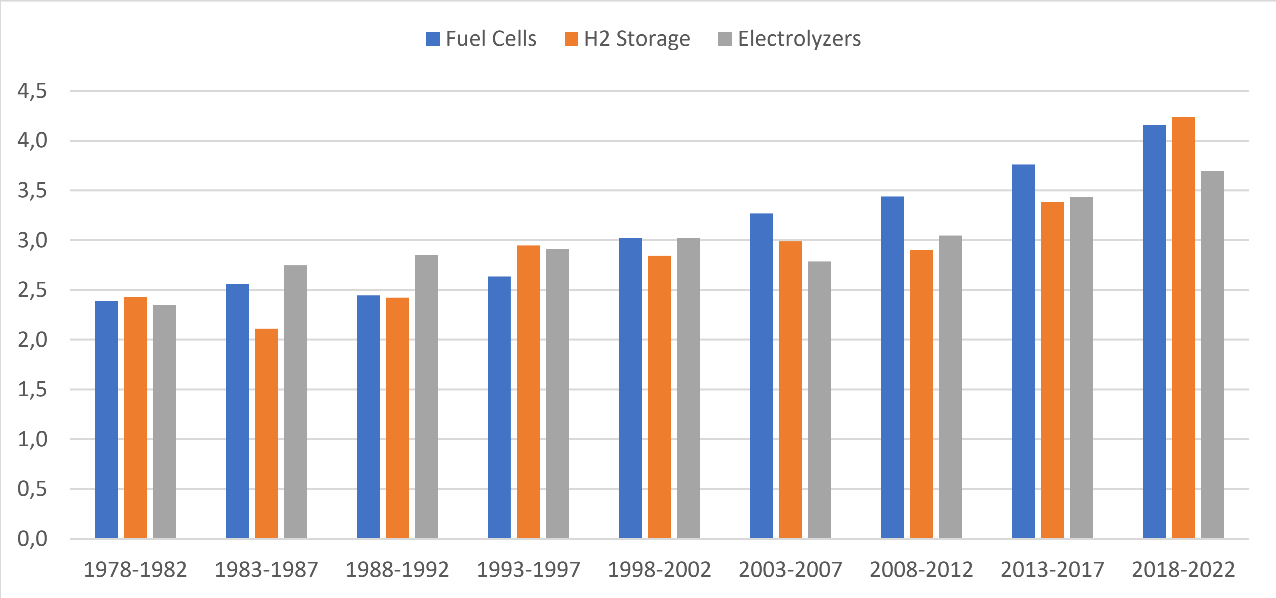

Figure 15: The Evolution of the Complexity in Hydrogen Technologies: Average Number of Inventors per Hydrogen Patent across the Main Categories of the Value Chain

The Collaborative Nature in Developing Hydrogen Patented Technologies

The number of patent assignees is an indicator of collaborative nature in the technology sector (Geum et al., 2021). In other words, the higher the number of assignees in the same patent, the higher propensity of dividing investments, sharing resources, and developing economies of scale in producing the innovation. Investigating the number of assignees that support the development of a specific technology can provide significant insights into the collaborative dynamics and collective accomplishments within a certain technological domain. According to WIPO, a collaborative patent is one that incorporates more than one assignee. It denotes the collaborative nature of numerous entities, such as businesses, research institutions, or people, to contribute their knowledge, resources, or intellectual property to the development, invention, or implementation of the patented technology. Vice versa, a non-collaborative patent, on the other hand, is one that has only one assignee. In this situation, a single entity, such as a firm or an individual, is entirely responsible for the patented technology's discovery, development, and ownership. Non-collaborative patents indicate that intellectual property rights and control over technologies are not shared.

Figure 16 provides insights regarding the collaborative nature of hydrogen related patented technologies across the entire value chain. It is important to mention that of the 101.834 patent applications that make up the dataset, 3.972 patents (less than 4% of the total) showed no assignees. Logically, this represents a misinformation and therefore all these patents were removed from the panel of data exclusively for the purpose of the following considerations.

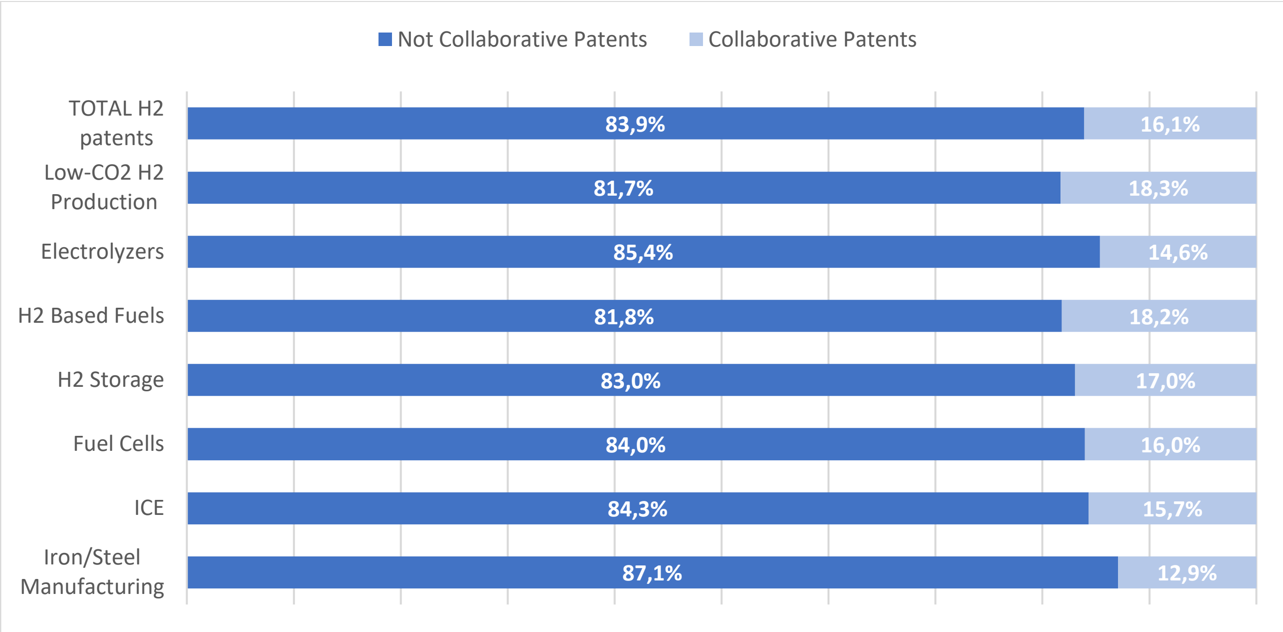

FIGURE 16: DISTRIBUTION OF COLLABORATIVE PATENTS ACROSS HYDROGEN PATENTS

The distribution of assignees in relation to hydrogen technology patents reveals interesting insights. Overall, 83.9%, have a single assignee, indicating individual ownership. However, 16.1% of the patents incorporate two or more assignees, also indicating the presence of a collaborative approach to hydrogen technology creation. This implies that a sizable part of hydrogen patents is the result of collaborative efforts between numerous firms. The prevalence of multi-assignee patents highlights the importance of collaborative efforts in advancing hydrogen technology.

Additionally, according to the data, low CO2 emission hydrogen production technologies have a higher collaborative nature, with around 18.3% of the patents in this category being collaborative. This implies that the development of sustainable hydrogen generation systems necessitates greater investments and resources, resulting in increased collaborative relationships and cost sharing. On the other hand, the adoption of hydrogen in the iron and steel manufacturing industry process appears to be a less collaborative field, with only 12.9% of patents classed as collaborative. This lower collaborative nature may be linked to variables such as the iron and steel industry's distinct needs and characteristics, which may necessitate a less comprehensive collaborative relationships or entail fewer resource-intensive technologies.

Additionally, it is interesting to track the evolution of the collaborative nature of assignees in developing hydrogen patented technologies over time. Thus, *Figure 17* shows the average number of assignees per patent over time.

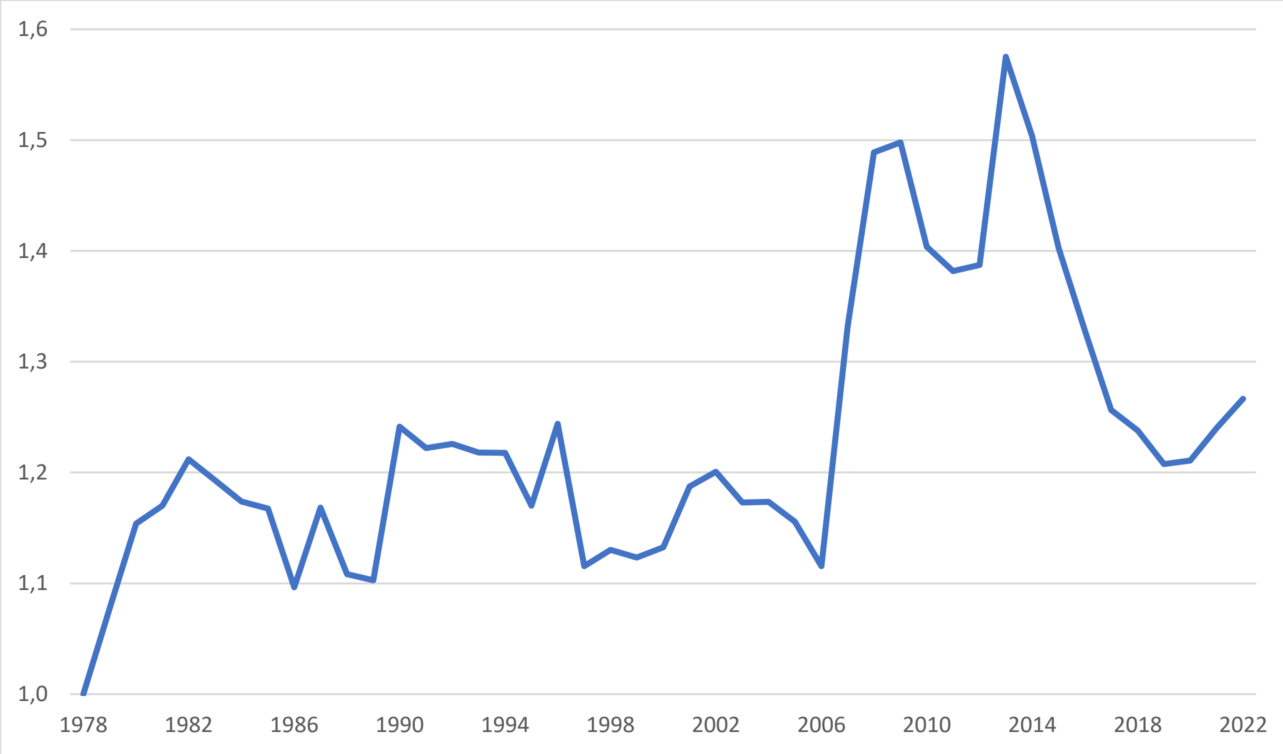

FIGURE 17: THE EVOLUTION OF THE COLLABORATIVE NATURE IN HYDROGEN TECHNOLOGIES: AVERAGE NUMBER OF ASSIGNEES PER HYDROGEN PATENT

The average number of assignees per patent remained relatively steady from 1978 until the early 1990s, ranging between 1.0 and 1.2. However, there are certain swings during this time frame. The average number of assignees per patent appears to have increased from the late 1990s to the early 2000s, peaking at roughly 1.575 in 2013. This shows that collaborative patent activity increased throughout that period. This rise could be attributed to the emergence of public-private partnerships and international collaborations in hydrogen research, particularly between 2005 and 2010. During this time, governments worldwide increased funding and support, establishing consortia and programs to accelerate hydrogen technology development. Additionally, an interdisciplinary approach involving experts from various fields gained momentum, leading to collaborative patent filings. After 2013, the average number of assignees per patent gradually declines, with slight volatility but generally remaining over 1.2.

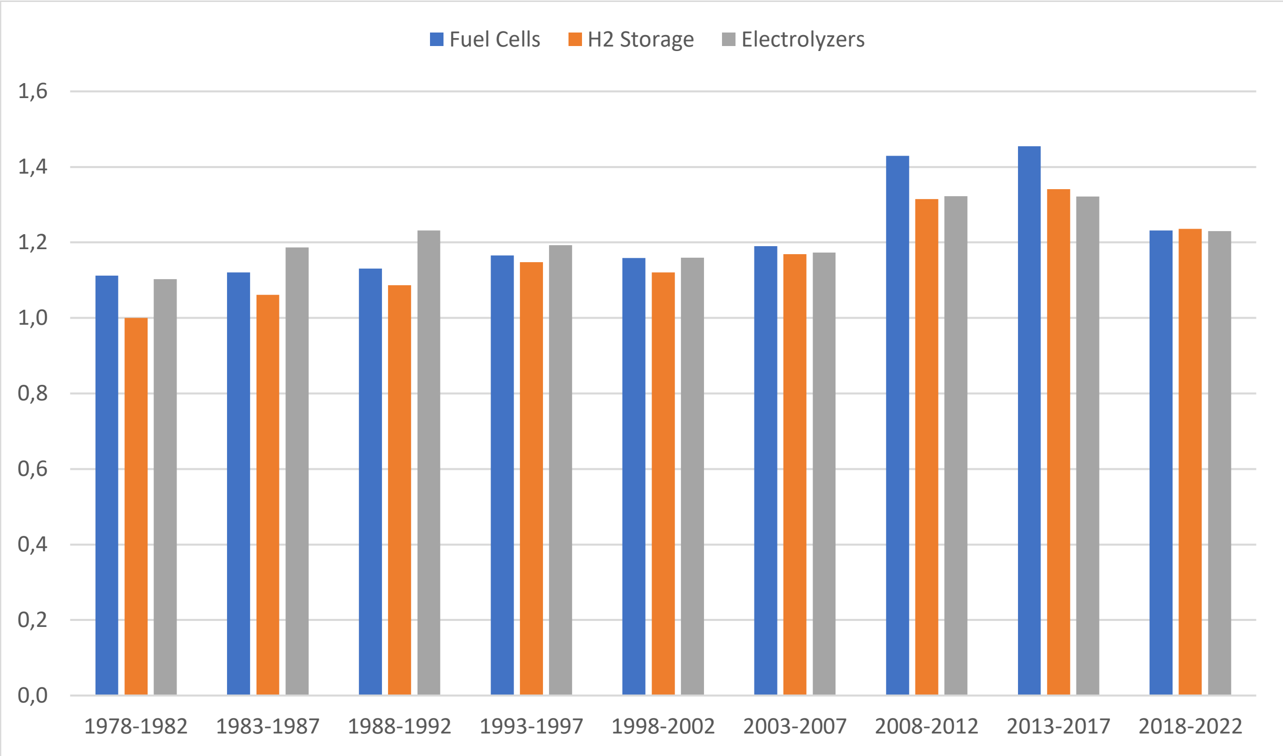

FIGURE 18: THE EVOLUTION OF THE COLLABORATIVE NATURE IN HYDROGEN TECHNOLOGIES: AVERAGE NUMBER OF ASSIGNEES PER HYDROGEN PATENT ACROSS THE MAIN CATEGORIES OF THE VALUE CHAIN

Figure 18 depicts the evolution of the collaborative nature in developing hydrogen patents among assignees, exclusively for three of the main macro technology groups of the hydrogen value chain (electrolysers, fuel cells and hydrogen storage technologies). From both graphs it is possible to evince that the collaborative nature for developing hydrogen patents is subject to fluctuations and cycles, which could be justified by a variety of factors. Technological improvements play a role, with discoveries necessitating greater collaborative relationships at first and then resulting in fewer assignees as the technology matures. Changes in research funding, government initiatives, and industry agendas can all have an impact on partnership patterns. Market dynamics and rivalry may influence fluctuations, as the collaborative nature may be viewed to obtain an advantage or share costs.

Top Innovators in the Hydrogen Sector

Table 3 displays a list of the 50 innovators that are assignees of the hydrogen patents identified in the dataset.

Innovator	Industry	Country	H2 Patents
PANASONIC	Consumer Electronics	Japan	1.376
TOYOTA	Automotive	Japan	1.326
MITSUBISHI	Conglomerate	Japan	1.209
HONDA	Automotive and motorcycles	Japan	882
SAMSUNG	Conglomerate	South Korea	845
SIEMENS	Engineering and electronics	Germany	816
NISSAN	Automotive	Japan	808
HITACHI	Conglomerate	Japan	784
GENERAL MOTORS	Automotive	United States	779
TOSHIBA	Conglomerate	Japan	741
SUMITOMO	Conglomerate	Japan	615
COMMISSARIAT ENERGIE ATOMIQUE	Research and development in nuclear energy	France	590
AGC INC	Glass manufacturing	Japan	559
MERCEDES-BENZ	Automotive	Germany	504
TOPSOE	Catalysts and sustainable energy solutions	Denmark	503
GENERAL ELECTRIC	Conglomerate	United States	495
TOTO LTD	Sanitary ware and plumbing fixtures	Japan	491
BOSCH	Engineering and electronics	Germany	488
FUJI ELECTRIC	Electrical equipment and systems	Japan	487
DALIAN INSTITUTE OF CHEMICAL PHYSICS	Research and development in chemical physics	China	483
LG	Conglomerate	South Korea	477
BLOOM ENERGY	Fuel cells and clean energy solutions	United States	444
EXXONMOBIL	Oil and gas	United States	382
KOREA INSTITUTE OF SCIENCE AND TECHNOLOGY	Higher education and research	South Korea	341
GUANGDONG HYDROGEN ENERGY SCIENCE AND TECHNOLOGY	Hydrogen energy solutions	China	334
SANYO ELECTRIC	Electronics and appliances	Japan	330
UNIVERSITY OF CALIFORNIA	Higher education and research	United States	300
ZHEJIANG UNIVERSITY	Higher education and research	China	288
CERES POWER	Fuel cells and energy systems	United Kingdom	286
PEKING UNIVERSITY	Higher education and research	China	284
UNITED TECHNOLOGIES CORPORATION	Conglomerate	United States	282
OSAKA GAS	Energy and utilities	Japan	281
BALLARD POWER SYSTEMS	Fuel cells and clean energy solutions	Canada	281
ZAHNRADFABRIK FRIEDRICHSHAFEN	Automotive components and systems	Germany	269

NGK INSULATORS	Ceramic products and electrical components	Japan	267
TORAY INDUSTRIES	Advanced materials and chemicals	Japan	262
HUANENG CLEAN ENERGY RESEARCH INSTITUTE (CERI)	Clean energy research and development	China	262
TOPPAN PRINTING	Printing and packaging solutions	Japan	258
HYUNDAI	Automotive	South Korea	253
FUELCELL ENERGY	Fuel cells and clean energy solutions	United States	251
DELPHI TECHNOLOGIES	Automotive components and systems	United Kingdom	245
TECHNICAL UNIVERSITY OF DENMARK	Higher education and research	Denmark	227
AIR LIQUIDE	Industrial gases and services	France	227
NIPPON CATALYTIC CHEMICALS	Chemicals and catalysts	Japan	222
KANSAI ELECTRIC POWER	Electric utility company	Japan	204
KOREA INSTITUTE OF ENERGY RESEARCH	Energy research and development	South Korea	204
TSINGHUA UNIVERSITY	Higher education and research	China	203
TIANJIN UNIVERSITY	Higher education and research	China	202
FORSCHUNGSZENTRUM JUELICH GMBH	Higher education and research	Germany	198
SHELL INTERNATIONALE RESEARCH MAATSCHAPPIJ	Oil and gas research and development	Netherlands	194
JOHNSON MATTHEY	Sustainable technologies and materials	United Kingdom	193
BRIDGESTONE	Automotive and rubber products	Japan	193
DUPONT DE NEMOURS	Chemicals and materials	United States	192

TABLE 3: LIST OF THE TOP 50 INNOVATORS BY PATENTING OF HYDROGEN VALUE-CHAIN-RELATED TECHNOLOGIES

It is crucial to note that the following geographical considerations are only estimates and may not be completely correct, as the country of the patenting organization may differ from the publication office where the innovation was patented.

Country	**Total H2 Patents**	**Patents from Recurring Assignees**	**Share of top 50 innovators**	**Count of Recurring Assignees**
Japan	20.028	11.295	56%	19
China	25.861	2.056	7.95%	7
United States	13.287	3.125	24%	8
South Korea	6.470	2.120	33%	5

TABLE 4: GEOGRAPHICAL DISTRIBUTION OF THE TOP 50 INNOVATORS BY PATENTING OF HYDROGEN VALUE-CHAIN-RELATED TECHNOLOGIES

Surprisingly, innovation in hydrogen technologies appears to be densely concentrated in Japan. In fact, 19 of the most recurrent assignees present in *Table 3* are from Japan, accounting for 11,295 patent applications out of the total 20,028 patents identified in Japan. This means that these organizations are responsible for more than 56% of all hydrogen patents in Japan. In contrast, hydrogen technology innovation in China presents to be much more widely spread. As a matter of fact, only 7 assignees are mentioned as the most frequent assignees of hydrogen patents, accounting for fewer than 8% of all hydrogen patents in China. Instead, the United States and South Korea have an intermediate situation. The US contains 8 organizations with considerable hydrogen patenting activity, accounting for 24% of all hydrogen patents found in the country. Similarly, South Korea has 5 organizations that account for 33% of the country's hydrogen patents.

It should be emphasized that drawing comparable conclusions for European countries would be deceptive because most assignees may have patented their innovations at the European Patent Office (EPO), making it impossible to assign these to single counties.

Most Recurring Industry/Sector of Recurring Assignees	**Count of Assignees**
Automotive	9
Education / Universities	8
Conglomerate	7
Energy / Utilities	6
Hydrogen Focus	5
Research Centers	5
Electronics	4
Oil & Gas	2
Engineering	2

TABLE 5: MOST RECURRING INDUSTRIES/SECTORS OF THE TOP 50 INNOVATORS BY PATENTING OF HYDROGEN VALUE-CHAIN-RELATED TECHNOLOGIES

As shown in *Table 5*, the organizations that have the most intense patenting activity across hydrogen technologies belong to the Automotive (9), Conglomerates (7) and Energy or Utility (6) industries. Additionally, much of the innovation activity in the field of hydrogen is carried out by universities (8) and or Public Research Centres (5).

It is interesting to note also that the actors driving hydrogen innovation in China, Japan, the United States, and Europe range significantly, with varying degrees of involvement from private enterprises to universities and national research organizations. The results displayed suggest that the hydrogen innovation landscape in China is characterized by the presence of numerous National Research Centres. This evidence could indicate that the Chinese government has a noteworthy inclination to exert control over innovation, particularly in strategic technologies that have the potential to shape the future, such as hydrogen. Universities typically focus on lower Technology Readiness Levels

(TRLs), which represent the maturity of a technology, compared to private companies. This is because universities often engage in early-stage research and development, aiming to explore new concepts and prove their feasibility. Private companies, on the other hand, prioritize commercialization and market-ready technologies, targeting higher TRLs for immediate deployment. Consequently, this suggests that the innovation conducted in China, where universities play a significant role, may be more concentrated at an embryonic stage compared to other regions with a stronger presence of private companies. In the context of hydrogen related technologies, private corporations, notably huge multinationals from the automotive industry and conglomerates, are the primary innovators in Japan and the United States. This demonstrates a definite tendency in these countries for private sector innovation in the hydrogen sector. Private parties own and control most of the hydrogen-related innovation, emphasizing the importance of market-driven techniques and the role of competition in pushing breakthroughs in hydrogen technologies. While cooperation with universities is possible, the emphasis is on the contributions of private sector entities in pushing hydrogen innovation, distinguishing it from China's state-led model.

Hydrogen Focused Corporations

This section will provide a brief overview of five most notable innovators that are exclusively involved in developing hydrogen technologies.

Bloom Energy (444 hydrogen patents) is a company established in the United States in 2001 that offers solid oxide fuel cell (SOFC) technology solutions. Their fuel cell technologies convert a variety of fuels, including natural gas, into lower-emission energy.

Guangdong Hydrogen Energy Science and Technology (334 hydrogen patents) is a Chinese company, founded in 2013, that specializes in the research, development, and application of hydrogen energy technologies. Their main area of expertise involves the manufacture of hydrogen fuel cells and related products for a variety of industries, helping to expand China's hydrogen energy sector.

Ceres Power (286 hydrogen patents), founded in 2001 and based in the United Kingdom, is a pioneer in solid oxide fuel cell (SOFC) technology. They design and build fuel cell systems that generate energy effectively from a variety of fuels, including natural gas and hydrogen. The fuel cell technology developed by Ceres Power has applications in distributed power production, combined heat and power (CHP) systems, and electric vehicle (EV) charging infrastructure.

Ballard Power Systems (281 hydrogen patents) is a Canadian firm, founded in 1979, that specializes in the design, development, and manufacture of proton exchange membrane (PEM) fuel cells and related hydrogen fuel cell products. They offer renewable energy solutions for a variety of applications such as transportation, backup power, and material handling.

FuelCell Energy (251 hydrogen patents), founded in 1969 and based in the United States, is a global pioneer in the development, production, and operation of fuel cell power plants. They specialize in the development of clean, efficient, and dependable fuel cell technologies, which generate energy via the electrochemical reaction of hydrogen and oxygen and have applications ranging from stationary power generation to carbon capture and utilization.

The Technological Domain of Hydrogen Patents: IPC Section

The International Patent Classification (IPC) is a hierarchical system for categorizing patents according to the technical subject matter they cover (*WIPO*). It is critical in organizing and retrieving patent documents all around the world. Each patent is assigned a unique code by the IPC categorization, which represents the specific technology or field to which it belongs. This classification system is significant for several reasons. To begin, it makes efficient patent searches possible, allowing patent examiners, inventors, and researchers to find relevant previous art and assess the uniqueness of an invention. The IPC classification is also useful for tracking technological changes and mapping the intellectual property landscape across businesses. It aids in the identification of developing technologies, possible areas for collaboration or licensing, and the distribution of technical information. Furthermore, the IPC classification is internationally recognized, providing patent offices with a uniform language, and assuring worldwide consistency in patent documentation and inspection procedures.

Figure 19 illustrates the breakdown of hydrogen related patented technologies per IPC section. It is important to mention that of the 101.834 patent applications that make up the dataset, 701 patents (less than 1% of the total) showed no IPC code. Logically, this represents a misinformation and therefore all these patents were removed from the panel of data exclusively for the purpose of the following considerations.

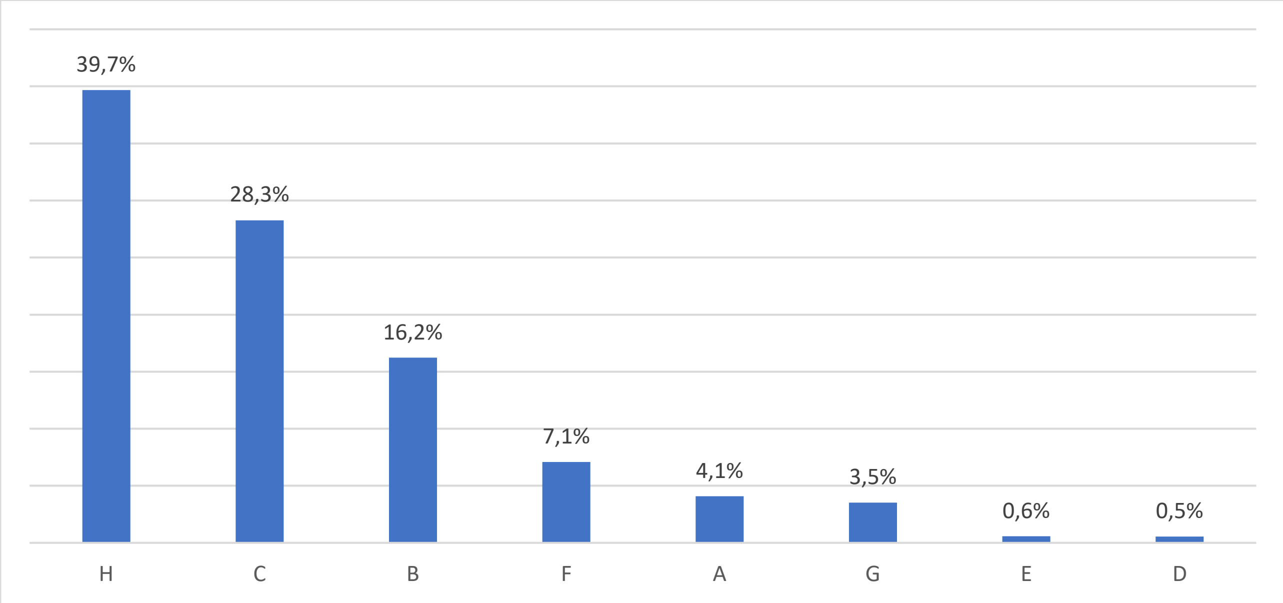

FIGURE 19: HYDROGEN PATENTS BREAKDOWN BY IPC SECTION

As depicted by the graph, the most recurring IPC Sections in the dataset are "H" (40%), "C" (28%) and "B" (16%).

IPC Section "H" (Electricity) is focuses on patents relating to electricity (*WIPO, IPC Section*). It encompasses a wide range of inventions and technologies related to the generation, distribution, and consumption of energy. This section contains several subcategories that deal with various aspects of electrical systems and equipment. IPC Section "H" is especially relevant in the context of hydrogen-related patents because it includes inventions related to hydrogen generation, storage, and utilization methods. Section "H" discusses hydrogen-related subjects such as fuel cells, electrolysis devices, hydrogen generators, hydrogen infrastructure, and hydrogen-powered vehicles. Patents relating to these inventions would be covered by IPC Section "H".

IPC Section "C" (Chemistry; Metallurgy) is dedicated to patents relating to chemistry and chemical processes (*WIPO, IPC Section*). It includes chemical compositions, reactions, and procedures as inventions. IPC Section "C" is relevant in the context of hydrogen because it encompasses patents on hydrogen synthesis, purification, and chemical processes linked with hydrogen generation or consumption. Patents for catalysts, materials, and techniques utilized in hydrogen-related applications may be included.

IPC Section "B" (Performing Operations; Transporting) includes a variety of technological topics, such as engineering and industrial processes (*WIPO, IPC Section*). It includes inventions involving machines, apparatus, and technological systems. IPC Section “B” is relevant in the context of hydrogen since it comprises patents for engineering and manufacturing techniques that are expressly related to hydrogen-related technology. Inventions relating to hydrogen storage tanks, hydrogen transportation systems, hydrogen infrastructure, and other engineering features relating to hydrogen generation, distribution, or consumption may be included.

IPC sections "H" (Electricity) and "C" (Chemistry; Metallurgy) Breakdown

As mentioned earlier, being the IPC a hierarchical system, it is possible to assess the technological classification of a patent into different levels of granularity. By adding two digits after the letter (Section identifier), the IPC Class is obtained.

Within IPC Section “H”, Class “H01” occurs 94.9% of the time. IPC Class “H01” specifically focuses on basic electric elements and electric power supplies. It covers inventions related to electrical components, circuits, and systems. IPC Class H01 encompasses electrical elements and components, therefore patents pertaining to the design, configuration, or improvement of electrical components used in fuel cells are contained within this class. Innovations in fuel cell electrodes, catalysts, membrane electrode assemblies (MEAs), bipolar plates, or current collectors fall under this category. Additionally, Class “H01” also includes ideas relating to electrical components and circuits utilized in electrolysis devices for hydrogen production. This includes patents for electrolyser designs, electrode materials, current distribution systems, or electrolysis-specific control circuits. Last, Class “H01” includes patents relating to the control and regulation of electrical systems in hydrogen technologies. Control circuits, power management systems, or monitoring devices specifically built for hydrogen fuel cells, electrolysers, or other hydrogen-related systems are included.

With respect to IPC “Section C”, the IPC Classes that are most recurring are IPC Class “C01” (21.5%), “C25” (20.1%), “C08” (13.5%) and “C07” (11.7%).

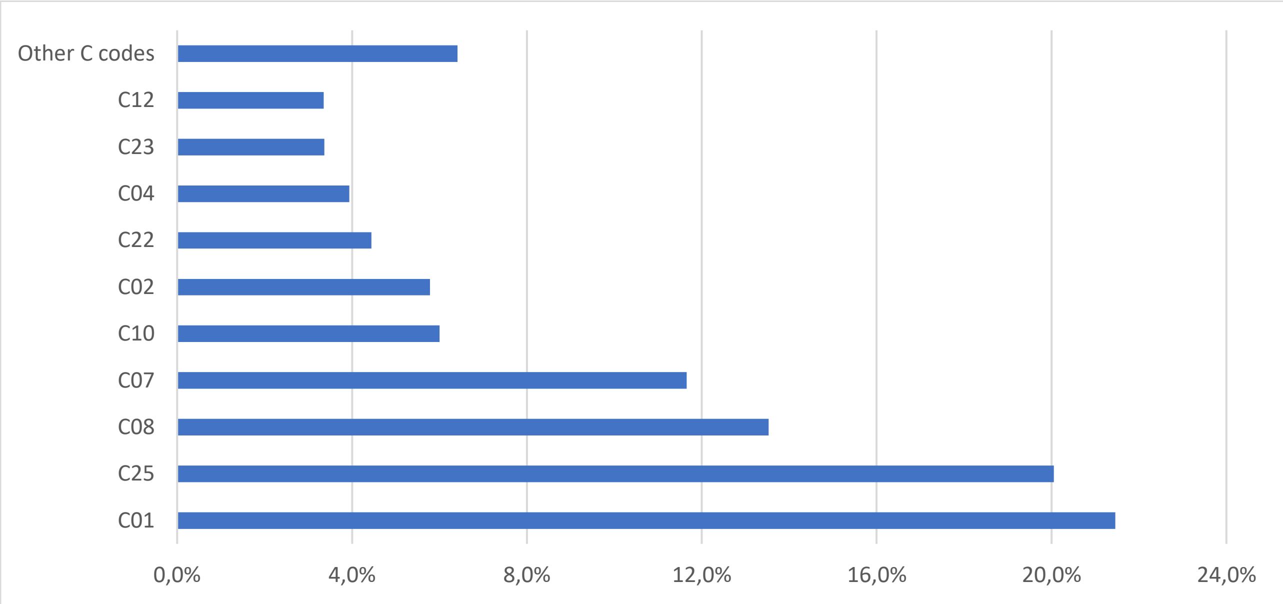

FIGURE 20: IPC SECTION "C" HYDROGEN PATENTS BREAKDOWN BY IPC CLASS

IPC Class "C01" focuses on inorganic chemistry, which includes inventions pertaining to hydrogen synthesis, purification, and chemical processes linked with hydrogen production or consumption. This category includes hydrogen-related technologies such as catalysts, materials, and procedures for hydrogen production, storage, and conversion.

IPC Class "C25" is connected to electrochemistry and covers patents relating to electrochemical processes, including those related to hydrogen technologies such as fuel cells and electrolysis devices. This category includes inventions relating to hydrogen fuel cells, electrolysers, and associated components.

IPC Class "C08" is concerned with organic macromolecular substances, such as polymers. While it is not entirely focused on hydrogen, it may include patents on hydrogen-related materials such as polymer electrolyte membranes used in fuel cells or hydrogen gas barrier materials.

IPC Class "C07" is dedicated to organic chemistry, and while it is less directly related to hydrogen, it may include patents related to organic compounds utilized in hydrogen-related applications, such as hydrogen storage materials or organic catalysts for hydrogen reactions.

Hydrogen Green Patents: CPC Code Y

The European Patent Office (EPO), in collaboration with the United Nations Environment Programme (UNEP) and the International Centre for Trade and Sustainable Development (ICTSD), created a dedicated tagging scheme to identify low-carbon, sustainable, and climate change mitigation technologies (CCMTs) (Veefkind et al., 2012; Favot et al., 2023). These technologies are targeted by specific classes (Y02 and Y04S) target those technologies directly. The tagging activity is defined in algorithms created by a group of experts, and they are re-run on a regular basis, so that new documents that meet the search requirements are automatically detected and tagged (Angelucci et al., 2018). Thus, the Y codes are added to the classification that already exists. This methodology is used by the European Commission's Joint Research Centre (JRC) to discriminate between green and non-green patents (Bellucci et al., 2021; Pasimeni et al., 2019).

Overall, the Cooperative Patent Classification system (CPC) is an extension of the International Patent Classification (IPC) system, which has been in use since January 2013 by the European Patent Office (EPO), the United States Patent and Trademark Office (USPTO). Subsequently, it has also been adopted by the State Intellectual Property Office of China (SIPO), the Korean Intellectual Property Office (KIPO) and the Japan Patent Office (JPO) as of 2013, 2015 and 2016, respectively. The presence of a specific "Y" technology segment in the CPC is one noticeable variation between the CPC and IPC classifications. This "Y" section comprehends the "General Tagging of New Technological Developments; General Tagging of Cross-sectional Technologies Spanning over Several Sections of the IPC; Technical Subjects Covered by Former USPC Cross-reference Art Collections [XRACs] and Digests" (USPTO, EPO). Within the "Y" section of the Cooperative Patent Classification (CPC), the "Y02" subclass specifically focuses on 'green' patents related to sustainable energy technologies: "Technologies or Applications for Mitigation or Adaptation Against Climate Change" (USPTO, EPO) and the "Y04S" subclass focuses on "Smart grid technologies, including hybrid vehicles interoperability" (USPTO, EPO).

The EPO produces a new list with all codes multiple times a year, making it simple to create a list of CPC Green codes. The "Y" CPC-section contains all Y02/Y04S codes. The final May 2022 list includes 381 CPC Green codes. The key components of the Tagging scheme are shown in *Table 6*. The Y02 and Y04S tags associated with climate change mitigation technologies (CCMT) are used in this methodology to detect patents in green technology (Favot et al. 2023).

CPC Section	Description
Y02	Technologies or applications for mitigation or adaptation against climate change
Y02A	Technologies for adaptation of climate change
Y02B	Climate change mitigation technologies related to buildings, e.g., housing, house appliances or related end-user applications
Y02C	Capture, storage, sequestration, or disposal of greenhouse gases [GHG]
Y02D	Climate change mitigation technologies in information and communication technologies [ICT], i.e. information and communication technologies aiming at the reduction of their own energy use
Y02E	Reduction of greenhouse gas [GHG] emissions, related to energy generation, transmission, or distribution
Y02P	Climate change mitigation technologies in the production or processing of goods
Y02T	Climate change mitigation technologies related to transportation
Y02W	Climate change mitigation technologies related to wastewater treatment or waste management
Y04	Information or communication technologies having an impact on other technology areas
Y04S	Systems integrating technologies related to power network operation, communication or information technologies for improving the electrical power generation, transmission, distribution, management or usage, i.e. smart grids

TABLE 6: LIST AND DESCRIPTION OF CPC "GREEN CODES" OF PATENTED TECHNOLOGIES

Therefore, for the purpose of the considerations addressed in this master thesis, coherently with the European Commission's Joint Research Centre (JRC) methodologies, the presence of the "Y02" or "Y04S" CPC code indicates whether a patent related to hydrogen technologies is categorized as "green" or sustainable. This classification provides valuable insights into the environmental alignment of patented hydrogen technologies, allowing for a better understanding of their sustainability implications. Overall, considering the entire dataset, as depicted in *Figure 21*, 78.1% of all hydrogen patented technologies have been labelled as "green" or "sustainable".

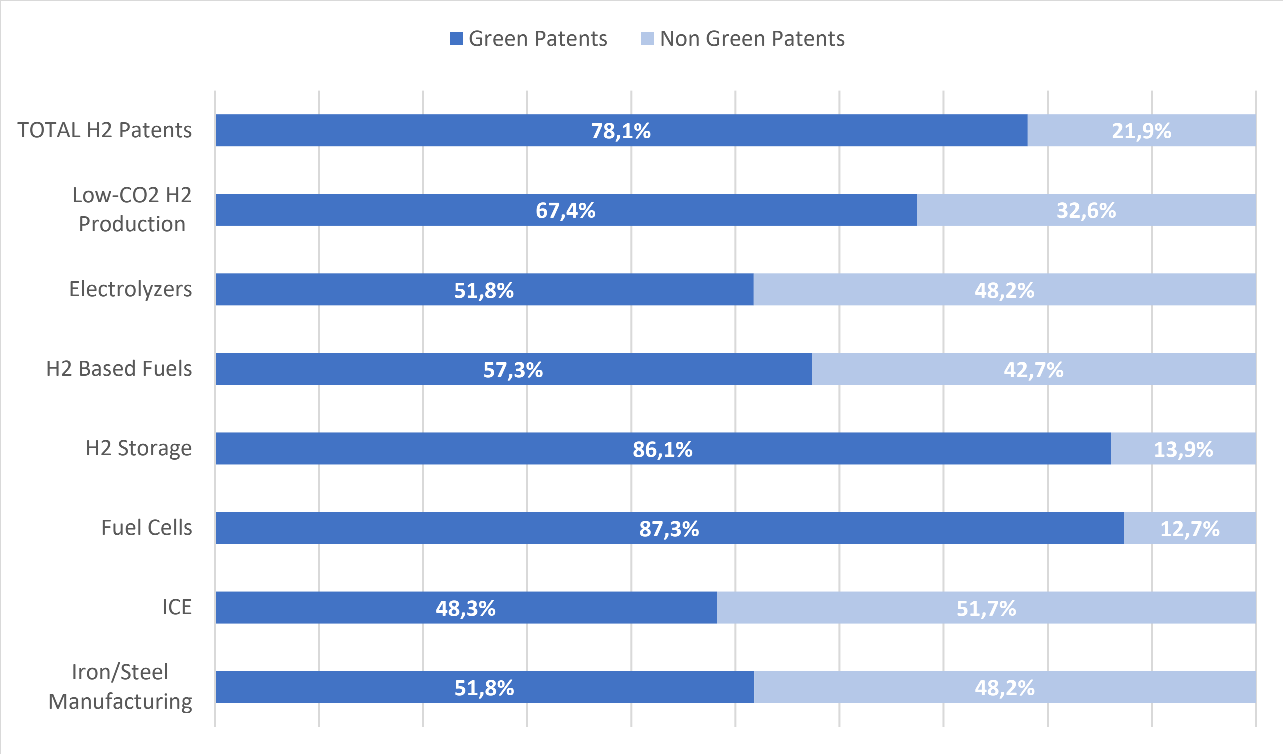

FIGURE 21: THE DISTRIBUTION OF GREEN PATENTS AMONG HYDROGEN PATENTED TECHNOLOGIES ACROSS THE ENTIRE VALUE CHAIN

The distribution of patents labelled with the “Y02” or “Y04S” CPC code across different macro categories of the hydrogen value chain, represented in *Figure 21*, reveals an interesting finding: only around 50% of certain macro technologies have been designated as "green."

However, it is important to consider several factors when interpreting these results. Firstly, the inclusion of the Y section in the CPC system began in 2013, and while efforts have been made to retroactively label older patents, there is a conservative tendency in assigning the "green" label to pre-2013 patents. Furthermore, the assignment of CPC codes relies on the interpretation and classification choices of patent examiners or applicants, leading to potential variations in labelling. Additionally, some patents may focus on technical advancements, efficiency improvements, or other aspects of hydrogen technology without explicitly highlighting their environmental or sustainability benefits. The extensive nature of the CPC classification system, encompassing various technological domains, adds further complexity to the labelling process. It is worth noting that the absence of the “Y02” or “Y04S” code in CPC classifications for hydrogen patents does not necessarily indicate a lack of sustainability. It may be a result of factors such as the patent's age, differing interpretations by examiners or applicants, specific focus, or limitations in the classification system's coverage.

THE USE AND ANALYSIS OF CITATIONS IN PATENTS

This chapter is built following the guidelines of the OCDE Patent Statistics Manual (OECD, 2009) and it outlines the purpose of patent citations and how Science & Technology indicators can be created using them. It specifically emphasizes the considerations to make while compiling indicators based on patent citations to analyse innovation.

Citations from both patents and non-patent works have grown significantly in recent years as indications of innovation. Citations act as indicators of technological and scientific predecessors in creations, allowing for the tracking of information. They offer a way to pinpoint the impact of discoveries or collections of discoveries and show how they have spread across the economy. In particular, the average technological and commercial relevance of a patent has been found to be reflected, in part, by the number of citations it receives, which aids in addressing the issue of the variability of patent value. Citations also make it possible to investigate relationships among businesses, sectors of the economy, nations, or geographic areas, as well as between technologies, science, and technology. These connections can be examined in a variety of ways, including by technical field, entity type (such as universities, domestic or foreign businesses, etc.), inventor, and more.

What are Citations?

Citations from both patent and non-patent sources are included in the search report and are used to evaluate an invention's patentability and clarify the veracity of the claims in a new patent application. They can be mentioned to demonstrate the lack of novelty of the citing innovation because they refer to the prior art, which indicates the knowledge that existed before the invention. Citations, however, also point out the boundaries of the law applicable to the claims of the relevant patent application. They consequently provide a crucial legal purpose by defining the boundaries of the property rights granted by the patent. If a patent B cites a patent A, it signifies that patent A represents a body of previously known information on which patent B is based or to which patent B is related and over which patent B is not entitled to make a claim. Due of this, citations may be used to prevent the granting of a patent or limit the protection provided to what was precisely known at the time the patent application was submitted. Citations are typically the result of a thorough state search examination of the state of the art performed by examiners to judge the novelty and inventiveness of innovations, which is required to establish their patentability. Citations can also be used to reject patent applications if it turns out that the invention being claimed is not new when put up against the state of the art. Any publicly accessible scientific or technical materials or other evidence that serves as a pertinent prior art for the invention are included in the search.

Citations generally fall into one of two categories. Patent references are referrals to earlier, pertinent technology that has been either protected by or detailed in other patents that have been filed at anytime, anywhere in the world, and in any language. On the other hand, scientific papers, conference proceedings, novels, database guides, technical manuals, standards descriptions, etc. are examples of references classified as non-patent literature (NPL).

Uses and Applications of Citations Indicators: Generality and Originality Index

Patent citation metrics have an enormous potential in assessing policy analysis. The innovation literature primarily uses patent citations for three purposes: first, to evaluate knowledge flows or spill overs; second, to assess the quality of patents; and third, to analyse corporate strategy. Patent citation analysis can be carried out both by considering references cited within a patent document or references made by later patents that cite a particular patent as prior art, known as backward and forward citations, respectively.

Backward citations, or references to earlier patent documents, can be used to monitor the diffusion of technological information. They enable the estimation of technological obsolescence curves and the spread of knowledge from inventions to institutions, regions, and other geographic locations, among other things (Jaffe and Trajtenberg, 2002).

The citations that a patent receives afterward, known as "forward citations," can be used to determine an invention's technological impact and influence, including its cross-technology and regional effects. Subsequently, the economic significance of a patent can be determined by the technological impact of inventions. As a matter of fact, it has been consistently discovered that a patent's value and the quantity and quality of its forward citations are related (Trajtenberg, 1990; Hall et al., 2005). The forementioned studies investigate the value of innovations by examining the relationship between patent citations and the economic value of patents, finding a positive correlation among the two.

The following paragraphs will define some relevant citation-based indicators, useful for the analysis that will be presented in the next section.

Count of Forward citations per patent: This is regarded as an indicator of the influence of inventions technologically. Studies have demonstrated that the number of citations a patent receives is related to its technological significance and social value (Trajtenberg, 1990; Harhoff, 1999). This indicator should be corrected into relative terms, thus accounting for invention date and technological sector to which the innovation pertains. The relative Count of Forward citations per patent measures how frequently a patent is cited in comparison to patents in the same technology sector (four-digit IPC subclass) and having the same invention date (priority year) on average. The purpose of adopting a truncation effect connected to time and disparities in citation frequency between technical domains is to avoid distortion biases as older patents have higher probabilities of being cited and some sectors tend to have citation practices that are more intense than others (Hall et al., 2001).

Generality/Originality of a Patent: The G*enerality* of a patent can be measured using a Herfindahl index (Trajtenberg et al., 1997; Hall et al., 2001).

$$Generality_i = 1 - \sum_j^{n_i} s_{ij}^2$$

The formula to account for the Generality of a given patent reported above depends on:

- ni, the number of patent classes of the citing patents
- sij, the proportion of citations received by a patent i that belong to patent class j.

Thus, if a patent is mentioned in later patents from a variety of fields, the measure will be high (near one), whereas if the majority of citations are focused in a small number of fields, it will be low (near zero). A high generality score indicates that the patent had a wide impact because it affected later ideas across numerous industries.

Overall, Generality refers to the capacity of an invention to be applied, reused, and adapted to create new knowledge across a wide range of diverse sectors or industries. It embodies the degree of transferability, adaptability, and versatility of the underlying technology, allowing it to transcend a variety of sectors and contribute to broader innovation.

Likewise, the definition of a patent's *Originality* is the same, with the exception that it refers to out backward citations. Therefore, referencing patents from a limited range of technologies will result in a low originality score, whereas citing patents from a wide variety of subjects will result in a high score.

$$Originality_i = 1 - \sum_{j=1}^{n} t_{ij}^2$$

The formula to account for the Originality of a given patent reported above depends on:

- ni, the number of patent classes of the cited patents
- tij, the proportion of the citations made by patent i to patents that belong to patent class j.

  Overall, Originality refers to the ability to create new knowledge by incorporating a wide range of diverse knowledge inputs that encompass various disciplines. It entails the blending and recombining of disparate fragments of knowledge to produce fresh and unique knowledge outcomes.

It goes without saying that the degree of originality and generality depends on the system used to classify patents; a finer system would result in higher measures, whilst a coarser system would result in lower measures. So, given that all other factors are equal, it is expected that a more precise classification within a field (such as the number of three-digit patent classes) will lead to higher generality and originality evaluations.

STATISTICAL INFERENTIAL ANALYSIS ON THE GENERALITY & ORIGINALITY OF HYDROGEN PATENTS

Data & Methodologies

The objective of the following analysis is to examine the level of Generality (or Specificity) and Originality (or Derivative) in EPO patents related to hydrogen technologies, using the tools defined in previous literature as described above. Testing Generality is of interest as it provides insights into the potential breadth and applicability of hydrogen technologies across a wide range of patent filings in the EPO database. On the other hand, testing Originality is interesting as it provides insights into the uniqueness and novelty of hydrogen technologies across a wide range of patent filings in the EPO database.

The dataset extracted from *Derwent Innovation*, widely described in the previous chapter, was then merged with the *PATSTAT* database, which contains additional bibliographic and legal data. More specifically, for the purposes of the following analysis it was crucial to obtain precise information regarding a specific subset of patents, those published through the Patent Office EP (European Patent Office). The decision of considering only EP patents, which represent approximately 7% of the entire dataset (6.994 patent applications), was made due to the availability of information: the *PATSTAT* database in fact guarantees a greater completeness of information for EPO patents. Additionally, it is important to note that Patent Offices differ for patenting and most importantly, citational practices, leading to potential comparability issues.

Therefore, it was decided to consider only EPO patent data to conduct inferential statistics analysis appropriately. As the dataset of hydrogen patents downloaded from *Derwent Innovation* was then filtered, dropping a minority of patents, all those published earlier than 1978 (entry in force year of the EPO patent Office) there is no additional loss of observations.

This operation, just like the following passages that will be described below have been carried out using *Python*[3], taking advantage of the functionalities of the *pandas*[4] library and have been replicated both for the Generality and Originality studies. Please refer to *Image 4* in *Annex* to visualize the code adopted to extract the generality indexes of all hydrogen EPO patented technologies.

Following the merge of the Hydrogen EPO patents codes with *PATSTAT* only 5.986 patent applications remain in the dataset. The loss of approximately 1000 patents is mainly because the initial dataset contains data up to May 2023, while the *PATSTAT* dataset contains patent applications only up to the beginning of June 2021, thus all the applications past this date cannot be matched.

As mentioned above, for the purpose of the Generality (Originality) analysis of a specific patent class, it is necessary to know the technological subclasses not only of the cited (citing) patents, but also of the citing (cited) patents and thus being able to compare the two. Therefore, after adding to the dataset all the additional information for hydrogen patents required (IPC subclass, identification of all forward/backward citations, including their count and IPC subclass), the Herfindahl index was

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[3] *Python* is a versatile programming language known for its simplicity and readability, widely used for web development, data analysis, artificial intelligence, and automation.
[4] The *pandas* library is a powerful data manipulation and analysis tool for Python, commonly used for handling and analysing structured data.

computed to account for the Generality (Originality) score of each patent that has received at least one forward citation (has cited at least one patent) from the entire EPO patent dataset.

The Generality (Originality) scores were obtained exclusively for 1.475 hydrogen patents (2.895 patents). This means that of the initial 5.986 hydrogen patents, only 1.475 (approximately 25%) have received at least one forward citation from other EPO patents, whereas 2.895 (approximately 50%) have cited at least one EPO patent.

At this point, a benchmark comparison is essential for assessing the amount of generality or specificity of hydrogen patented technology (at the European Patent Office). To generate relevant findings, all EPO patents are used as the benchmark in this analysis. In fact, the OECD Patent Stastics Manual (OECD, 2009) reports: “Information on patent citations is meaningful only when used comparatively. There is no natural scale or value measurement associated with citation data, so the fact that a given patent has received 10 or 100 citations does not indicate whether or not that patent is “highly” cited. In other words, the evaluation of the citation intensity of an invention, an inventor, an institution, or any other group of reference, can only be made with reference to some “benchmark” citation intensity.”

The approach described above was replicated for the whole *PATSTAT* dataset, to find the Generality (and Originality) score of all patents published at the European Patent Office (EPO).

By following the procedure, it was possible to find that a total of 1.072.069 EPO patents have received citations from other EPO patents. Considering the entire EPO patent dataset, consisting of 3.848.243 patents, it can be inferred that approximately 28% of all EPO patents have obtained forward citations from other EPO patents. Although this percentage is slightly higher than that observed for hydrogen EPO patents, it does not necessarily indicate that hydrogen patents, on average, possess lower technological impact compared to other patents. Drawing proper conclusions on this matter requires the consideration of numerous additional factors. For instance, hydrogen patents are associated with a relatively less mature technology, resulting in a more extensive distribution of more recent patents. Consequently, it is evident that hydrogen patents may have had less time to accumulate forward citations from other patents. Moreover, geographical factors might come into play, as hydrogen innovation could span across borders more extensively than other technologies. Consequently, patents may be cited in jurisdictions outside the EPO, which are not accounted for in this analysis.

In the same way, the procedure was carried out on backward citations, finding that a total of 1.743.683 EPO Patents have cited other EPO patents. Considering the entire EPO patent dataset, consisting of 3.848.243 patents, it can be inferred that approximately 45% of all EPO patents have cited other EPO patents. As this percentage is slightly higher than that observed for hydrogen EPO patents, it is possible that hydrogen patents are built upon or references a broader range of existing knowledge or technologies compared to all other patents. The higher quantity of citations suggests a stronger reliance on prior work and a potentially more comprehensive examination of related inventions and prior art during the patenting process. Again, however, numerous additional factors should be considered before driving to proper conclusions. For instance, it could be that hydrogen patents tend to cite other patents from jurisdictions outside the EPO, which are not accounted for in this analysis.

At this point, the Generality (and Originality) Index (HHI) for hydrogen EPO patents and all EPO patents were imported into *Stata*[5]. To compare the means of the Generality Index of hydrogen patents and Generality Index of all patents, a Two-sample t-test was selected. The t-test is a statistical inference test that allows for the comparison of means between two populations. In this case, it is useful to determine if there is a significant difference between the Generality of hydrogen patents and all patents, providing insights into the relative breadth or specificity of the technological innovations. The t-test is unpaired because there is no match or pairing between observations in the two populations. Additionally, the data have unequal variances, making the unpaired unequal variances (Welch's) approximation appropriate. The confidence level used for the test is set to the default level of 95%. Given the substantial difference in sample sizes (n=1.475 for hydrogen patents and m=1.072.069 for all patents in the Generality study; n=2.895 for hydrogen patents and m=1.743.683 for all patents in the Originality study), employing Welch's approximation is justified. Welch's test accounts for unequal variances and is robust when dealing with imbalanced sample sizes, ensuring accurate and reliable statistical comparisons. In summary, an unpaired, unequal variance, ttest, using Welch’s approximation with default confidence level (equal to 95), was run to assess if there is significant difference between the Generality of hydrogen patents and all patents.

Results on the Generality of EPO Hydrogen Patented Technologies

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[5] *Stata* is a versatile statistical software for data analysis and modelling, widely utilized in research, academia, and industry.

The statistics provided in *Figure 22* present the distribution for two variables: the Generality Index of EPO hydrogen patents and the Generality Index of all EPO patents.

Variable	Obs	Mean	p1	p25	p50	p75	p99
gen_hydrogen	1,475	.514206	0	0	0.6666667	0.8163266	1
gen_all	1,072,069	.5279202	0	0	0.6666667	0.8271605	1

FIGURE 22: DESCRIPTIVE STATISTICS ON THE GENERALITY INDEX OF EPO HYDROGEN PATENTS AND ON THE GENERALITY OF ALL EPO PATENTS

Examining the percentiles, we find that the first quartile (p25) for both variables is reported as 0. This suggests that 25% of patents in both groups have a generality value of 0 or less, indicating a subset of patents with limited generality or a more specific technological focus. Additionally, it is noteworthy that the median generality value, represented by the 50th percentile (p50), is the same for both variables, approximately 0.67. It is interesting to observe that the median is significantly higher than the mean in both cases. This suggests that the distribution of generality is skewed towards the higher values, as there are relatively more patents with higher-than-average generality scores. Furthermore, the third quartile (p75) for Generality Index for all patents is approximately 0.8271605, whereas it is approximately 0.8163266 for hydrogen patents. These data reveal that, overall, the distribution of Generality of hydrogen patents is quite comparable to the one of all other patented technologies.

Variable	Obs	Mean	Std. err.	St. dev	[95% conf. Interval]	
gen_hydrogen	1,475	.514206	.0095836	.3680639	.4954071	.5330048
gen_all	1,072,069	.5279202	.0003541	.3666369	.5272261	.5286142
diff		(.0137142)	.0095901		(.0325259)	.0050975
diff = mean(gen_hydrogen) - mean(gen_all)						t = (1.4300)
H0: diff = 0				Welch's degrees of freedom = 1478.03		
Ha: diff < 0			Ha: diff != 0		Ha: diff > 0	
Pr(T < t) = 0.0765			Pr(|T| > |t|) = 0.1529		Pr(T > t) = 0.9235	

FIGURE 23: TWO- SAMPLE T TEST WITH UNEQUAL VARIANCES: GENERALITY OF EPO HYDROGEN PATENTS VS GENERALITY OF ALL EPO PATENTS

The statistical analysis, shown in *Figure 23* examines the generality of hydrogen EPO patents in comparison to all EPO patents and reveals that the generality means for hydrogen patents, based on 1.475 observations, is approximately 0.514206, while the mean generality for all patents, with a much larger sample size of 1.072.069, is approximately 0.5279202.

Moreover, the calculated difference in mean generality between the two groups is -0.0137142. Although this difference is negative, indicating slightly lower generality in hydrogen patents, it is important to assess its statistical significance. The t-value of -1.4300 associated with the t-test provides evidence against the null hypothesis of no difference in generality. However, it is crucial to consider the level of significance and confidence associated with this rejection.

At a 90% confidence level, the p-value of 0.0765 reaches statistical significance. Thus, we can reject the null hypothesis of no difference in generality at this confidence level and support the alternative hypothesis stating that there is a directional expectation or belief that the difference between the mean generality of hydrogen patents and all patents is less than zero. In other words, it suggests that hydrogen patents, on average, may have lower generality compared to all patents.

However, it is worth noting that at a higher confidence level of 95%, the p-value should be less than 0.05 to achieve statistical significance. In this case, the p-value of 0.0765 does not meet that threshold, leading us to accept the null hypothesis at the 95% confidence level.

Results on the Originality of EPO Hydrogen Patented Technologies

The statistics provided in *Figure 24* present the distribution for two variables: the Originality Index of EPO hydrogen patents and the Originality Index of all EPO patents.

Variable	Obs	Mean	p1	p25	p50	p75	p99
orig_hydrogen	2,895	.5429209	0	0	0.75	0.8641976	1
orig_all	1,743,683	.5415988	0	0	0.75	0.8611111	1

FIGURE 24: DESCRIPTIVE STATISTICS ON THE ORIGINALITY INDEX OF EPO HYDROGEN PATENTS AND ON THE ORIGINALITY INDEX OF ALL EPO PATENTS

Examining the percentiles for the "originality" variable, we find that the first quartile (p25) for both hydrogen patents and all patents is reported as 0. This indicates that 25% of patents in both groups have an originality value of 0 or less, suggesting a subset of patents with limited originality or potentially incremental innovations. Interestingly, the median originality value, represented by the 50th percentile (p50), is the same for both hydrogen patents and all patents, approximately 0.75. This implies that there is a cluster of patents in both groups with relatively higher originality scores, indicating a certain level of significant inventive contributions. Moreover, it is noteworthy that the median is significantly higher than the mean in both cases, suggesting that the distribution of originality is skewed towards higher values. This implies that there is a larger number of patents with relatively higher originality scores, potentially representing more transformative and novel innovations. Regarding the third quartile (p75), the value for all patents is in the range of 0.86 for both technologies. These data reveal that, overall, the distribution of Originality of hydrogen patents is quite comparable to the one of all other patented technologies.

Variable	Obs	Mean	Std. err.	St. dev	[95% conf. Interval]	
orig_hydrogen	2,895	.5429209	.0069912	.3761637	.5292127	.5566292
orig_all	1,743,683	.5415988	.0002843	.3753708	.5410417	.542156
diff		0.0013221	.006997		(.0123975)	.0150417
diff = mean(orig_hydrogen) - mean(orig_all)						t = 0.1890
H0: diff = 0				Welch's degrees of freedom = 2903.58		
Ha: diff < 0			Ha: diff != 0		Ha: diff > 0	
Pr(T < t) = 0.5749			Pr(|T| > |t|) = 0.8501		Pr(T > t) = 0.4251	

FIGURE 25: TWO- SAMPLE T TEST WITH UNEQUAL VARIANCES: ORIGINALITY OF EPO HYDROGEN PATENTS VS ORIGINALITY OF ALL EPO PATENTS

The statistical analysis, shown in *Figure 25* examines the Originality of hydrogen EPO patents in comparison to all EPO patents and reveals that the originality means for hydrogen patents, based on 2.895 observations, is approximately 0.5429209, while the mean generality for all patents, with a much larger sample size of 1,743,683, is approximately 0.5415988.

The calculated t-value of -0.1890, with Welch's degrees of freedom estimated as 2903.58, compares the difference in means to the null hypothesis that the difference is zero. The p-value associated with the t-test is 0.4251, suggesting that there is no statistically significant difference in mean originality values between hydrogen EPO patents and all EPO patents.

Therefore, we fail to reject the null hypothesis, indicating that there is no evidence to suggest a significant difference in originality between hydrogen EPO patents and all EPO patents. These results suggest that both hydrogen and non-hydrogen patents exhibit similar levels of originality in the EPO patent database.

Results on the Evolution of Generality of EPO Hydrogen Patented Technologies

Figure 26 displays the generality trends of EPO hydrogen patents and of all EPO patents.

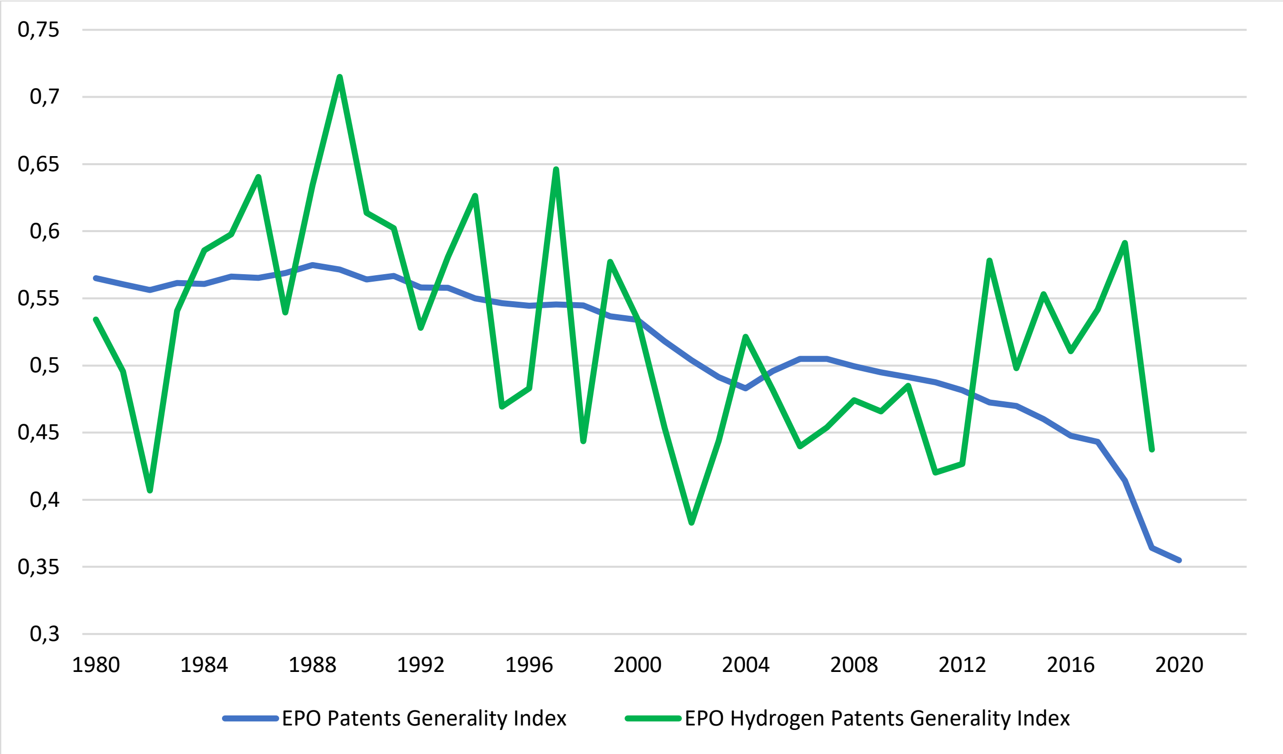

FIGURE 26: THE EVOLUTION OF THE AVERAGE GENERALITY INDEX OF EPO HYDROGEN PATENTS AND ALL EPO PATENTS

From the graph it is possible to evince that there has been a rather declining generality trend for all EPO patents, whereas the evolution of generality of EPO hydrogen patents is characterized by many ups and downs. Clearly, being the sample size much smaller than the other distribution, it is normal that a very general patent or a very specific patent will have a much stronger effect in shifting the overall generality score in a specific year. Nevertheless, it seems that also the generality of EPO hydrogen patents is subject to a slightly declining trend, therefore the following analysis will test using statistical inference methods if this is the case.

For this reason, the distribution of EPO hydrogen patents that received at least one forward citation from other EPO patents was divided into two groups of the same sample size, the first comprises EPO hydrogen patents from 1978 to mid-2001, the second covers patents from mid-2001 to 2020. At this point, the same n unpaired, unequal variance, ttest, using Welch's approximation with default confidence level (equal to 95), was run to assess if there is significant difference in the mean of the Generality of hydrogen patents "older" hydrogen patents and "younger" hydrogen patents.

Variable	Obs	Mean	Std. err.	St. dev	[95% conf. Interval]	
gen_1978-2001	737	.556316	.0128149	.3478961	.5311578	.5814741
gen_2001-2020	738	.472153	.0140908	.3827929	.4444901	.4998159
diff		0.0841629	.0190466		0.0468014	.1215245
diff = mean(gen_1978-2001) - mean(gen_2001-2020)						t = 4.4188
H0: diff = 0				Welch's degrees of freedom = 1462.08		
Ha: diff < 0			Ha: diff != 0		Ha: diff > 0	
Pr(T < t) = 1.0000			Pr(|T| > |t|) = 0. 0000		Pr(T > t) = 0. 0000	

FIGURE 27: TWO- SAMPLE T TEST WITH UNEQUAL VARIANCES: GENERALITY OF "OLD" EPO HYDROGEN PATENTS VS GENERALITY OF "NEW" EPO HYDROGEN PATENTS

The results of the statistical analysis, shown in *Figure 27*, illustrate a statistically significant difference in means, with a calculated t-statistic of 4.4188 and a corresponding p-value of less than 0.0001. This low p-value provides strong evidence to reject the null hypothesis (H0: diff = 0) in favour of the alternative hypothesis (Ha), indicating a non-zero difference between the means of the two distributions. The mean for the generality index of older patents is 0.556316, significantly higher than the mean of the generality index of younger patents at 0.472153. These findings suggest that older hydrogen patents have a higher generality compared to the younger patents, emphasizing the significance of age in the distribution of hydrogen patents. In conclusion, the t-test results provide compelling evidence of a significant disparity between the older and younger hydrogen patents, supporting the notion that age plays a significant role in the distribution of these patents.

Results on the Evolution of Originality of EPO Hydrogen Patented Technologies

Figure 28 displays the generality trends of EPO hydrogen patents and of all EPO patents.

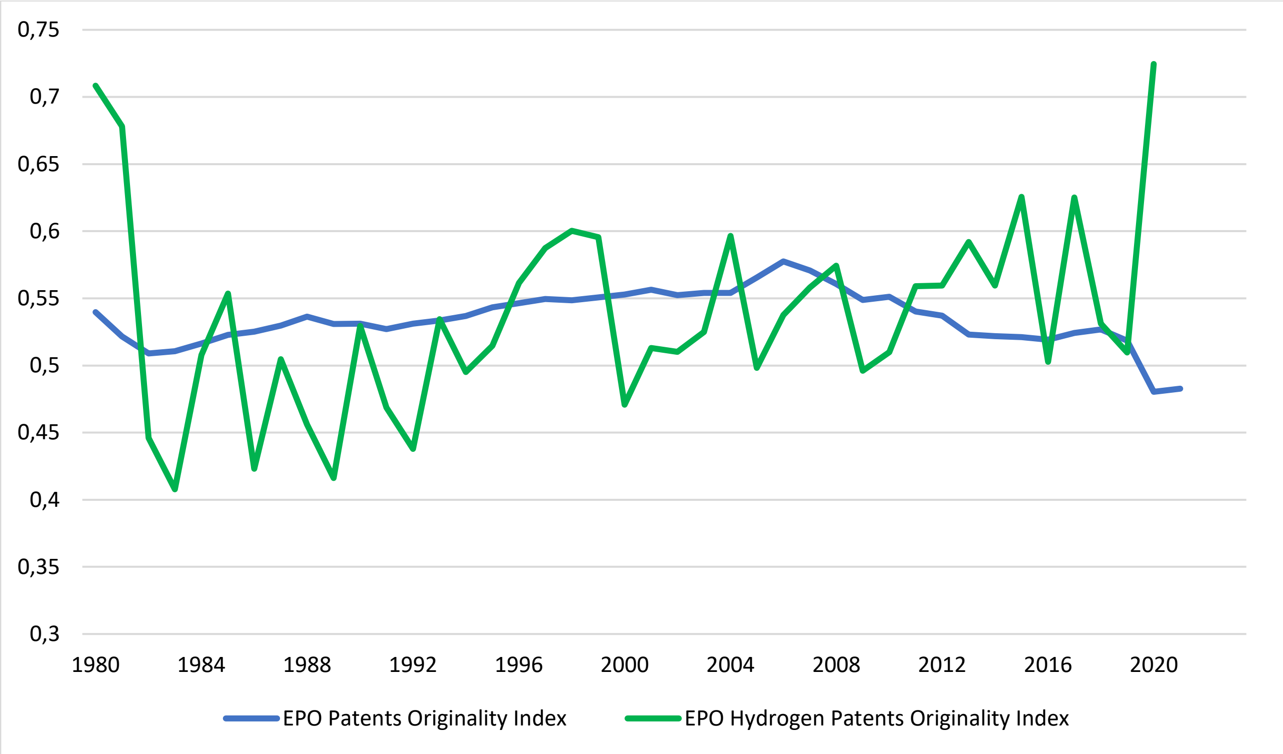

FIGURE 28: THE EVOLUTION OF THE AVERAGE ORIGINALITY INDEX OF EPO HYDROGEN PATENTS AND ALL EPO PATENTS

From the graph it is possible to evince that there has been a strong decline in the originality of EPO patents from 1978 to 1882, followed by a modestly increasing trend from 1982 to 2007 and a new visible decline from 2007 to 2020. On the other hand, for the same reasons illustrated for Generality, the Originality evolution of EPO hydrogen patents is characterized by many ups and downs. Nevertheless, it seems that, following the sharp decline in originality of hydrogen patents from 1978 to 1883, there has been a slightly increasing trend up until 2020, therefore the following analysis will test using statistical inference methods if this is the case.

Again, the distribution of hydrogen patents that received at least one forward citation was divided into two groups of the same sample size, the first comprises EPO hydrogen patents from 1978 to mid-2006, the second covers patents from mid-2006 to 2020. At this point, the same n unpaired, unequal variance, ttest, using Welch's approximation with default confidence level (equal to 95), was run to assess if there is significant difference in the mean of the Originality of "older" hydrogen patents and "younger" hydrogen patents.

Variable	Obs	Mean	Std. err.	St. dev	[95% conf. Interval]	
orig_1978-2006	1,447	.5319143	.0097246	.3699196	.5128385	.5509902
orig_2006-2020	1,448	.5539199	.0100417	.3821127	.5342221	.5736177
diff		(.0220056)	.0139787		(.0494148)	.0054037
diff = mean(orig_1978-2006) - mean(orig_2006-2020)						t = (1.5742)
H0: diff = 0				Welch's degrees of freedom = 2892.09		
Ha: diff < 0			Ha: diff != 0		Ha: diff > 0	
Pr(T < t) = 0.0578			Pr(|T| > |t|) = 0. 1155		Pr(T > t) = 0. 9422	

FIGURE 29: TWO- SAMPLE T TEST WITH UNEQUAL VARIANCES: ORIGINALITY OF "OLD" EPO HYDROGEN PATENTS VS ORIGINALITY OF "NEW" EPO HYDROGEN PATENTS

The mean for the originality of older patents is 0.5319143, whereas the originality of younger patents has a slightly higher mean of 0.5539199, with the calculated difference between the means of -0.0220056, indicating a negative disparity. The t-statistic of -1.5742 suggests that this difference is not statistically significant at the 95% confidence level. As a matter of fact, the p-value is slightly higher than the 5% threshold. Consequently, we fail to reject the null hypothesis (H0: diff < 0), and there is insufficient evidence to conclude that there is a difference between the means of the two distributions. However, the p-value associated with the hypothesis test, Pr(T < t), is 0.0578, which is greater than the 5% threshold but smaller than the 10% threshold. This suggests a marginally significant result, implying a potential difference that warrants further investigation.

ECONOMETRIC ANALYSIS

After studying the hydrogen patent sample from a descriptive standpoint and having conducted some preliminary statistical analysis this chapter presents and comments on the results of the econometric analyses. Thus, the following chapter aims at investigating the determinants of originality and generality of patents, with a specific focus on understanding to what extent a hydrogen patented technology influences the two main studied variables. For this purpose, different econometric models have been employed to achieve these objectives, including an OLS (Ordinary Least Squares) and a Tobit regression.

Variables adopted in the Econometric Analysis

The sample used to conduct this analysis is the entire EPO Patent dataset described in the previous chapter, with the addition of a series of bibliometric variables, derived from *PATSTAT*. This sample is controlled with a dummy variable that assesses whether a patent consists of a hydrogen technology or not. The list of variables adopted in the models is presented in *Table 7*.

Variable	**Label**
apln_id	Identification code associated with the patent application
apln_nr	Identification number associated with the patent application
apln_cd	Identification EPO code associated with the patent application
apln_dt	Date of patent application
apln_yr	Year of patent application
prty_dt	First date of filing a patent application
prty_yr	First year of filing a patent application
grnt_dt	Date the patent was granted
grnt_yr	Year in which the patent was granted
grnt_lg	Time delta between patent filing and grant
grnt_dm	Dummy: patent granted
apct_nb	Number of patent applicants
apct_dm	Dummy: multiple patent applicants
invt_nb	Number of patent inventors
sbcls_nb	Number of distinct IPC subclasses to which the patent belongs (4 IPC digits)
cls_nb	Number of distinct IPC classes to which the patent belongs (3 IPC digits)
sctn_nb	Number of distinct IPC sections to which the patent belongs (1 IPC digit)
sctr_nb	Number of distinct economic sectors to which the patent belongs
bckw_apln_nb	Number of backward citations made
frwd_apln_nb	Number of forward citations received
is_hydrogen	Dummy: hydrogen patent
generality	Generality Index of a patent
originality	Originality Index of a patent
sctn_A_dm	Dummy: IPC Section A
sctn_B_dm	Dummy: IPC Section B

sctn_C_dm	Dummy: IPC Section C
sctn_D_dm	Dummy: IPC Section D
sctn_E_dm	Dummy: IPC Section E
sctn_F_dm	Dummy: IPC Section F
sctn_G_dm	Dummy: IPC Section G
sctn_H_dm	Dummy: IPC Section H

Table 7: List and labels of variables adopted in the econometric analysis

Statistical Analysis on the relevant econometric variables

The following descriptive analysis, presented in *Table 8*, provides some statistics regarding the most significant variables adopted in the models.

Control Variables	Count	Mean	Median	SD	Min	Max
Originality Index	1,743,683	0.542	0.750	0.375	0.000	1.000
Generality Index	1,072,069	0.528	0.667	0.367	0.000	1.000
Hydrogen dummy	3,848,243	0.002	0.000	0.039	0.000	1.000
Grant lag	2,041,711	5.180	4.592	2.505	0.666	24.912
Grant dummy	3,848,243	0.533	1.000	0.499	0.000	1.000
Number of applicants	3,848,243	1.078	1.000	0.364	0.000	62.000
Multiple applicants dummy	3,848,243	0.062	0.000	0.241	0.000	1.000
Number of inventors	3,848,243	2.656	2.000	1.937	0.000	133.000
Number of sections	3,848,243	1.365	1.000	0.579	0.000	7.000
Number of classes	3,848,243	1.585	1.000	0.843	0.000	23.000
Number of subclasses	3,848,243	1.920	2.000	1.170	0.000	44.000
Number of sectors	3,848,243	1.564	1.000	0.803	0.000	13.000
Number of backward citations	3,848,243	0.793	0.000	1.369	0.000	215.000
Number of forward citations	3,848,243	0.793	0.000	3.241	0.000	1414.000

Table 8: Statistics on the variables of the econometric models

Furthermore, a set of descriptive statistics concerning the variables of interest are illustrated in *Tables 9* and *10* to provide wider insights on how the distributions of these compare between hydrogen and non-hydrogen patents.

Descriptive Statistics by Group: EPO Patents	Mean	1st perc.	25th perc.	50th perc.	75th perc.	99th perc.
Originality Index	0.542	0.000	0.000	0.750	0.861	1.000
Generality Index	0.528	0.000	0.000	0.667	0.827	1.000
Grant lag	5.179	1.589	3.391	4.590	6.318	13.586
Grant dummy	0.533	0.000	0.000	1.000	1.000	1.000
Number of applicants	1.078	1.000	1.000	1.000	1.000	3.000
Multiple applicants dummy	0.062	0.000	0.000	0.000	0.000	1.000
Number of inventors	2.655	1.000	1.000	2.000	3.000	9.000
Number of sections	1.364	1.000	1.000	1.000	2.000	3.000
Number of classes	1.585	1.000	1.000	1.000	2.000	4.000
Number of subclasses	1.920	1.000	1.000	2.000	2.000	6.000
Number of sectors	1.564	1.000	1.000	1.000	2.000	4.000
Number of backward citations	0.793	0.000	0.000	0.000	1.000	5.000
Number of forward citations	0.793	0.000	0.000	0.000	1.000	9.000

TABLE 9: DESCRIPTIVE STATISTICS BY GROUP: EPO PATENTS

Descriptive Statistics by Group: EPO Hydrogen Patents	Mean	1st perc.	25th perc.	50th perc.	75th perc.	99th perc.
Originality Index	0.543	0.000	0.000	0.750	0.864	1.000
Generality Index	0.514	0.000	0.000	0.667	0.816	1.000
Grant lag	5.359	1.748	3.526	4.749	6.614	13.490
Grant dummy	0.558	0.000	0.000	1.000	1.000	1.000
Number of applicants	1.095	1.000	1.000	1.000	1.000	3.000
Multiple applicants dummy	0.082	0.000	0.000	0.000	0.000	1.000
Number of inventors	3.237	1.000	2.000	3.000	4.000	11.000
Number of sections	1.583	1.000	1.000	1.000	2.000	4.000
Number of classes	1.800	1.000	1.000	2.000	2.000	5.000
Number of subclasses	2.131	1.000	1.000	2.000	3.000	7.000
Number of sectors	1.783	1.000	1.000	2.000	2.000	5.000
Number of backward citations	0.824	0.000	0.000	0.000	1.000	5.000
Number of forward citations	0.713	0.000	0.000	0.000	0.000	9.000

TABLE 10: DESCRIPTIVE STATISTICS BY GROUP: EPO HYDROGEN PATENTS

To facilitate the interpretation of the evidence presented, it is pivotal to understand the economic significance associated with the variables used in the analyses. Therefore, *Table 11* provides a description of the main patent features analysed, accompanied by their economic significance.

Variable	Economic Description
Number of distinct IPC classes to which the patent belongs (3 IPC digits)	This variable indicates the technological breadth of the invention. A lower number of CPI classes corresponds to a lower technological width, while a high value of class IPC is indicative of a greater number of potential uses of the patented technology.
Number of patent inventors	This variable indicates the size of the team. Typically, teams with larger work groups correspond to more complex nature of innovation. Thus, the number of inventors is often used as a proxy of the complexity of the innovation.
Dummy: multiple patent applicants	This dummy variable indicates co-assignment of a patent. Having more than one assignee implies the collaborative nature of the invention. For example, the emergence of inventions within the scope of consortia.
Number of backward citations made	This variable is proxy for the radicality of the invention. A high number of citations made indicates that the technology is strongly anchored in the pre-existing art and thus identifies incremental, rather than radical.
Number of forward citations received	This variable is a proxy for the technical value of the patent. Typically, the higher the number of citations receives, the higher the intrinsic technological value of the patent itself.

TABLE 11: ECONOMIC SIGNIFICANCE OF THE VARIABLES ADOPTED IN THE ECONOMETRIC ANALYSIS

Moreover, *Table 12* illustrates the correlation matrix of the most relevant bibliometric patent variables adopted in the econometric analysis.

	Originality Index	Generality Index	# of applicants	+ applicants dummy	# of inventors	# of sections	# of classes	# of subclasses	# of sectors	# of backward citations
Originality Index	1.0000									
Generality Index	0.3106	1.0000								
# of applicants	0.0145	0.0176	1.0000							
+ applicants dummy	0.0156	0.0200	0.8805	1.0000						
# of inventors	0.0645	0.0598	0.1214	0.1192	1.0000					
# of sections	0.1936	0.1945	0.0218	0.0242	0.0775	1.0000				
# of classes	0.2228	0.2277	0.0198	0.0215	0.0746	0.7984	1.0000			
# of subclasses	0.2574	0.2606	0.0232	0.0255	0.0999	0.6776	0.8439	1.0000		
# of sectors	0.2249	0.2287	0.0194	0.0215	0.0820	0.7814	0.8884	0.8200	1.0000	
# of backward citations	0.1638	0.0267	0.0065	0.0048	0.0780	0.0311	0.0282	0.0458	0.0319	1.0000
# of forward citations	0.0339	0.1050	0.0052	0.0083	0.0498	0.0449	0.0521	0.0756	0.0551	0.0518

TABLE 12: CORRELATION MATRIX OF THE VARIABLES ADOPTED IN THE ECONOMETRIC ANALYSIS

It is not surprising to observe the high correlations among the number of IPC sections, number of IPC classes and the number of IPC subclasses as these all identify, even though with different levels of aggregation, the technological domain to which a specific invention pertains. Similarly, it is also intuitive that these measures are also strongly correlated with the number of sectors.

Furthermore, it is reasonable that these are all positively correlated with the originality and generality of a given patent. As a matter of fact, the wider the technological domain of the invention, the higher the chances of recombining in different ways existing knowledge (originality) and the higher the chances of citing patents belonging to the same knowledge environment (generality).

Additionally, because of how the HHI index is built, it is intuitive that a higher number of backward citations will increase the chances of recombining in different ways existing knowledge (originality). Likewise, a higher number of forward citations will increase the chances of citing patents to fall within the same knowledge environment (generality).

Regression Analysis

OLS (Ordinary Least Square) Model

The first group of empirical analysis is aimed at identifying a relationship, positive or negative, between the originality and generality indexes of patents with respect to some features of the patents themselves. Initially, an OLS (Ordinary Least Squares) model, a linear regression technique that estimates the relationship between a dependent variable and one or more independent variables by minimizing the sum of squared differences between observed and predicted values, has been adopted. Thus, the following analysis were set:

$$originality = f(\ \beta 0 + \beta nXn + \varepsilon n)$$

$$generality = f(\ \beta 0 + \beta nXn + \varepsilon n)$$

$$n = 1, \dots, N$$

Where generality/originality is the dependent variable indicating the generality/originality index scores of a specific patent, computed with a HHI index, as described in the previous chapters.

Xn is a vector of regressors identifying some characteristics of the patents. In the models shown below, the following variables are included: number of inventors, number of backward citations, number of forward citations, hydrogen patent dummy, multiple applicants dummy, number of technology subclasses, grant dummy, grant lag. Additionally, two other regressors have been added to some models. These represent a combination of the variable set listed above. More specifically, the hydrogen patents dummy has been multiplied by the number of applicants dummy and the number of inventors, respectively. This strategy is commonly used to study whether the combined effect of the two independent regressors significantly impacts the dependent variable.

To conduct a more robust analysis, multiple models have been run, sequentially adding additional variables at each iteration. This will allow to better observe the effect of each additional variable both on the dependent variable and on the rest of the regressors (independent variables).

Tables 12 and *13* illustrate the average marginal effects. The standard errors are presented in parentheses. The stars, from * to ***, indicate statistical significance, at 10%, 5% and 1%, respectively.

Model	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Dependent variable	Originality	Originality	Originality	Originality	Originality	Originality
Constant	0.337***	0.367***	0.391***	0.389***	0.327***	0.327***
	(0.002)	(0.049)	(0.049)	(0.049)	(0.057)	(0.057)
Number of inventors	0.007***	0.002***	0.002***	0.002***	0.002***	0.002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Number of backward citations	0.032***	0.029***	0.030***	0.030***	0.031***	0.031***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Number of forward citations				0.000***		0.000
				(0.000)		(0.000)
Hydrogen patents dummy	-0.017**	-0.040***	-0.039***	-0.039***	-0.043***	-0.043***
	(0.007)	(0.007)	(0.007)	(0.007)	(0.008)	(0.008)
Multiple applicants dummy	0.024***	0.021***	0.020***	0.020***	0.021***	0.021***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)
Number of subclasses	0.066***	0.053***	0.053***	0.053***	0.057***	0.057***
		(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Grant dummy			-0.030***	-0.030***		
			(0.001)	(0.001)		
Grant lag					0.002***	0.002***
					(0.000)	(0.000)
Application year	No	Yes	Yes	Yes	Yes	Yes
IPC Section	No	Yes	Yes	Yes	Yes	Yes
Observations	1,743,683	1,743,683	1,743,683	1,743,683	1,011,680	1,011,680
Log-likelihood	-704,498.4	-687,165.5	-685,836.8	-685,833.3	-388,133.1	-388,132.9

TABLE 13: OLS MODEL ON THE ORIGINALITY INDEX OF PATENTS

Model	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**
Dependent variable	Generality	Generality	Generality	Generality	Generality	Generality
Constant	0.365***	0.416***	0.435***	0.424***	0.394***	0.385***
	(0.001)	(0.006)	(0.006)	(0.007)	(0.007)	(0.007)
Number of inventors	0.006***	0.003***	0.004***	0.003***	0.004***	0.003***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Number of backward citations	0.002***	0.000	0.000**	-0.001**	0.001***	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Number of forward citations				0.005***		0.004***
				(0.000)		(0.000)
Hydrogen patents dummy	-0.033***	-0.050***	-0.049***	-0.049***	-0.046***	-0.046***
	(0.009)	(0.009)	(0.009)	(0.009)	(0.011)	(0.011)
Multiple applicants dummy	0.015***	0.010***	0.010***	0.011***	0.011***	0.011***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.002)
Number of subclasses	0.073***	0.056***	0.057***	0.056***	0.059***	0.058***
		(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Grant dummy			-0.025***	-0.027***		
			(0.001)	(0.001)		
Grant lag					0.001***	0.001***
					(0.000)	(0.000)
Application year	No	Yes	Yes	Yes	Yes	Yes
IPC Section	No	Yes	Yes	Yes	Yes	Yes
Observations	1,072,069	1,072,069	1,072,069	1,072,069	711,247	711,247
Log-likelihood	411,564.2	397,036.6	396,435.1	393,260.5	253,821.9	251,912.2

TABLE 14: OLS MODEL ON THE GENERALITY INDEX OF PATENTS

Models (1) and (7) run on a limited set of regressors and most importantly they do not account for the application year and IPC section fixed effects. It is interesting to note, by observing at models (2) and (8) how controlling for these 2 fixed effects shifts the correlation between the dependent variable and the rest of the regressors. Even though these have not been reported in *Tables 13* and *14* for a matter of space, still it is interesting to cast light on the fact that all the time and section variables are statistically significant (at different levels).

All other things equal, hydrogen is less original and less general than non-hydrogen (always less than 1% significance level), 5% significance for (1).

Instead, backward citations have a positive correlation with originality. Patents that are more incrementally innovative (those that cite more) are more original than radically innovative patents (those that cite less). It is not reasonable to establish a clear relationship between the incrementally or radically innovative nature of a patents with its generality, as models (7)-(12) present diverse correlation directions with varying levels of significance. This finding is not surprising as the generality of a patent is linked to its forward, not with backward citations.

Furthermore, forward citations have a positive correlation with generality at 1% significance level, as shown by models (10) and (12). On the other hand, an extremely weak, but positive correlation can be observed with Originality in model (4) at a 1% significance level. Even though the relationships are significant, they are all equal to 0. This only suggests that, all other things equal, the number of backward citations does not drive up or down the originality index, which as a matter of fact, is built on backward citations.

Additionally, the complexity of innovation (proxied with the number of inventors), the collaborative nature of innovation (proxied with the multiple applicants dummy) and the technological knowledge width (proxied with positively correlated at the 1% significance level across all models both with originality and generality.

The length of the grant lag is positively correlated at the 1% significance level both with originality, as observed in models (5) and (6), as well as with generality, as observed in models (13) and (14). The grant dummy instead, is negatively correlated at the 1% significance level both with originality, as observed in models (3) and (4), as well as with generality, as observed in models (9) and (10).

Tobit Model

Subsequently, a Tobit model, presented in *Tables 15* and *16*, has been used to account for the fact that the dependent variable is censored or limited, meaning it has a range and values below or above that range are unobservable. Thus, a Tobit model combines a binary selection model with a linear regression model to estimate the relationship between independent variables and the censored dependent variable. These models are appropriate for studying a dependent variable between 0 and 1 because they can handle continuous variables within a limited range, accounting for the censored nature of the data.

Model	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
Dependent variable	Originality	Originality	Originality	Originality	Originality	Originality
Constant	0.176***	0.214*	0.249**	0.248**	0.151	0.151
	(0.001)	(0.110)	(0.110)	(0.110)	(0.124)	(0.124)
Number of inventors	0.010***	0.003***	0.003***	0.003***	0.003***	0.003***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Number of backward citations	0.043***	0.040***	0.040***	0.040***	0.043***	0.043***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Number of forward citations				0.000**		0.000
				(0.000)		(0.000)
Hydrogen patents dummy	-0.031***	-0.064***	-0.062***	-0.062***	-0.070***	-0.070***
	(0.010)	(0.010)	(0.010)	(0.010)	(0.013)	(0.013)
Multiple applicants dummy	0.035***	0.030***	0.029***	0.029***	0.031***	0.031***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
Number of subclasses	0.096***	0.077***	0.078***	0.078***	0.083***	0.083***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.001)	(0.001)
Grant dummy			-0.044***	-0.044***		
			(0.001)	(0.001)		
Grant lag					0.003***	0.003***
					(0.000)	(0.000)
Application year	No	Yes	Yes	Yes	Yes	Yes
IPC Section	No	Yes	Yes	Yes	Yes	Yes
Observations	1,743,683	1,743,683	1,743,683	1,743,683	1,011,680	1,011,680
Log-likelihood	1,503,495.6	1,488,660.0	1,487,386.4	1,487,383.7	849,663.8	849,663.7
Chi-squared	111,056.3	140,727.5	143,274.5	143,280.1	94,235.7	94,235.8

TABLE 15: TOBIT MODEL ON THE ORIGINALITY INDEX OF PATENTS

Model	**(7)**	**(8)**	**(9)**	**(10)**	**(11)**	**(12)**
Dependent variable	Generality	Generality	Generality	Generality	Generality	Generality
Constant	0.228***	0.299***	0.325***	0.312***	0.271***	0.260***
	(0.001)	(0.011)	(0.011)	(0.011)	(0.012)	(0.012)
Number of inventors	0.009***	0.005***	0.005***	0.005***	0.006***	0.005***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Number of backward citations	0.003***	0.000	0.001*	-0.001**	0.001***	-0.000
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Number of forward citations				0.007***		0.005***
				(0.000)		(0.000)
Hydrogen patents dummy	-0.056***	-0.080***	-0.078***	-0.078***	-0.072***	-0.072***
	(0.014)	(0.014)	(0.014)	(0.014)	(0.016)	(0.016)
Multiple applicants dummy	0.021***	0.016***	0.015***	0.016***	0.016***	0.017***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.003)	(0.003)
Number of subclasses	0.103***	0.079***	0.080***	0.078***	0.082***	0.080***
	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Grant dummy			-0.036***	-0.039***		
			(0.001)	(0.001)		
Grant lag					0.001***	0.001***
					(0.000)	(0.000)
Application year	No	Yes	Yes	Yes	Yes	Yes
IPC Section	No	Yes	Yes	Yes	Yes	Yes
Observations	1,072,069	1,072,069	1,072,069	1,072,069	711,247	711,247
Log-likelihood	903,359.1	891,089.3	890,550.3	887,727.0	578,988.7	577,275.0
Chi-squared	61,250.7	85,790.3	86,868.3	92,514.8	65,581.3	69,008.7

TABLE 16: TOBIT MODEL ON THE GENERALITY INDEX OF PATENTS

The results presented for both the originality and generality Tobit regressions are in line with the ones described for the OLS analysis, confirming the robustness of the relationships/correlations.

CONCLUSIONS

Hydrogen patents have proved to be less general compared to all other patents both in the ttest and regression analysis. This indicates that the patents related to hydrogen technologies tend to be more focused and precise in their claims and descriptions. Hydrogen technologies, while innovative and unique, have a narrower range of applicability compared to general-purpose technologies (GPTs). Unlike GPTs, which have broad applications across multiple sectors, hydrogen technologies are more specific and tailored to specific uses. This distinction often leads to a divergence in public funding, with a tendency for public parties to allocate more resources towards GPTs and support basic research that can be expanded into various applications. Additionally, it is extremely evident that hydrogen technologies have undergone a significant evolution towards increased specificity over time (ttest), proving to be a market niche with a high degree of specialization, resulting in higher barriers to entry and lower market competition among industry players.

Concerning originality instead, based on the ttest results, hydrogen patents appear to be as original as other technologies, but have proven to be less original than other patents when conducting multivariate regressions. This second result suggests that, when compared to all other patents, hydrogen innovations tend to rely on a narrower set of diverse knowledge inputs.

Nonetheless, hydrogen patents have shown an increasingly tendency to become more original over time (ttest). This evolution reflects the growing complexity and articulation of the technology. The shift towards environmentally friendly and sustainable solutions, such as green technologies, has played a crucial role in driving this increased originality. One notable example is the development of fuel cells, a prominent hydrogen technology. Fuel cells have evolved from traditional, simple designs to specialized variations tailored for specific targeted end-uses, such as power generation in specific environmental circumstances. Therefore, the increased originality over time is explained by the fact that different knowledge inputs are recombined, reused, and readapted to create new knowledge. This integration approach contributes to the originality of hydrogen patents, as inventors find new ways to combine existing technologies and create innovative solutions for harnessing the potential of hydrogen. This trend highlights the ongoing refinement and advancement within the hydrogen sector, as the technology continues to adapt to meet diverse and specific demands.

Overall, these findings can be useful in their intent to inform resource allocation and research priorities on the need for focused research to overcome technical challenges and optimize hydrogen applications.

In conclusion, the patent landscape in the hydrogen sector clearly reflects the exponential growth in attention and interest over the past two decades. This surge in interest can be attributed to the urgent need to address climate change challenges and seek sustainable solutions. The development of new hydrogen technologies is at various stages of Technology Readiness Levels (TRL) and maturities, highlighting the diverse range of innovations in progress. It is crucial for the entire value chain, encompassing production, storage, transportation, and utilization of hydrogen, to advance in parallel. This coordinated development is essential to fully exploit the benefits of hydrogen and enable the full potential it holds for the economy, the environment and society. Notably, developing countries, particularly China, have made remarkable investments and committed significant resources towards the advancement of hydrogen technologies, underscoring the global recognition of its importance in shaping a sustainable future.

POTENTIAL IMPROVEMENTS AND FUTURE DEVELOPMENTS

The study of innovation using patent data faces inherent limitations due to biases in the data, including the underrepresentation of certain industries, incomplete coverage of inventions, and potential time lags between innovation and patent filings. To address comparability issues, the assessment of generality/originality of hydrogen patents will focus on those published at the European Patent Office. However, it is worthwhile to replicate the study in other geographical regions such as the USPTO and JPO to gain a more comprehensive understanding.

Additionally, to evaluate the levels of generality and originality in patents, the study employed the use of subclasses identified by four alphanumeric characters, which provided a detailed technological classification of the patents. However, it would be valuable to conduct a new study using a broader classification system, such as the IPC class represented by three alphanumeric characters. This would allow for an examination of the extent to which the levels of generality and originality decrease when adopting a less granular classification approach. Such an analysis could provide insights into the impact of varying classification systems on the assessment of innovation dynamics.

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ANNEX

Hydrogen Technology	**Query – Derwent Innovation**	**Individual Records**	**Applications**	**Families**
Steam Methane Reforming: with CCUS (Blue Hydrogen)	CTB=(((((methan* OR (natural* adj gas*) OR CH4) OR (therm* NEAR1 plasma) OR solar OR (molten NEAR1 metal*)) NEAR3 pyrolys*) OR ((methan* OR (natural* adj gas*) OR CH4) NEAR3 (cracking or thermolys*)) OR (solid ADJ carbon NEAR1 produc* NEAR2 (methan* OR (natural* adj gas*) OR CH4) NEAR1 (dissociat* OR decompos*))) AND ((hydrogen* OR H2 OR H) NEAR2 (produc* OR generat* OR synthesis* OR creat* OR manufact* OR fabric*)))	560	442	197
Steam Methane Reforming: Electrically Heated (Grey Hydrogen)	CTB=((((electr* or (electr* NEAR2 steam*)) NEAR3 (methan* OR (natural* ADJ1 gas*) OR CH4) NEAR1 reform*) OR (eSMR* OR e-SMR* OR (electr* NEAR2 SMR*))) AND ((hydrogen* OR H2 OR H) NEAR2 (produc* OR generat* OR synthesis* OR creat* OR manufact* OR fabric*)))	112	100	69
Steam Methane Reforming: Sorption-enhanced (Grey Hydrogen)	CTB=((((sorpt* NEAR2 reform*) AND (methan* OR (natural* ADJ1 gas*) OR CH4*)) OR (SESMR* OR (sorpt* NEAR2 SMR*)) OR (SMR* NEAR2 (in-situ OR integrat*) NEAR2 (CO2* OR (carbonic* NEAR1 anhydrid*) OR (carbon NEAR1 dioxid*)) NEAR2 (captur* OR sorpt*))))	49	41	21
Steam Methane Reforming: Plasma Reforming (Grey Hydrogen)	CTB=((((plasma* OR (electr* NEAR1 discharg*)) NEAR3 (reform* OR pyroly*)) AND (methan* OR (natural* ADJ1 gas*) OR CH4*)) AND ((hydrogen* OR H2 OR H) NEAR2 (produc* OR generat* OR synthesis* OR creat* OR manufact* OR fabric*)))	173	143	106
Methane Pyrolysis (Turquoise Hydrogen)	CTB=(((((methan* OR (natural* adj gas*) OR CH4) OR (therm* NEAR1 plasma) OR solar OR (molten NEAR1 metal*)) NEAR3 pyrolys*) OR ((methan* OR (natural* adj gas*) OR CH4) NEAR3 (cracking or thermolys*)) OR (solid ADJ carbon NEAR1 produc* NEAR2 (methan* OR (natural* adj gas*) OR CH4)	984	819	658

	NEAR1 (dissociat* OR decompos*))) AND ((hydrogen* OR H2 OR H) NEAR2 (produc* OR generat* OR synthesis* OR creat* OR manufact* OR fabric*)))			
Alkaline Electrolysers (AEL)	CTB=(((alkalin* OR bacon OR ((potassium OR sodium) NEAR2 hydroxid*) OR AEL* OR AEC*) NEAR3 (electrolyz* OR electrolys* OR electrodialys* OR (electrolytic* ADJ cell*) OR ((Hydrogen* OR H2 OR H) NEAR3 (produc* OR generat* OR synthesis* OR creat* OR manufact* OR fabric*)) OR (water NEAR1 (split* OR decompos* OR (oxidat* NEAR3 reduct*) OR electrodissociat*)))))	8.211	6.851	5.257
Polymer Electrolyte Membrane (PEM) or Proton Exchange Membrane Electrolysers (PEMEL)	CTB=(((proton* NEAR1 exchang* NEAR1 membran*) OR (proton-exchang* NEAR1 membran*) OR (Polymer* NEAR1 Electrolyt* NEAR1 Membran*) OR Polymer* OR PEM* OR SPE) NEAR3 (electrolyz* OR electrolys* OR electrodialys* OR (electrolytic* ADJ cell*) OR ((Hydrogen* OR H2 OR H) NEAR3 (produc* OR generat* OR synthesis* OR creat* OR manufact* OR fabric*)) OR (water NEAR1 (split* OR decompos* OR (oxidat* NEAR3 reduct*) OR electrodissociat*))) NOT (FUEL ADJ CELL*));	6.264	5.106	3.468
Solid Oxide Electrolysers (SOEL)	CTB=(((Solid ADJ Oxide) OR SOE* or CERAMIC* OR HIGH-TEMPERATUR* OR (HIGH NEAR1 TEMPERATUR*)) NEAR3 (electrolyz* OR electrolys* OR electrodialys* OR (electrolytic* ADJ cell*) OR ((Hydrogen* OR H2 OR H) NEAR3 (produc* OR generat* OR synthesis* OR creat* OR manufact* OR fabric*)) OR (water NEAR1 (split* OR decompos* OR (oxidat* NEAR3 reduct*) OR electrodissociat*))) NOT (FUEL ADJ CELL*));	4.244	3.488	2.550
Anion Exchange Membrane Electrolysers (AEMEL)	CTB=(((Anion* NEAR1 exchang*) OR AEM*) NEAR3 (electrolyz* OR electrolys* OR electrodialys* OR (electrolytic* ADJ cell*) OR ((Hydrogen* OR H2 OR H) NEAR3 (produc* OR generat* OR synthesis* OR creat* OR manufact* OR fabric*)) OR (water NEAR1 (split* OR decompos* OR (oxidat* NEAR3 reduct*) OR electrodissociat*))));	763	658	486
Transformation of Pure Hydrogen into Low-emission Hydrogen-based Synthetic Fuels: Synthetic Methane & Others	CTB=((((((low-emission* OR (low* ADJ emission*) OR low-carbon* OR (low* ADJ carbon*) OR sustainabl* OR clean* OR green* OR (climat* ADJ friendl*) OR CO2-neutral OR (CO2 ADJ neutral*) OR (carbon ADJ neutral) OR synthetic* OR bio*) NEAR3 (fuel* OR gas* OR methan* OR CH4 OR kerosen* OR diesel OR hydrocarbon*)) OR (synfuel* OR biofuel* OR syngas* OR synthetic ADJ oil* OR e-methan* OR e-diesel OR e-kerosen*)) NEAR3 (produc* OR generat* OR transform* OR reduc* OR conver* OR process* OR synthes*)) NEAR3 (hydrogen* OR H2 OR H)) NOT coal);	3.660	2.925	1.951
Transformation of Pure Hydrogen to Ammonia & Low-temperature Ammonia Cracking	CTB=((((low-temperatur* OR low NEAR1 temperatur*) NEAR3 ((Haber-Bosch OR Haber ADJ Bosch)) OR ((Ammonia OR NH3) NEAR3 (produc* OR generat* OR transform* OR reduc* OR conver* OR crack* OR decompos* OR process* or synthes*) NEAR3 (hydrogen* OR H2 OR H)))) NOT (Methan*	4.724	3.951	3.019

(from Ammonia to Pure Hydrogen)	OR synthetic* OR CH4 OR (Natural ADJ Gas) OR Coal OR Electrol* OR (FUEL ADJ CELL*)));			
Transformation of Pure Hydrogen to Liquid Organic Hydrogen Carriers	CTB=(((LOHC OR liquid* ADJ hydrogen ADJ carrier* OR (liquid NEAR1 organic* NEAR3 hydrogen) OR Hydrogenat* ADJ (Liquid* ADJ Organic ADJ Compound* OR Organic* ADJ Liquid*) OR *cyclohexan* OR *Dibenzyltoluen* OR *ethylcarbazol* OR methyldecalin* OR *naphthalene) NEAR3 (produc* OR generat* OR transform* OR reduc* OR conver* OR crack* OR decompos* OR process*) NEAR3 (hydrogen* OR H2 OR H)) NOT (synthetic* OR Electrol* OR (FUEL ADJ CELL*) OR coal));	1.396	1.122	838
Gaseous Storage (Fuel stations, Terminals or Platforms, by Burying Tanks, by Digging Cavities, by using Natural Cavities, Deep Sea, Offshore)	CTB=((((hydrogen* OR H2 OR H) NEAR1 (stor* OR stock* OR deposit*)) NEAR3 (gas* OR compress* OR pressur* OR high-pressur*)) NOT ((solid* OR liquid* OR liquef* OR hydrid* OR cryogen* OR cryonic*) NEAR3 (hydrogen OR H2 OR H)));	5.972	4.987	4.038
Liquid Storage (Fuel stations, Terminals or Platforms, by Burying Tanks, by Digging Cavities, Deep Sea, Offshore)	CTB=((((hydrogen* OR H2 OR H) NEAR1 (stor* OR stock* OR deposit*)) NEAR3 (liquid* OR liquef* OR cryogen* OR cryonic* OR dewar* OR (insulated ADJ1 tank*))) NOT ((solid* OR hydrid* OR gaseous* OR compress*) NEAR3 (hydrogen OR H2 OR H)));	1.727	1.427	1.242
Solid storage (Hydrides/Adsorption)	CTB=((((hydrogen* OR H2 OR H) NEAR1 (stor* OR stock* OR deposit*)) NEAR3 (solid* OR (metal* NEAR1 (hydrogen OR H2 OR compound*)) OR hydride* OR ((AB5 OR AB2) NEAR1 alloy*) OR (magnesium* NEAR1 hydride*) OR MgH2 OR (sodium* NEAR1 borohydride*) OR NaBH4 OR adsorpti* OR physisorpti* OR chemisorpti* OR (activated* NEAR1 carbon*) OR (metal-organic* NEAR1 framework*) OR (metal* NEAR1 organic* NEAR1 framework*) OR MOF OR MOFs OR (covalent-organic* NEAR1 framework*) OR (covalent* NEAR1 organic* NEAR1 framework*) OR COF OR COFs OR (absorb* NEAR1 (material* OR matter* OR compound* OR mixtur* OR substanc* OR component* OR constituent* OR element* OR structur*)) OR clathrat* OR (cage-like NEAR1 structur*) OR ((cage ADJ like) NEAR1 structur*) OR (crystal* NEAR1 solid*) OR (water ADJ cage))) NOT ((liquid* OR liquef* OR cryogen* OR cryonic* OR gaseous* OR compress* OR (gas* NEAR1 compress*)) NEAR3 (hydrogen OR H2 OR H)));	2.983	2.390	1.854
Proton-exchange membrane fuel cells (PEMFC)	CTB=((PEM* OR (proton* ADJ exchang* ADJ membran*) OR (proton-exchang* ADJ membran*) OR (proton-conduct* ADJ membran*) OR (proton* ADJ conduct* ADJ membran*) OR (polymer* ADJ electrolyt*)) NEAR1 (((Fuel* OR Electrochemical*) ADJ (cell* OR Batter*)) OR (Fuel* ADJ Power* ADJ System*) OR Electrochemical* NEAR1 ((Power OR Energy) ADJ (Conver* OR Generat* OR Sourc*))) OR (*PEMFC* AND (Hydrogen* OR H2 OR H))) OR (CTB=((PEM* OR (proton* ADJ exchang* ADJ membran*) OR (proton-exchang* ADJ membran*)	30.647	22.404	13.749

	OR (proton-conduct* ADJ membran*) OR (proton* ADJ conduct* ADJ membran*) OR (polymer* ADJ electrolyt*))) AND AIC=(H01M000800));			
Alkaline Fuel Cells (AFC)	CTB=((bacon* OR alkalin* OR (anion-exchang*) OR (anion* NEAR1 exchang*) OR (hydroxid* NEAR1 exchang*) OR (basic* NEAR1 membran*) OR (basic* NEAR1 polymer*)) NEAR1 (((Fuel* OR Electrochemical*) ADJ (cell* OR Batter*)) OR (Fuel* ADJ Power* ADJ System*) OR Electrochemical* NEAR1 ((Power OR Energy) ADJ (Conver* OR Generat* OR Sourc*))) OR ((*AFC* OR AEMFC* OR AMFC* OR HEMFC* OR SAFC*) AND (Hydrogen* OR H2 OR H))) OR (CTB=((bacon* OR alkalin* OR (anion-exchang*) OR (anion* NEAR1 exchang*) OR (hydroxid* NEAR1 exchang*) OR (basic* NEAR1 membran*) OR (basic* NEAR1 polymer*))) AND AIC=(H01M000800));	15.315	13.810	10.255
Phosphoric Acid Fuel Cell (PAFC)	CTB=(((phosphoric* near2 acid*) near3 (((Fuel* OR Electrochemical*) ADJ (cell* OR Batter*)) OR (Fuel* ADJ Power* ADJ System*) OR Electrochemical* NEAR1 ((Power OR Energy) ADJ (Conver* OR Generat* OR Sourc*)))) OR (phosphoric* near1 acid* near3 electrolyt*) OR (*PACF* AND (Hydrogen* OR H2 OR H))) OR (CTB=(phosphoric* near2 acid*) AND AIC=(H01M000800));	5.186	4.325	2.965
Molten Carbonate Fuel Cell (MCFC)	CTB=(((((molten* OR liquid*) near2 carbonat*) or molten-carbonat* OR liquid-carbonat*) near3 (((Fuel* OR Electrochemical*) ADJ (cell* OR Batter*)) OR (Fuel* ADJ Power* ADJ System*) OR Electrochemical* NEAR1 ((Power OR Energy) ADJ (Conver* OR Generat* OR Sourc*)))) OR (MCFC* AND (Hydrogen* OR H2 OR H))) OR (CTB=(((molten* OR liquid*) near2 carbonat*) or molten-carbonat* OR liquid-carbonat*) AND AIC=(H01M000800));	4.897	3.802	2.108
Solid Oxide Fuel Cell (SOFC)	CTB=((((solid ADJ oxide) or ceramic) NEAR1 (((Fuel* OR Electrochemical*) ADJ (cell* OR Batter*)) OR (Fuel* ADJ Power* ADJ System*) OR Electrochemical* NEAR1 ((Power OR Energy) ADJ (Conver* OR Generat* OR Sourc*)))) OR (*SOFC* AND (Hydrogen* OR H2 OR H))) OR (CTB=((solid ADJ oxide) or ceramic) AND AIC=(H01M000800));	31.548	22.169	12.937
Direct Methanol Fuel Cell (DMFC)	CTB=((methanol* NEAR3 (((Fuel* OR Electrochemical*) ADJ (cell* OR Batter*)) OR (Fuel* ADJ Power* ADJ System*) OR Electrochemical* NEAR1 ((Power OR Energy) ADJ (Conver* OR Generat* OR Sourc*)))) or (DMFC* AND (Hydrogen* OR H2 OR H))) OR (CTB=(methanol) and AIC=(H01M000800));	10.589	7.922	4.910
Internal Combustion Engine (ICE)	CTB=(((((combust* OR piston* OR reciprocating* OR otto OR spark-ignition* OR (spark* NEAR1 ignition*) OR compression-ignition* OR (compression* NEAR1 ignition*)) NEAR3 engin*) OR ICE) AND (hydrogen* OR H2 OR H)) NOT (((Fuel* OR Electrochemical*) ADJ (cell* OR Batter*)) OR Electrochemical* NEAR1 ((Power OR Energy) ADJ (Conver* OR Generat* OR Sourc*)))) AND (AIC=(B60) OR AIC=(B62) OR AIC=(B63));	9.746	9.621	6.512

Direct Reduced Iron	CTB=(((direct* NEAR1 reduc* NEAR3 (iron* OR Fe OR Fe2O3 OR (iron* ADJ ore*) OR steel* OR ferrous* OR ferrum*)) OR DRI ADJ H-DRI OR H2-DRI OR sponge-iron* OR (spong* NEAR1 iron*)) NEAR5 (hydrogen* OR H2 OR H));	282	244	188
Blending in Blast Furnaces	CTB=(((hydrogen* OR H2 OR H) NEAR3 (mix* OR blend* OR reduc* OR inject* OR introduc* OR incorporat*)) NEAR3 (iron* OR Fe OR Fe2O3 OR (iron* ADJ ore*) OR steel* OR ferrous* OR ferrum*) AND (furnac* OR BF OR blast));	598	511	464
Smelting Reduction	CTB=(((smelt* NEAR3 (hydrogen* OR H2 OR H)) OR H-smelt* OR H2-smelt* OR hydrogen-smelt* OR Hlsarna* OR Hyl-SR OR (Hyl ADJ1 SR) OR HylSr) NEAR5 (iron* OR Fe OR Fe2O3 OR (iron* NEAR1 ore*) OR ferrous* OR ferrum* OR steel*));	147	122	120

TABLE 2: SEARCH QUERIES HYDROGEN VALUE-CHAIN-RELATED TECHNOLOGIES

```
import pandas as pd #import library pandas

df_hydrogen = pd.read_excel('LISTA.xlsx') #read the excel file containing the
application code of all EP hydrogen patents and save these into variable
df_hydrogen

df_applications = pd.read_csv('applications.csv', sep=';').set_index('APLN_CD')
#read the csv file from PATSTAT containing the application code of all EPO patents
and save these into variable df_applications; set it in the first column of the
table

df_merged = pd.merge(df_hydrogen, df_applications, left_on='CODE',
right_index=True)
#merge df_applications with df_hydrogen and match them using the Application Code;
save this into the variable df_merged

df_cited = pd.merge(df_merged_with_classes, df_citations) #merge
df_merged_with_classes with df_citations and match them using the APLN_ID of the
cited patent;  display each cited-citing couple in each line

df_full_cited = pd.merge(df_cited, df_subclasses, left_on='FRWD_APLN_ID',
right_on='APLN_ID', suffixes=['_HYDR', '_FWD']).groupby(['CODE', 'APLN_ID_HYDR',
'SBCLS_CD_HYDR', 'APLN_ID_FWD']).aggregate({'SBCLS_CD_FWD': [set, lambda g:
len(set(g))] }).rename({'<lambda_0>': 'count'}, axis='columns') #merge df_cited and
df_subclasses; display on the same line a list of all the subclasses to which the
citing patents belong; add all other desired fields

df_subclasses = pd.read_csv('subclasses.csv', sep=';') #read the csv file from
PATSTAT containing the subclasses of all EPO patents and save these into variable
df_subclasses

df_merged_with_classes = pd.merge(df_merged, df_subclasses).groupby(['CODE',
'APLN_ID']).aggregate({'SBCLS_CD': frozenset }).reset_index() #merge df_merged with
```

```
df_subclasses and match them using the APLN_ID; keep application code; aggregate in
the same line all the subclasses for each patent; save this into the variable
df_merged_with_classes

df_citations = pd.read_csv('citations.csv', sep=';') #read the csv file from
PATSTAT containing the application IDs of the forward citations of all EPO patents
for all EPO patents and save these into variable df_citations

def compute_index(code_rows):
    #get the classes of the cited patent
    classes = set(code_rows['SBCLS_CD_HYDR'].iloc[0])
    #compute the HHI index for each cited hydrogen patent patent
    sum_of_squares = 0.0
    for cl in classes:
        sum_of_squares += (code_rows[('SBCLS_CD_FWD', 'set')].map(lambda r: cl in
r).astype(int).sum() / code_rows[('SBCLS_CD_FWD', 'count')].sum())**2
    return 1.0 - sum_of_squares

df_citing_patents_total =
df_full_cited.reset_index().groupby(['CODE']).apply(compute_index) #display the EP
Application Code of the cited hydrogen patent and its corresponding HHI index
```
IMAGE 4: PYTHON CODE TO DERIVE GENERALITY INDICATORS FOR ALL HYDROGEN EPO PATENTS